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ORIGINAL PAPER

Legume Biochar Fertilizer Can Be an Efficient Alternative to Compost in Integrated Nutrient Management of Paddy (*Oryza sativa* L.)

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Abstract

Continuous use of chemical fertilizers is detrimental to soil health and crop productivity. Therefore, we need to recycle the agroresidues in the valorized form (e.g., biochar or compost) to improve soil quality while maintaining crop yield. This study compares different nutrient management practices using varied dose combinations of biochar/compost for sustainable production of rice. We present the results from a controlled environment study under nine different nutrient management options to assess the effect of a novel legume biochar fertilizer compared with legume-derived compost. Our results suggest that a relatively smaller dose of soil test-based balanced fertilization (75% of required nutrients) added with novel biochar (25% nutrient equivalence) is the best combination in nutrient-poor vertisols of semi-arid tropics. The yield benefits from novel biochar fertilizer might find relevance to similar total–N content to compost, although there are noticeable differences in other macronutrients, secondary, and micronutrients. The surface area and C:N ratio are significantly higher for biochar (i.e., 4.47 m^2g^{-1}; 37.68) than that of compost (i.e., 0.87m^2g^{-1}; 10.5) which provides a boost to rhizospheric interactions resulting in higher plant nutrient uptake resulting in improved plant growth attributes at lower doses. In addition, integrated biochar with mineral fertilizers improves soil organic carbon at the harvest of paddy by 44–54% than sole mineral fertilizer compared to a meager increase (10–15%) in compost. This study suggests a novel alternative (as legume biochar fertilizer) to compost that can have policy implications for developing a carbon-negative fertilization technique in paddy farming.

Keywords Agroresidues · Recycling · Biochar · Compost · Nutrient management · Paddy

1 Introduction

Grain legumes are an essential component of cereal-based crop rotation in India and have grown to 23.5 million hectares with an annual production status of 12.2 million mt in India, making it one of the world's leading legume-producing countries. These grain legumes have access to atmospheric nitrogen through symbiosis with rhizobium bacteria and contribute to the success of non-legumes after the decomposition of the leaf litter and its roots. However, pigeon pea (*Cajanus cajan*) and chickpea (*Cicer arietinum*) stovers, which are rich in biopolymers, lignin and cellulose, are usually removed from the field and are also of less importance as feed due to hardness. Traditionally, legumes stovers have been used as green manures to maintain soil fertility, but these are known to be "problems" in conventional tillage schemes. Furthermore, since legumes are eventually decomposed in soil when used as green manure, the elimination or field burning of residues has been commonly performed to accelerate their degradation, contributing ammonia and aerosols to the environment. However, these high lignin contents in legume stovers can be utilized to produce organic fertilizers by rapid pre-decomposition using microbial culture (composting) or heat (pyrolysis). Many studies report using various agricultural residues such as paddy husk, corn stover, corn cobs, and cotton stalks for organic fertilizer preparation (Lateef et al. 2019; Trivedi et al. 2018)

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and a few reports the use of legume stover. Organic fertilizers produced from more nutritious agricultural residues such as legume stovers can have beneficial effects (Mukherjee et al. 2014) for soil carbon sequestration and crop yield (Agegnehu et al. 2017).

Nevertheless, the supply of essential plant nutrients in soil is a growth-limiting factor towards production; the optimal supply of all nutrients required by a plant improves growth and yield parameters necessary for staple food crops to ensure food security (Wani et al. 2018). Rice is a staple food for Asian countries and an important cereal crop in India with a production status of 100 million tons that back to 41% of the country's total food production. Exertions are being made to improve the rice yield by adopting various measures to accomplish global food security goals. However, the lowest hanging fruit to achieve this target has been the vehement use of chemical fertilizers for decades (Lal 2010; Wani et al. 2018). Over the last few years, Indian farmers have faced the challenges of a fertilizer crisis with unsustainable price increases, and their supply on time has become a matter of grave concern.

Furthermore, chemical fertilizers lower the nutrient use efficiency and cause acidification of soil and fast degradation of soil organic matter (SOM), besides causing environmental problems through leaching and volatilization of trace gases such as ammonia and other greenhouse gases (Savci 2012). As a result, farmers use the available organic inputs and the appropriate quantity of chemical fertilizers for higher crop yields and economic benefits. Additionally, due to energy scarcity, increased prices of fertilizers, degradation of soil quality, and environmental issues, the use of organic amendments is gaining importance (Moe et al. 2019). However, selecting a suitable organic amendment for different soils is a challenge (Sánchez-Monedero et al. 2019) and should not be generalized to compost in every case.

Still, the critical issue regarding conventional organic fertilizers (e.g., compost and vermicompost) as part of nutrient management strategies in rice is the rise in metal concentration (Baldwin and Shelton 1999). Apart from this, methane emissions originating from pre- and post-application of conventional organic fertilizers in paddy soils are distressing the climate. However, the relatively recent idea of using biochar as part of nutrient management techniques in various crops has been documented to minimize greenhouse emissions by modulating soil nutrient dynamics, decreasing soil metal concentration, and increasing yield (Agegnehu et al. 2015). Due to its inherent recalcitrance and durability in the soil, the use of biochar instead of conventional compost in semi-arid tropics can have long-term benefits considering severe climate conditions (Rawat et al. 2019). Biochar could add environmental benefits by reducing the uptake and bioavailability of pesticides and metals in plants where recycled water emerges as an irrigation solution, particularly in frequent drought-prone peninsular India. Biochar becomes oxidized and preserves more nutrients with aging even in poor weather than compost, which decomposes relatively quickly in soil and has to be replenished regularly. However, the biochar must be designed to meet the needs and requirements of soil for more significant benefits. For example, biochar can be charged with nutrient-rich organic solutions, depending on their properties, to harness more substantial returns.

Biochar properties depend on different conditions, viz. feedstock, pyrolysis, feed moisture, and nutritional content (Tag et al. 2016). Though woody biomass is commonly used to produce biochar due to high lignin content, forest-wood use is discouraged, and agricultural residues for biochar production are gaining importance (Domingues et al. 2017). Furthermore, the biochar produced with slow pyrolysis of more nutritious agrarian residues such as legume stover can have beneficial effects (Mukherjee et al. 2014) on soil carbon sequestration and crop yield (Agegnehu et al. 2017). Biochar's sorption property is key to designer biochars and primarily relies on the structure of carbohydrate biopolymers (e.g., cellulose and lignin, Li et al. 2014). However, biochar's adsorptive properties are predominantly controlled by lignin content, whereas aliphatic cellulose molecules are essential to the desired aromaticity of biochar (Cagnon et al. 2009). The aromaticity of the biochar surface is vital for nutrient charging and can be ensured with the low initial moisture of feedstock being pyrolyzed. In addition, low feed moisture also decreases energy demand and pyrolysis time, providing a more polyaromatic biochar surface (Darmstadt et al. 2000; Tripathi et al. 2016).

In addition to the feedstock type and moisture, pyrolysis temperature also significantly affects biochemical characteristics such as specific surface area, pH, and surface functional groups (Tomczyk et al. 2020). Although higher activation temperature can result in increased porosity in biochar, it results in substantial loss of nutrient nitrogen (N) and sulfur (S) elements (Middleton et al. 2016). Few studies also found that the biochar produced at higher temperatures may not be helpful in alkaline soil (Spokas et al. 2012). One of the main problems with high-temperature pyrolyzed biochar is the immobilization of nutrient elements that can reduce crop yields (El-Naggar et al. 2019). However, slow-pyrolysis at low temperature can result in biochar that can be used as a sluggish N-release fertilizer as a part of nutrient management strategies in paddy cultivation (Dong et al. 2020) and might show better agronomic performance when charged with organic solvents (Schmidt et al. 2017). Low-temperature biochar is hydrophilic due to incomplete conversion of lignin to polycyclic aromatic hydrocarbons. Therefore, it is necessary to evaluate the potential of legume biochar as a biofertilizer alternative to compost in alkaline soils. Apart from these, the role of biochar as a biofertilizer in submerged soils (i.e., paddy soil) is needed to be looked at in detail.

Furthermore, producing more food to feed the ever-increasing population sustainably needs consistent efforts through different nutrient management schemes involving suitable organic amendments (Abrol and Gupta 2019). There is also a dearth of knowledge regarding the comparative evaluation of organic materials as organic fertilizer in integrated nutrient management (INM) of paddy, which is differentially decomposed from the same feedstock (Sánchez-Monedero et al. 2019). The novel legume biochar may be an effective alternative to legume-derived compost in vertisols of semi-arid tropical zones. However, legume biochar dosage must be ascertained considering alkaline soil pH. Therefore, we planned a comparative nutrient management analysis in paddy crops grown in vertisol to assess nutrient management strategies, including two levels (i.e., low and high doses) of biochar vis-à-vis compost and inorganic fertilizers (i.e., a blanket recommendation as farmers practice and soil test-based balanced fertilization).

2 Material and Methods

2.1 Preparation, Characterization, and Performance Evaluation of Biochar vis-à-vis Compost

Biochar and compost fertilizers were prepared using legume stovers obtained from the International Crops Research Institute for Semi-Arid Tropics (ICRISAT) in Patancheru, India. After cutting pigeon pea and chickpea shoots into pieces of less than 5 cm, composite samples were collected for chemical analysis after mixing them in a 1:1 ratio (w/w). We prepared compost through a microbial consortium culture using the methods defined by Chander et al. (2018). The biomass was laid in layers on a cemented floor, and each layer was covered with cow dung slurry (in a ratio of 80:20; Biomass: Cow dung) with added microbial culture (@ 1 kg ton-1 biomass). Frequent turning of compost heap was done to facilitate decomposition, and temperature of the heap was measured weekly at 0.15 and 0.30 m. The maturity of compost was determined by color, texture, and temperature stabilization of the compost heap. We also prepared the biochar using the same shredded mixture by feeding them to an adapted, portable, indigenously fabricated, and single barrel Kiln for slow pyrolysis at 409 °C with a biomass loading rate of 26.5 kg per Kiln (Govindarajan 2014). It was ensured that the shredded biomass had a moisture content of 10–12% before it was fed to the Kiln. The biochar thus produced was quenched with cow dung leachate and water mixture (1:5 ratio; v/v) when the cooling reached 100 °C. The biochar was then air-dried in the shade, crushed manually, and applied to the experimental soil in pots. We collected the composite samples for prepared biochar, cow dung leachate mixture, and mature compost, homogenized and dried at 65 °C for 24 h, manually ground using a mortar, and sieved using 0.2-mm sieve before the physico-chemical characterization.

The volatile matter (VM) and ash content of the biochar were determined following the procedures explained by the American Society for Testing and Materials (ASTM 2013) D 1762–84 using a laboratory muffle furnace. Biochar samples are heated for 6 min and 6 h at 950 °C and 750 °C, respectively, to determine VM, ash content, and fixed Carbon (Wang et al. 2017). Thermogravimetric analysis was performed at a heating rate of 10 °C per min in the nitrogen environment using the Thermogravimetric instrument (Model: Universal SDT Q600 V20.9) from 25 to 1200 °C. The surface morphology of biochar and compost was investigated using a scanning electron microscope (SEM) (Model: JEOL- JSM-IT500HR SEM) for identifying their surfaces and structures. Energy-dispersive X-ray spectrometry (EDS) was performed using a simultaneous multi-scan-enabled EDS instrument (Model: JPS-9030, JEOL Ltd. JAPAN) and used for quantitative analyses of elemental atomic ratios. The surface area of biochar and compost samples was determined using Sear's method (Al-Qodah and Shawabkah 2009). The surface functionalities of both compost and biochar were determined using transmission Fourier transform Infrared spectroscopy (FTIR) (Liu et al. 2015). The infrared spectra in 4000–400 cm^{-1} were recorded using the FTIR spectrophotometer (Model: Perkin-Elmer 2000) by KBr pellet method with having fifty scans for each sample in each spectrum. Background correction for ambient air was also done for the reported average value in each spectrum. Spectra peaks were reported in the form of a printed spectrum, having *Y*-axis in absorbance and *X*-axis in wavenumbers (cm^{-1}); interpreted using results from the previous experiments (Liu et al. 2019; Shi et al. 2020). A double-distilled water suspension of compost and biochar in a ratio of 1:10 (w/v), after mechanical agitation of 30 min, was used to measure pH and electrical conductivity (Tag et al. 2016). We analyzed the samples for N, phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), boron (B), zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn) in triplicates by following the standard procedures described in Jones et al. (1991) and Sahrawat et al. (2002).

The experiment was conducted in a greenhouse located at the controlled environment research facility (CERF) with steady temperature and humidity conditions at ICRISAT global headquarters, Patancheru, India, (17.5° N, 78.2° E) in the year 2019 (June–October) to evaluate the performance of legume biochar in comparison with the conventional organic and inorganic nutrient management practices for paddy. We collected the top layer (0–15 cm) soil from an uncultivated area of ICRISAT campus for this experiment. The soil was cleaned, crushed, and sieved to remove debris. Physical and chemical analysis followed conventional procedures (Rathje 1959), and results are reported in Table S1. The soil belongs to the US soil taxonomy's Vertisol order, distinguished by its high clay content. We filled the soil (15 kg per cylinder-shaped pot) in plastic pots (30-cm top diameter, 30-cm bottom diameter, and 25-cm height) and tapped it with a wooden hammer to achieve the desired bulk density. The pots were then fully saturated with water through capillary rise by putting them in a water bath for a week to allow the soil to set. During the experiment, we collected the soil 55 days after transplantation (DAT) (i.e., maximum tillering stage) and 140 DAT (Harvest stage) for chemical analysis following the standard procedure for soil chemical analysis (Rego et al. 2007). For instance, the soil available macronutrients such as Total-N were determined by the Kjeldahl distillation method, P by the NH4F-extraction method, and K by the NH_4OAc-extraction method (Rathje 1959). Apparent nutrient recovery (ANR) for N, P, and K in all treatments was calculated according to Sadaf et al. (2017) using Eq. (1):

$$\mathrm{ANR}(\%) = \frac{(\mathrm{NCT} \times \mathrm{DMT}) - (\mathrm{NCC} \times \mathrm{DMC})}{\mathrm{TN}} \times 100 \quad (1)$$

where NCT is nutrient content in fertilization treatment, DMT is dry matter from the respective treatment, NCC is nutrient content in the control treatment, DMC represents dry matter in the control treatment, and TN is the total amount of applied nutrient.

2.2 Experimental Design

The experiment was laid in a completely randomized design with nine different nutrient management treatments in six replications using various organic and mineral fertilizer combinations. We planned various treatments to determine the use of different doses (low/high) of biochar relative to compost as part of the INM strategies of paddy. Besides, we also compared the sole applications of alternative organic fertilizers with different INM and sole mineral fertilization at recommended and soil test levels of N, P, and K to test the overall efficacy of all possible strategic alternatives for organic, inorganic, and INM in paddy cultivation. We maintained absolute control without any fertilizer application to observe the native soil fertility. The combinations of each fertilizer used in the experiment are shown in Table 1, specifying the different amounts of individual fertilizers added to make distinct nutrient formulations or treatments (T) in terms of fertilizer use. We supplied the nutrients N,

Table 1 Description of nutrient management treatments for cultivation of rice

T. No	Nutrient management treatments	Nutrient management treatment abbreviation	Urea (g/pot)	Single super phosphate (g/pot)	Muriate of potash (g/pot)	Zinc sulfate (g/pot)	Aerobic compost (g/pot)	Biochar (g/pot)
T1	Control without any fertilizer application	Con	—	—	—	—	—	—
T2	NPK at recommended dose (farmer's practice)	CF_{FP}	1.50	2.00	0.65	—	—	—
T3	Soil test-based NPK + deficient micronutrients (STB)	CF_{STB}	1.72	2.50	0.50	0.47	—	—
T4	Sole biochar application (@100% N equivalence)	BC_{100}	—	—	—	—	—	76.36
T5	Sole compost application (@100% N equivalence)	CO_{100}	—	—	—	—	76.36	—
T6	Low-dose biochar-based INM (75% STB + biochar @25% N equivalence)	$CF_{STB75}+BC_{25}$	1.29	1.87	0.37	0.35	—	19.00
T7	Low-dose compost-based INM (75% STB + compost @25% N equivalence)	$CF_{STB75}+CO_{25}$	1.29	1.87	0.37	0.35	19.00	—
T8	High-dose biochar-based INM (50% STB + biochar @50% N equivalence)	$CF_{STB50}+BC_{50}$	0.86	1.25	0.25	0.23	—	38.18
T9	High-dose compost-based INM (50% STB + compost @50% N equivalence)	$CF_{STB50}+CO_{50}$	0.86	1.25	0.25	0.23	38.18	—

Note: NPK means nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O); INM means integrated nutrient management

P, and K at a rate of 100, 50, and 60 kg ha^{-1}, respectively, as recommended fertilization dosage, whereas 125, 62.5, and 45 kg ha^{-1} of N, P, and K, respectively, as soil test-based (STB) recommendation in the form of urea, single superphosphate (SSP), and muriate of potash (MOP). STB treatments were provided with deficient micronutrient Zn as a basal application in the form of $ZnSO_4$ at a rate of 25 kg ha^{-1} for the recommended full dose. We applied the organic fertilizers (i.e., compost and biochar) at a dose to accomplish 100% N recommendation when used as a single nutrient source and 75% or 50% dose of N when integrated with mineral fertilizers. The mineral fertilizers were applied as a concentrated solution evenly in pots a day before planting, while biofertilizers (organic fertilizers) were mixed thoroughly in the top-soil (5 cm). We added all mineral fertilizers basal as of their full dose except mineral N, which has been used 50% basal and 50% at the panicle development stage.

2.3 Plant Material

The rice plant cultivar 'Swarna' (MTU7029) is used as a test crop in the experiment. This is a medium-long duration (140–150 days) cultivar suitable for heavy clay soils. This variety has a comparatively long vegetative period and can be expected to sufficiently capture the variability in plant available nutrients compared to slow nutrient release organic fertilizers. We transplanted the seedlings (21–days old) after taking them out from the nursery (seed rate 30 g m^{-2}, fertilizer rate 100–60–40 of N-P_2O_5-K_2O), and two seedlings $hill^{-1}$ were planted in each pot in two preformed holes.

2.4 Crop Growth Attributes, Leaf Chlorophyll, Grain Yield, Quality, and Economics

We measured the plant height, tiller number, and leaf nitrogen (measured using the soil plant analysis development system or SPAD) at 30-day intervals from the transplanting day. The effect of different nutrient management practices on leaf chlorophyll of rice crop was measured for the third fully open leaf at leaf-lamina and mid-rib region at three other spots, and average values are compared. The rice yield components such as panicles number, filled spikelet, test weight, and harvest index are calculated. Plant parts such as straw and grain were oven-dried at 65 °C for 72 h before chemical analysis, and the shelled grains and straw were ground and passed through a 1-mm sieve and homogenized before the chemical analysis. The total N, P, and K contents are analyzed in straw and grain subsamples using previously described standard protocols (Jones et al. 1991; Sahrawat et al. 2002). The amylose and protein contents in rice grain, which corresponds to glutelin, are obtained using the method described by Nayak et al. (2019). The cost of production is estimated using the data for the production of biochar/compost, including processing and operation, and is following the bulk production cost and market value for fertilizers. The yield per pot and cost per gram of grain produced are estimated to have a preliminary assessment of cost trend for different nutrient management strategies.

2.5 Statistical Analysis

We have expressed the results as the average value of replicates together with standard deviation (SD) (mean ± SD). The significance test is performed using one-way ANOVA, followed by Tukey's post hoc test to compare the mean values of variables between the treatments. We have also used a two-way ANOVA to examine the interaction effect of cultivation time and fertilizer treatments. The canonical variate analysis is conducted to assess the performance of treatments with respect to their growth and yield attributes. All the statistical analyses are subjected to the significance level of 0.05 using GenStat software (Edition 15th, VSNi, UK).

3 Results

3.1 Characterization of Legume Biochar and Compost as Biofertilizer Amendments to Soil

3.1.1 Proximate and Surface Analysis

The electron micrographs (Fig. 1a, b) revealed that biochar is highly porous with visible pore spaces having crystalline depositions near and in the pores (e.g., red circle in Fig. 1a), while the compost shows a highly irregular surface with few pores and surfaces covered with structures like fungal mycelium. The porous structure of both organics is further ascertained with results for the specific surface area of biochar (4.47 m^2g^{-1}), which is significantly ($p = 0.014$) more extensive than the compost (0.87 m^2g^{-1}). Legume biochar has shown higher fixed carbon (53.1%) than the respective compost (12.5%). However, biochar is low in the volatile matter (12.5% vs. 34.1%) and ash content (34.4% vs. 53.8%) than compost. The FTIR spectra of compost and biochar illustrate the functional groups present on their surface (Fig. 2). The peaks associated with 1400–1436 cm^{-1} indicate phenolic and carboxylic hydroxyl group (OH), whereas the peak at 1580 cm^{-1} in biochar represents N–O bonds' vibration, which might be a part of nitro compounds. The FTIR spectra obtained for legume biochar and compost samples show the presence of polar groups on their surface. The presence of carbohydrates as denoted by a FTIR peak of 1080 cm^{-1} compared to biochar is a special feature of the compost made from legume stover. Subsequently, as carbohydrates are hydrophilic, the saturation with the –OH group (i.e.,

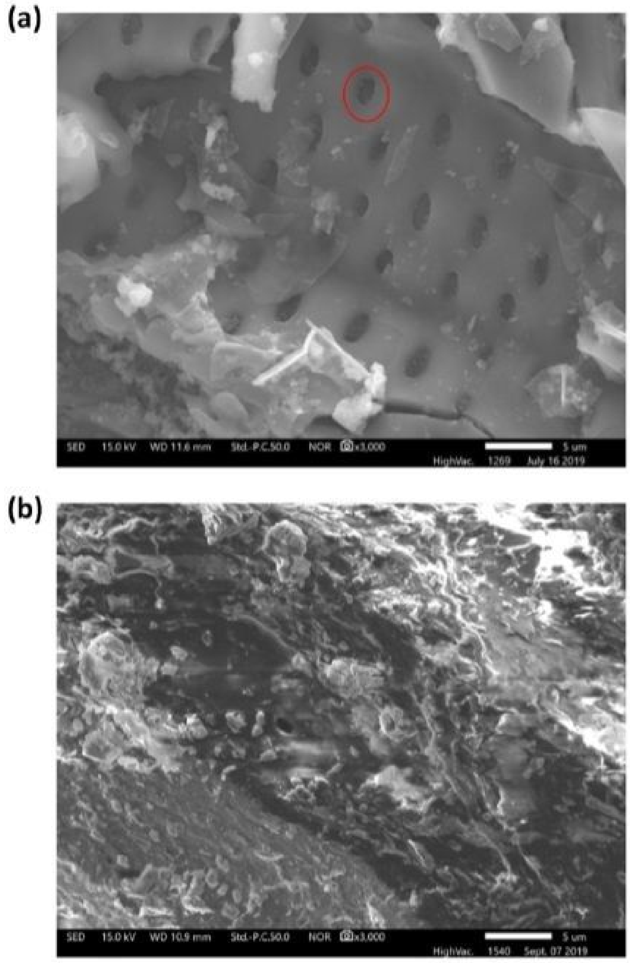
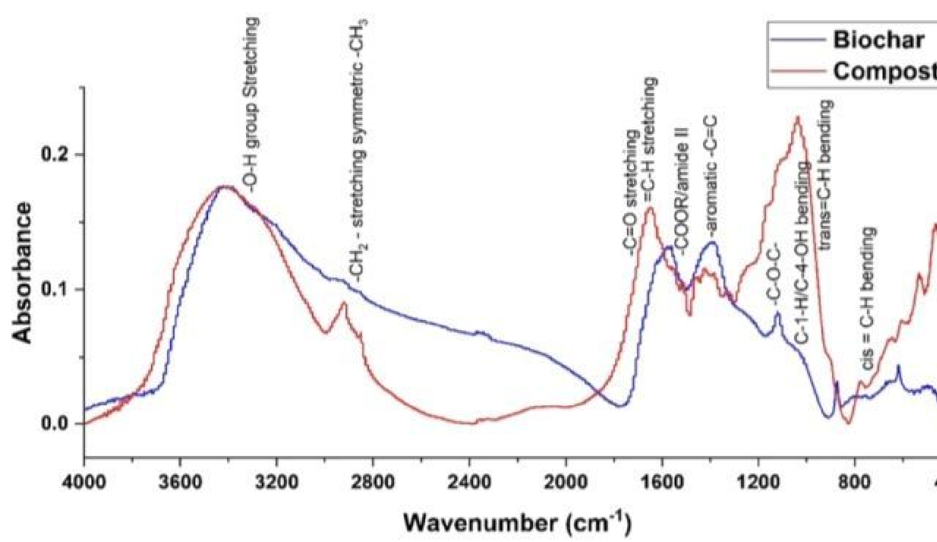


Fig. 1 Scanning electron micrographs: Surface of (a) biochar and (b) compost, at a resolution of 3000× with probe current corresponding to 15.0 kV in secondary electron detection (STD) mode. The red circle on biochar micrographs showing crystalline deposits near pore lumen

about 3400 cm^{-1} suggesting C=O carbohydrate stretching) for compost is apparent in spectra. The improved signals of biochar in FTIR spectra at 2000–3000 cm^{-1} represent vibrations for saturated carbon, which may be considered chemically inert/stable, but can participate in the formation of weak H- bonds. FTIR spectra below 2000 cm^{-1} confirm the different nature of both organic materials (i.e., biochar and compost); however, spectral region beyond 3000 cm^{-1} denotes degree of unsaturation and thus chemical reactivity of carbon atoms present in both materials. Comparatively weak, but distinct and separate peaks for both biochar and compost samples are found at 400–600, 890, and 1016 cm^{-1} relative to compost, reflecting the bending of C–H bonds and the stretching of C=C and C=N bonds, respectively; however, these can be attributed to differences in chemical nature of both products.

The thermal stability of biochar and compost is analyzed through thermograms presented in Fig. S1. The thermogravimetric peak below 200 °C (Temp. < 200 °C) is due to the depletion of moisture and water-soluble compounds (Matusiak et al. 2020), between 250 and 500 °C reflects hemicellulose and cellulose degradation and 650–750 °C, lignin degradation, in all organic matter. The peak is narrow and sharp for the derivative weight (dW/dT) in biochar, whereas a comparatively broader peak in compost represents the sorption of water-soluble nutrients in biochar pores as depicted in SEM and the moisture present in compost. The weight loss due to loss of moisture is 8.5% in biochar but 10% in compost, indicating more initial moisture content in freshly prepared compost. However, a comparatively smaller peak for hemicellulose and cellulose degradation and larger for lignin degradation in biochar show that slow-pyrolysis at low temperature (409 °C) results in the degradation of most hemicellulose and cellulose compounds in legume stover.

Fig. 2 Fourier transform infrared (FTIR) spectrum: Comparative spectra of biochar and compost ranging from wavenumber 4000–400 cm^{-1} showing peaks with the description of the functional groups



3.1.2 Ultimate and EDS Analysis

The ultimate analysis of biochar and compost, shown in Table 2, reveals that both are comparable in total–N content. The compost and biochar show improved nutrient value than raw legume stover feedstock due to microbial and thermal decomposition of lignocellulosic biomass in compost and biochar. Compost is rich in Fe, Zn, Ca, Mg, S, B, and total–P content, whereas biochar is rich in K, Mn, and Cu content. On the other hand, C:N ratio is higher in the biochar (37.68) than compost (10.5), suggesting comparatively higher stability of biochar in soil. EDS spectra of biochar and compost samples are presented in Fig. S2. The energy spectra in the 0.277 keV range show relatively higher counts of elemental Carbon (C) in biochar (56.24%) than compost (29.13%) and justify the ultimate analysis. Nevertheless, the signals for N are comparable for both biochar and compost (Biochar: 9.92%; compost: 9.49%), which indicates the sorption of N (0.392 keV) on the biochar surface due to nutrient charging. The presence of more hydroxyl groups in compost as depicted in FTIR spectra reflected as more oxygen (O) counts in compost (59.12%) than biochar (19.75%) for the 0.525 keV region.

3.2 Effect of Different Fertilizer Treatments on Soil Properties

The effect of nutrient management practices at the active growth (maximum tillering) and harvest stage of the crop is observed on the pH and electrical conductivity (EC) of soil, as presented in Fig. 3a, b, respectively. The mineral fertilizer treatment (soil test based), receiving the highest N, shows the lowest pH (7.8) at the maximum tillering and harvest stage. Similarly, it is observed that treatments in INM, receiving 75% doses of soil test-based mineral fertilizers (i.e., T6 and T7), are significantly lower in pH (7.9–8.1) than those receiving 50% dose (i.e., T8 and T9). On the other hand, the sole mineral fertilizer treatments (i.e., T2 and T3) have shown higher EC at the maximum tillering stage.

The effect of fertilizer treatments on soil organic carbon (OC) status is significantly different among the treatments at the rice plant's active tillering and harvest stage (Table 3). Sole application of biochar resulted in a higher OC content than sole compost or any other treatments. INM treatments have significantly higher OC content than exclusive mineral fertilizer treatments (i.e., T2 and T3) at both the early and harvest stage of paddy. However, at the harvest stage, sole biochar treatment is showing an insignificant increase in OC from its active tillering stage, contrary to sole compost treatment.

Table 2 Nutrient composition of legume straw, compost, cow dung leachate, and biochar used in the experiment

Parameters	Straw	Values for component Compost	Cow-dung leachate	Biochar
pH	—	6.86 ± 0.21^a	6.77 ± 0.04^a	7.84 ± 0.08^b
EC (dSm^{-1})	—	6.30 ± 0.07^a	1.23 ± 0.11^b	5.51 ± 0.02^c
Surface area (m^2g^{-1})	—	0.87 ± 0.08^a	—	4.47 ± 1.85^b
Ash (%)	—	53.37 ± 0.51^a	—	34.41 ± 1.31^b
Fixed carbon (%)	—	12.53 ± 1.46^a	—	53.11 ± 2.17^b
Volatile matter (%)	—	34.10 ± 1.97^a	—	12.48 ± 1.40^b
Fe (mg/kg)	80.67 ± 8.61^a	5092.5 ± 43.13^b	12.44 ± 1.17^c	1774.84 ± 126.21^d
Cu (mg/kg)	3.66 ± 0.30^a	14.695 ± 0.45^b	1.4 ± 0.04^c	17.7 ± 0.31^d
Mn (mg/kg)	23.61 ± 0.05^a	311.82 ± 0.25^b	4.6 ± 0.85^c	399.50 ± 28.62^d
Zn (mg/kg)	8.13 ± 0.43^a	110.22 ± 1.73^b	6.66 ± 0.52^c	90.94 ± 5.37^d
B (mg/kg)	12.15 ± 0.34^a	57.94 ± 1.67^b	3.23 ± 0.65^c	45.65 ± 1.90^d
Ca (mg/kg)	4170.78 ± 270.21^a	$39{,}825.5 \pm 212.84^b$	340.33 ± 7.64^c	$31{,}573.07 \pm 785.53^d$
Mg (mg/kg)	1242.12 ± 158.46^a	7800.12 ± 125^b	128.33 ± 9.45^c	4233.2 ± 21.31^d
S (mg/kg)	494.79 ± 63.86^a	1790.5 ± 48.79^b	79.66 ± 15.12^c	1455.18 ± 18.32^d
Total N (%)	0.90 ± 0.09^a	1.04 ± 0.08^a	0.09 ± 0.003^b	1.01 ± 0.02^a
Total P (%)	0.12 ± 0.02^a	0.92 ± 0.01^b	0.07 ± 0.001^c	0.34 ± 0.01^d
Total K (%)	0.52 ± 0.06^a	1.25 ± 0.02^b	0.19 ± 0.05^c	6.7 ± 0.49^d
C:N ratio	—	10.5 ± 0.54^a	—	37.68 ± 8.4^b
O:C ratio	—	2.02 ± 0.02^a	—	0.37 ± 0.01^b

Data were presented as mean ± standard deviation of replicates ($n=3$); different superscript letters in a row represent significant ($p<0.05$) difference among the substances (straw, compost, cow dung leachate, biochar) for respective row variable

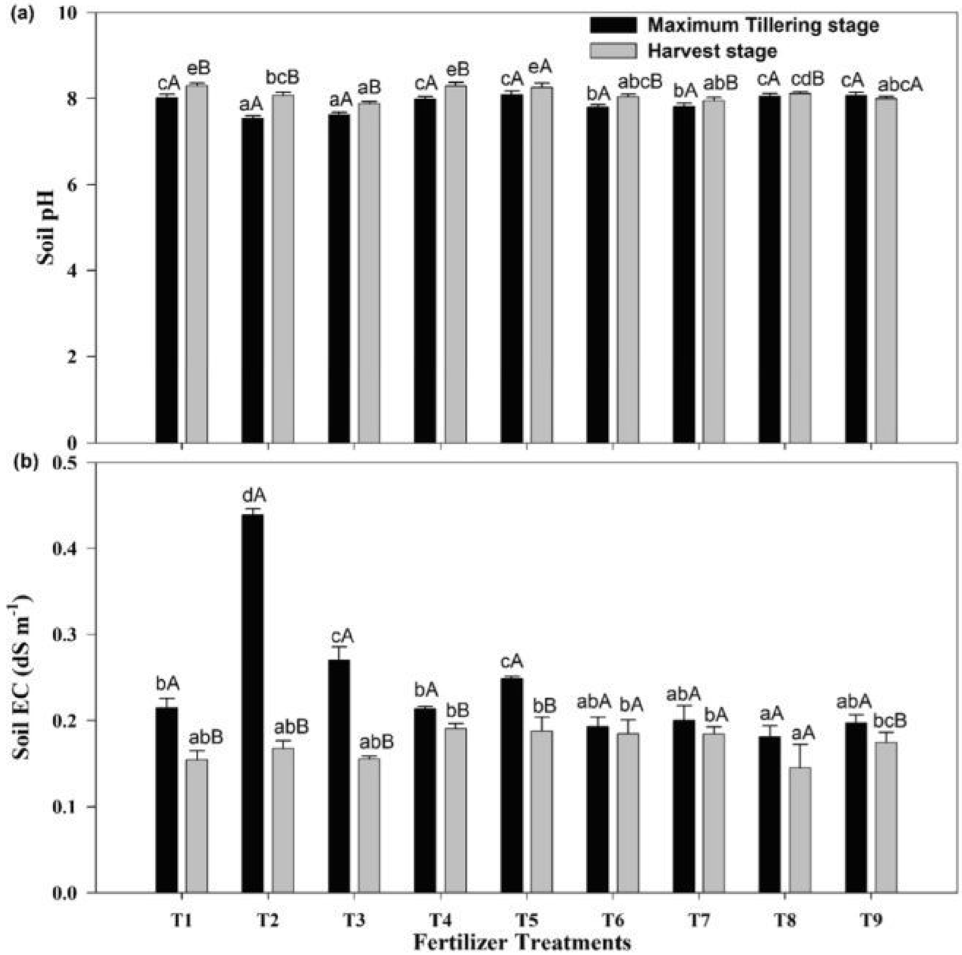


Fig. 3 Variation in soil pH and EC: The soil pH (a) and EC (b) in different fertilizer treatments during maximum tillering and harvest stages of paddy. The error bars represent the standard deviation of means ($n=3$). Bars indicated by different small and capital letters denote significant differences ($p<0.05$) among treatments and between stages respectively. The treatment details are T1 (Control) means (no fertilization), T2 (CF_{FP}) means (chemical fertilizers as farmers practice), T3 (CF_{STB}) means (soil test-based chemical fertilizers), T4 (BC_{100}) means (biochar@ 12 t/ha), T5 (CO_{100}) means (compost @12 t/ha), T6 ($CF_{STB75}+BC_{25}$) means (biochar@3 t/ha + 75% soil test-based chemical fertilizers), T7 ($CF_{STB75}+CO_{25}$) means (compost@3 t/ha + 75% soil test-based chemical fertilizers), T8 ($CF_{STB50}+BC_{50}$) means (biochar@6 t/ha + 50% soil test-based chemical fertilizers), T9 ($CF_{STB50}+CO_{50}$) means (compost@6 t/ha + 50% soil test-based chemical fertilizers)

Table 3 Influence of different treatments on soil organic carbon and macronutrients during tillering and harvest stage of rice

Fertilizer treatments		Organic carbon (%)		Total–N (%)		Available–P (mg kg^{-1})		Exchangeable–K (mg kg^{-1})	
T. No		Tillering	Harvest	Tillering	Harvest	Tillering	Harvest	Tillering	Harvest
T1	Con	$0.48^{abcA}\pm0.03$	$0.19^{aB}\pm0.05$	$0.10^{aA}\pm0.01$	$0.09^{aA}\pm0.01$	$20.81^{dA}\pm0.31$	$1.85^{aB}\pm0.18$	$293.7^{aA}\pm2.09$	$230.2^{cB}\pm0.48$
T2	CF_{FP}	$0.41^{aA}\pm0.02$	$0.35^{bcB}\pm0.003$	$0.10^{aA}\pm0.007$	$0.10^{abA}\pm0.007$	$15.81^{cA}\pm0.29$	$20.82^{deB}\pm0.63$	$727.4^{fA}\pm8.18$	$228.1^{cB}\pm2.86$
T3	CF_{STB}	$0.42^{aA}\pm0.01$	$0.28^{abB}\pm0.05$	$0.10^{aA}\pm0.01$	$0.11^{abcA}\pm0.006$	$7.37^{aA}\pm0.37$	$24.86^{fB}\pm0.17$	$325.4^{bA}\pm3.61$	$204.5^{aB}\pm0.71$
T4	BC_{100}	$0.71^{eA}\pm0.06$	$0.79^{eA}\pm0.03$	$0.15^{cdA}\pm0.02$	$0.15^{dA}\pm0.01$	$7.61^{aA}\pm0.20$	$8.92^{bB}\pm0.39$	$382.1^{cA}\pm2.97$	$394.9^{eB}\pm3.52$
T5	CO_{100}	$0.42^{aA}\pm0.04$	$0.89^{eB}\pm0.08$	$0.10^{aA}\pm0.006$	$0.20^{eB}\pm0.01$	$10.30^{bA}\pm0.25$	$7.58^{bB}\pm0.35$	$293.1^{aA}\pm5.84$	$234.1^{cB}\pm1.40$
T6	$CF_{STB75}+BC_{25}$	$0.45^{abA}\pm0.03$	$0.50^{dA}\pm0.04$	$0.13^{bcA}\pm0.01$	$0.14^{dA}\pm0.02$	$22.15^{deA}\pm0.81$	$21.26^{eA}\pm0.98$	$478.9^{eA}\pm6.75$	$376.2^{dB}\pm4.94$
T7	$CF_{STB75}+C_{25}$	$0.54^{cdA}\pm0.02$	$0.48^{cdA}\pm0.05$	$0.11^{abA}\pm0.01$	$0.13^{bcdB}\pm0.007$	$14.74^{cA}\pm0.23$	$30.37^{gB}\pm1.19$	$449.9^{dA}\pm6.26$	$230.2^{cB}\pm0.96$
T8	$CF_{STB50}+BC_{50}$	$0.52^{bcdA}\pm0.02$	$0.44^{cdB}\pm0.05$	$0.18^{dA}\pm0.01$	$0.14^{cdB}\pm0.02$	$15.18^{cA}\pm0.03$	$17.58^{cB}\pm0.49$	$385.9^{cA}\pm6.62$	$381.5^{dA}\pm6.62$
T9	$CF_{STB50}+CO_{50}$	$0.58^{dA}\pm0.02$	$0.51^{dB}\pm0.04$	$0.13^{bcA}\pm0.01$	$0.14^{cdA}\pm0.01$	$23.30^{eA}\pm1.15$	$19.41^{dB}\pm0.16$	$340.5^{bA}\pm15.92$	$216.7^{bB}\pm5.56$

Notes: Data were presented as mean ± standard deviation of replicates ($n=3$). Values in the same column and same rows followed by the different small and capital superscript letters denote significant differences among treatments and stages respectively ($p<0.05$)

The total nitrogen (Total–N) is exhibiting insignificant change between the growth stages in the control treatment, sole mineral, and sole biochar fertilizer treatment, except in the sole compost treatment, in which the difference observed was very high (Table 3). Sole biochar treatment also shows considerable Total–N content but does not change significantly at the harvest stage. The highest availability of P at the early growth stages of rice is observed in the low-dose biochar-based INM treatment (i.e., T6). Sole mineral fertilizer treatment at the recommended dose resulted in higher availability of P when compared to its soil test-based counterpart at the early growth stages of rice

(Table 3). However, compost's sole organic fertilizer treatment shows higher available P at the early growth stage of rice than the sole biochar fertilizer-based treatment. The highest exchangeable–K (Exch.–K) is observed for the recommended mineral fertilizer treatment, followed by low-dose biochar-based INM treatment. A higher dose of basal K has resulted in higher exchangeable K in the soil, but the role of a low dose of biochar and compost in the expansion of soil exchange complex for K from results can be observed. However, INM treatments involving low-dose biochar and compost (i.e., T6 and T7) show similar results during the early growth stages of rice. Therefore, biochar and compost can be considered analogous in their effect on Exch.–K in paddy soil at lower doses. At harvest, the highest Exch.-K has been found for the sole biochar treatment and is followed by high-dose and low-dose biochar-based INM treatments. This result indicates that the residual nutrient availability at the harvest of paddy in the biochar treatments is better than compost treatments in general due to the high surface charge and stability of biochar.

3.3 Effect of Fertilizer Treatments on Plant Growth and Yield Attributes of Rice

The effect of nutrient management practices is observed on the rice crop's growth and yield attributes and is presented in Table 4. We show the impact of nutrient management practices on plant height and SPAD value measured at different growth stages of rice (from 30 to 120 DAT) in Fig. 4. The results show that low-dose biochar-based INM treatment has the highest plant height (till 60 DAT) and leaf chlorophyll (Table S2) and thus facilitates the uptake of N by plants in the rhizosphere during the early growth stages of paddy. The STB mineral fertilizer treatment is also showing comparable

Table 4 Influence of different treatments on plant growth characters, yield attributes, and yield of paddy in the pot experiment

Parameters	Fertilizer treatments								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
	Con	CF_{FP}	CF_{STB}	BC_{100}	CO_{100}	$CF_{STB75}+BC_{25}$	$CF_{STB75}+CO_{25}$	$CF_{STB50}+BC_{50}$	$CF_{STB50}+CO_{50}$
Growth									
Maximum plant height (cm)	$50.63^{a} \pm 0.32$	$91.17^{f} \pm 0.25$	$92.63^{g} \pm 0.42$	$74.60^{b} \pm 1.13$	$86.40^{e} \pm 0.90$	$93.80^{g} \pm 0.53$	$82.83^{c} \pm 0.49$	$84.33^{d} \pm 1.71$	$83.07^{cd} \pm 0.55$
Maximum tillers $hill^{-1}$	$8.66^{a} \pm 0.57$	$15.67^{d} \pm 0.57$	$17.33^{e} \pm 1.15$	$13.00^{c} \pm 1.00$	$13.33^{c} \pm 0.58$	$16.67^{de} \pm 0.58$	$13.00^{c} \pm 1.00$	$11.33^{b} \pm 0.58$	$12.67^{c} \pm 0.58$
Above-ground biomass (g $hill^{-1}$)	$0.71^{a} \pm 0.04$	$5.12^{c} \pm 0.73$	$6.48^{d} \pm 0.28$	$3.38^{b} \pm 0.08$	$5.73^{c} \pm 0.06$	$7.94^{e} \pm 0.03$	$3.84^{b} \pm 0.11$	$3.54^{b} \pm 0.58$	$4.01^{b} \pm 0.85$
Yield attributes									
No. of panicles $hill^{-1}$	$3.33^{a} \pm 0.57$	$10.0^{bc} \pm 1.00$	$10.33^{c} \pm 0.58$	$8.33^{b} \pm 0.58$	$9.00^{bc} \pm 1.00$	$10.67^{c} \pm 0.58$	$9.00^{bc} \pm 1.00$	$9.33^{bc} \pm 1.53$	$8.33^{b} \pm 0.58$
Length of panicles (cm)	$16.00^{a} \pm 1.00$	$20.67^{b} \pm 0.57$	$21.97^{c} \pm 0.42$	$21.23^{bc} \pm 0.70$	$21.13^{bc} \pm 0.32$	$20.50^{b} \pm 0.50$	$21.60^{bc} \pm 0.36$	$20.57^{b} \pm 0.40$	$20.54^{b} \pm 0.56$
No. of grains $panicle^{-1}$	$54.33^{a} \pm 1.52$	$86.67^{c} \pm 2.08$	$128.0^{g} \pm 1.00$	$83.33^{b} \pm 1.53$	$95.67^{d} \pm 1.53$	$145.0^{h} \pm 1.00$	$126.67^{g} \pm 2.08$	$122.33^{f} \pm 1.15$	$116.67^{e} \pm 1.15$
Filled grain (%)	$65.77^{c} \pm 1.35$	$53.79^{a} \pm 1.47$	$76.70^{e} \pm 1.48$	$62.76^{b} \pm 0.73$	$62.68^{b} \pm 0.93$	$85.52^{f} \pm 1.28$	$74.70^{e} \pm 1.23$	$69.56^{d} \pm 0.50$	$69.05^{d} \pm 1.55$
Test weight (1000 grain)	$22.02^{a} \pm 0.12$	$22.16^{ab} \pm 0.01$	$22.31^{abc} \pm 0.13$	$22.58^{bc} \pm 0.19$	$22.74^{c} \pm 0.24$	$22.53^{bc} \pm 0.44$	$22.03^{a} \pm 0.03$	22.66^{bc} 0.42	$22.55^{bc} \pm 0.36$
Yield									
Grain yield $hill^{-1}$ (g)	$4.61^{a} \pm 0.49$	$23.58^{d} \pm 1.27$	$30.19^{f} \pm 1.08$	$17.80^{b} \pm 0.39$	$21.69^{c} \pm 1.46$	$37.65^{g} \pm 0.33$	$27.96^{e} \pm 0.50$	$28.28^{e} \pm 1.60$	$23.35^{cd} \pm 1.05$
Straw yield $hill^{-1}$ (g)	$6.04^{a} \pm 0.45$	$33.27^{d} \pm 0.84$	$38.06^{f} \pm 0.02$	$22.95^{b} \pm 0.43$	$36.39^{e} \pm 0.61$	$45.77^{g} \pm 1.02$	$33.32^{d} \pm 0.61$	$33.66^{d} \pm 0.15$	$31.35^{c} \pm 0.32$
Grain harvest index (%)	$0.43^{bcd} \pm 0.02$	$0.41^{b} \pm 0.01$	$0.44^{cd} \pm 0.01$	$0.43^{bcd} \pm 0.01$	$0.37^{a} \pm 0.01$	$0.45^{d} \pm 0.01$	$0.45^{d} \pm 0.01$	$0.45^{d} \pm 0.01$	$0.42^{bc} \pm 0.02$

Notes: Data were presented as mean ± standard deviation of replicates ($n = 3$). Values in the same row followed by the different superscript letters denote significant differences among treatments ($p < 0.05$)

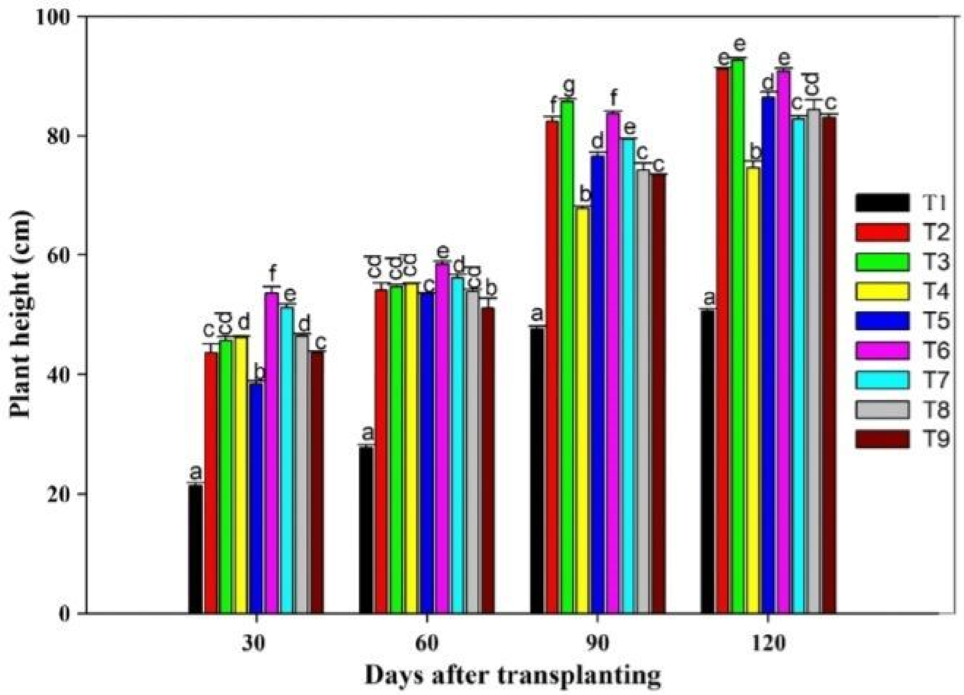


Fig. 4 Variation in plant height at different times of cultivation: The plant height in different fertilizer treatments during different growth stages (30-day interval) of rice crop. The error bars represent the standard deviation of means ($n=3$). Bars indicated by different letters denote significant differences ($p<0.05$) among treatments: T1 (Control) means (no fertilization), T2 (CF_{FP}) means (chemical fertilizers as farmers practice), T3 (CF_{STB}) means (soil test-based chemical fertilizers), T4 (BC_{100}) means (biochar@ 12 t/ha), T5 (CO_{100}) means (compost @12 t/ha), T6 ($CF_{STB75}+BC_{25}$) means (biochar@3 t/ha + 75% soil test-based chemical fertilizers), T7 ($CF_{STB75}+CO_{25}$) means (compost@3 t/ha + 75% soil test-based chemical fertilizers), T8 ($CF_{STB50}+BC_{50}$) means (biochar@6 t/ha + 50% soil test-based chemical fertilizers), T9 ($CF_{STB50}+CO_{50}$) means (compost@6 t/ha + 50% soil test-based chemical fertilizers)

results for the plant height with low-dose biochar-based INM treatment at 120 DAT, indicating the effect of balanced fertilization. Furthermore, biochar-based treatment shows higher plant height during the early stages of rice growth but has been superseded by the compost-based treatment during later stages of rice growth. The mineral fertilizer treatment STB has shown a maximum number of tillers per hill (17.3), comparable to the low-dose biochar-based INM treatment and recommended mineral fertilizer treatment.

Nevertheless, the highest AGB (7.94 g $hill^{-1}$) and panicles $hill^{-1}$ (10.67) are obtained from the low-dose biochar-based INM treatment (Table 4). Sole organic and mineral fertilizer treatment combinations are observed alike in respective combinations, but mineral fertilizer treatments have given greater panicles than organic treatments as they readily supply available nutrients at the critical growth stages. The highest length of panicle, grain filling % is statistically insignificant in the sole biochar, sole compost, and low-dose compost-based treatments. However, grain $panicle^{-1}$ (145), grain and straw yield $hill^{-1}$(37.65 g $hill^{-1}$ grain and 45.77 g $hill^{-1}$ straw), and grain filling (85.52%) are observed the highest in low-dose biochar-based INM treatment. These findings indicate that legume biochar fertilizer in low doses can be a beneficial strategy in the yield improvement of paddy. Furthermore, to visualize the overall performance of each treatment without biases for any single attribute (Fig. S3), the performance of each treatment can be inferred from the intergroup distances in biplot for CVA (Darlington et al. 1973). Similar performing treatments show the same degree of relatedness in terms of the newly formed canonical variates while taking all growth and yield attributes into account, whereas dissimilar treatments denote non-relatedness. Fertilizer treatments in INM (i.e., T6, T7, T8, and T9) show relatedness with soil test-based mineral fertilizer treatment (T3) as observed in the biplot. Additionally, the low-dose biochar-based INM (i.e., T6) showed maximum canonical variate mean (77.01), whereas the minimum (− 127.88) was obtained in the control treatment (i.e., T1) for CV 1, which corroborates the findings of grain yield in rice.

3.4 Effect of Nutrient Management on Straw, Grain Quality of Paddy, and Economics of Production

3.4.1 Total N, P, and K Contents in Straw and Grains

The total N, P, and K contents in rice straw and grain are analyzed and provided in Supplementary Table S3. Total–N content in the straw of paddy does not show significant differences among the fertilizer treatments, but sole mineral fertilizer treatments (i.e., T3 and T2) are higher in grain total–N content than sole organic fertilizer treatments (i.e., T4 and T5). Although plants grown in low-dose compost-based INM treatment are showing significantly higher N content in straw, the sole organic treatments of biochar and compost and mineral fertilizer treatments (i.e., T2 and T3) are comparable. The total–P content of both straw and grain of rice is significantly higher in sole biochar treatment but at par with sole compost-based treatment in the total–K content. The ANR analysis (Fig. S4) shows that low-dose biochar INM (T6) better recovers most of the macronutrients (N, P, K) in straw and grain than any other treatment.

3.4.2 Amylose and Protein Contents of Rice Grains

Amylose and protein contents are two vital components of rice grains and thus crucial for determining the quality of grains. We can observe the effects of different fertilizer treatments on grain amylose and protein contents in Fig. 5. The sole organic fertilizer treatments of biochar and compost show improved grain amylose content and lower protein content than mineral fertilizer treatments. Although grain protein content in the low-dose biochar-based INM treatment is significantly higher than sole organic treatments of compost and biochar but comparable with STB mineral fertilizer treatment, thus suggesting a better availability and uptake of N in low-dose biochar treatment. On the other hand, sole compost treatment showed grain protein content lower than sole biochar treatment. However, a higher dose of biochar and compost in INM treatments (i.e., T8 and T9) slightly underperformed concerning amylose content compared with the respective lower dose INM treatments.

3.4.3 Economic Analysis of Fertilizer Treatments for Rice Grain Production

The preliminary economic assessment is performed to compare the cost of rice grain production under different fertilizer management practices. Yield scaled (USD g^{-1} of rice grain) production cost of rice grain (Table S4) is compared to find the most economic nutrient management practice. The sole compost treatment is the highest (USD $17.6e^{-5}$) due to the low grain yield and the large quantity of fertilizer required. The lowest cost (USD $1.1e^{-5}$) is incurred in low-dose biochar treatment because of the

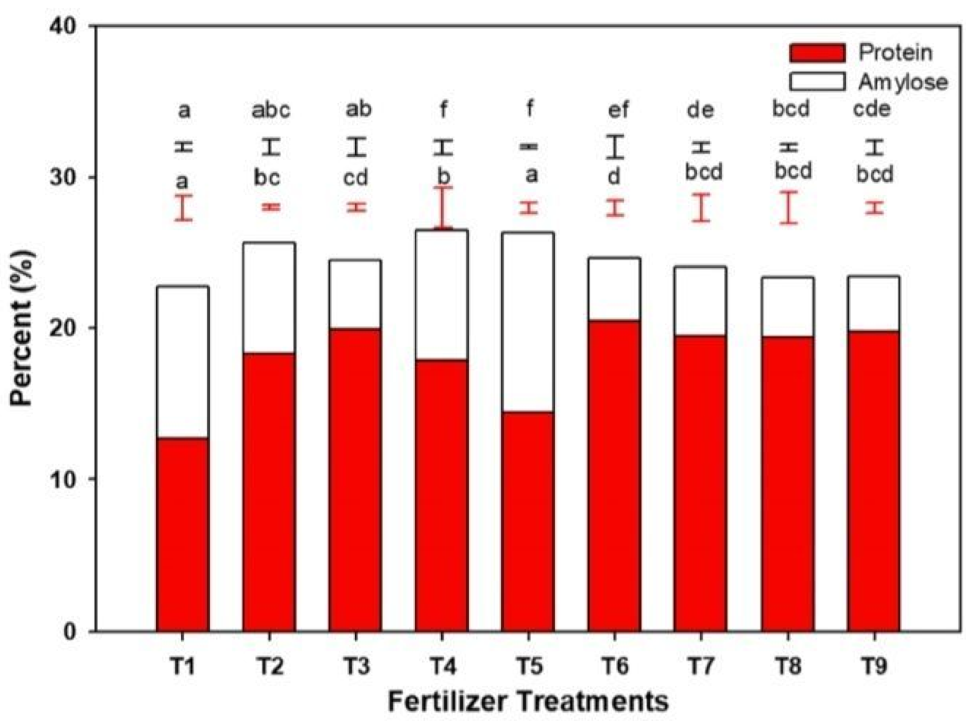


Fig. 5 The rice grain quality: Protein and amylose contents in rice grain for different fertilizer treatments: T1 (Control) means (no fertilization), T2 (CF_{FP}) means (chemical fertilizers as farmers practice), T3 (CF_{STB}) means (soil test-based chemical fertilizers), T4 (BC_{100}) means (biochar@ 12 t/ha), T5 (CO_{100}) means (compost @12 t/ha), T6 ($CF_{STB75}+BC_{25}$) means (biochar@3 t/ha + 75% soil test-based chemical fertilizers), T7 ($CF_{STB75}+CO_{25}$) means (compost@3 t/ha + 75% soil test-based chemical fertilizers), T8 ($CF_{STB50}+BC_{50}$) means (biochar@6 t/ha + 50% soil test-based chemical fertilizers), T9 ($CF_{STB50}+CO_{50}$) means (compost@6 t/ha + 50% soil test-based chemical fertilizers) in rice crop. The error bars represent the standard deviation of means ($n=3$). Red (protein) and black (amylose) colored error bars indicated by different letters denote significant differences ($p<0.05$) in protein and amylose content, among treatments

highest grain yield in low-dose biochar treatment (i.e., T6) than any other treatments.

4 Discussion

4.1 Plant Nutrient Availability from Biochar vis-à-vis Compost

FTIR reveals that compost has multiple functional groups present on their surface, holding and retaining the cationic and anionic mineral elements and radicals. However, compost provides nutrients mainly by microbial decomposition, which often does not satisfy the need for crops at crucial stages, as it takes longer to release the nutrients. Our study revealed that the nutrient-charged novel biochar demonstrates sorption of nutrients at the mesopores and micropores as crystalline deposits in electron micrographs, which can endow them with a similar capability as compost in terms of plant-available nutrients in the rhizosphere (Schmidt et al. 2015; Liu et al. 2019). The increased nutrient availability in soil after biochar addition can be attributed to the initial addition of soluble nutrients through desorption and the mineralization of the labile fraction of biochar containing organically bound nutrients (Lehmann et al. 2009). For example, our leaf nitrogen results through SPAD values indicate an increased supply of nitrogen to rice plants in low-dose biochar-based INM treatments at crucial growth stages. However, our results also agree with Batista et al. (2018) that biochar can result in lower plant uptake of nutrients at higher doses. The FTIR spectra for legume biochar suggest that the presence of hydroxylic and carboxylic groups can contribute to conjugation and cation binding with aging and can also use bridged cations (Al^{3+}, Fe^{3+}, and Mg^{2+}) to form stable six-member phosphate ring complexes. Such ring complexes can form hydrogen bonds to stabilize anions like pyrophosphate in soil (Uchimiya et al. 2015). Furthermore, retention of P and S associated with the increase in biological activities or community shifts (Yua et al. 2018) depending upon the surface area of biochar is also reported as possible mechanisms to increase their availability after biochar addition. However, our study suggests that a comparatively high surface area of biochar shows higher benefits in low doses through enhanced sorption, nutrient retention, and uptake, which may reflect in crop performance and thus agrees with Ibrahim et al. (2020). Our results for ANR showing higher recovery of nutrients in straw and grain sample of rice indicate that at low doses of biochar, multi-layer adsorption of plant-available nutrients occurs, increasing their availability in the rhizosphere (De Melo et al. 2014).

4.2 Efficacy of Biochar as Compared to Compost for Long-term Soil Fertility

EDS and ultimate analyses show that the nutrient-charged legume biochar fertilizer has lower O content than compost marked by a lower O:C ratio, making it a more stable organic fertilizer in soil (Spokas et al. 2012). Furthermore, higher fixed carbon in legume biochar can guarantee higher preservation of carbon in the soil than the respective compost and can play a crucial role in long-term soil carbon sequestration in agricultural soils (Domingues et al. 2017). Although our study shows that novel legume biochar fertilizer is low in volatile matter and ash content than respective compost due to thermal decomposition, it may provide a better soil quality through recalcitrant OC after paddy harvest and assist in ecosystem functioning in the long run (Ronsse et al. 2013). Still, some un-pyrolyzed compounds and deposited volatiles are present on the biochar surface and can be decomposed by soil microbes to release trapped nutrients (Yua et al. 2018). In addition, our results with TGA analysis show the perseverance of more lignin compounds in low temperature (409 °C) pyrolyzed legume biochar compared to respective compost, which can provide improved ecosystem services through better retention, uptake, and apparent recovery of nutrients in plant parts. Our results agree with Gul and Lu (2014), as they indicate that lignin compounds require high temperatures for degradation and can facilitate uptake of plant nutrients in biochar-amended soils for a longer period of time. While legume-derived compost also shows the persistence of lignin compounds as defined by derivative weight (Deriv. Weight) peak in TGA analysis, just 2.5% reduction in weight marks pre-degradation due to extracellular lignocellulolytic bacterial enzymes (Gopalakrishnan et al. 2009), which present in the microbial consortium culture. The assertion finds support from 16S rDNA sequencing followed by phylogenetic analysis of consortium culture reported in Chander et al. (2018), identifying 16 isolates of cellulase-producing bacteria.

4.3 Effect of Different Nutrient Management Strategies on Soil Properties

The rise in soil OC in organic fertilizer treatments may be attributed to the priming effect due to large doses of compost and biochar over soil organic matter turnover, resulting in less decomposition of organic matter (Kuzyakov et al. 2000). Biochar displays higher soil OC at the early stages of crop growth due to its stable carbon content but remains unchanged at the harvest. However, the FTIR findings revealed the presence of some degree of aliphatic carbon in biochar which might be with volatile deposits on the surface. Such compounds are suitable for lignolytic bacterial and also facilitate fungal decomposition resulting in more dissolved OC at the harvest (Yua et al. 2018). Our results find similarity to Yang et al. (2020), reporting an increase in water-soluble organic carbon in paddy soil after amending with biochar. The comparative study of the impact of compost and biochar on soil EC revealed that the decomposition of organic matter, the release of cations by solubilization of $CaCO_3$ and other soil minerals, might have increased the soil EC in the compost treatments at the tillering stage, which decreased at the harvest stage due to the leaching of soluble salts in submersible soils (Kochba et al., 2004). On the other hand, equivalent EC may be found in biochar treatments due to soluble alkaline elements released from the biochar (Wu et al. 2016). Most of INM treatments are comparable for soil EC during the maximum tillering stage and harvest stage, suggesting that availability of mineral ions is ensured at later stages also in these treatments. However, low EC for the higher-dose biochar INM treatment at the harvest stage of paddy indicates low desorption of ions from the biochar surface, which might result from immobilization (Ding et al. 2016).

Nevertheless, insignificant change in Total–N for organic treatments suggests minor mineralization of N from organic matter under submerged soil conditions (Sahrawat 2003). Biochar contains a fraction of unpyrolyzed starch and hydrolyzable N, which improves N mineralization at the early growth stage and agrees with Naeem et al. (2017). On the other hand, greater availability of P in compost-based treatments and INM treatments may be due to a higher overall P content in compost than biochar and a decrease in P sorption on the solid phase of submerged paddy soil (Guo et al. 2009). The statistical insignificance of high-dose biochar-based INM treatment and single biochar treatment at the early stages of rice growth for Exch.–K suggests that biochar may contribute as a K supply to plants without the use of any mineral forms.

4.4 Effect of Nutrient Management Strategies on Plant Growth, Yield Attributes, and Grain Quality

We observed that a lower dose of legume biochar could provide higher overall agronomic benefits in the INM strategy as the yield attributes are highly correlated with each other and represent the best in terms of newly formed canonical variates for low-dose biochar INM treatment. For instance, higher AGB and grain yield in low-dose biochar-based INM treatment in our study finds support from greater availability of nutrients during crop growth in low-dose biochar treatment, which also agrees with Amoah-Antwi et al. (2020). Furthermore, our results also indicate higher uptake and translocation of nutrients in low-dose biochar treatment, as reflected in increased N grain content. Biochar fertilizer treatments result in more overall – P and K contents in paddy straw, as biochar increases the absorption of P and K in plants (Pandit et al. 2018). Comparative assessment of nutrient management strategies reveals that INM treatments do better than single inorganic or organic nutrient management treatments in N uptake and translocation, as shown by grain N content results. Similar findings are also reported by Surekha et al. (2013) for total–N and P contents in rice grains grown with various organic and inorganic fertilizer doses suggesting a better quality of grain with organic integration in mineral fertilization. Besides, our study shows the nutritional benefits of applying biochar in terms of improved protein content of rice grains compared to sole compost treatments. However, the amylose content of rice grains was observed equivalent in low-dose biochar INM, sole compost, and biochar treatments which depicts that even a small dose of biochar as a part of INM can increase the production of starch-related enzymes during nutrient translocation at the grain filling point (Ali et al. 2020; Chen et al. 2012; Kaur et al. 2016).

5 Conclusion

Opulent but less useful hardy legume stovers obtained in cereal-legume sequence can be successfully valorized in form of biochar and compost. However, adjudging a better option in nutrient management strategies for obtaining improved yield is still a challenge for farmers. We prepared, characterized, and compared novel legume biochar with respective compost under different nutrient management treatments in paddy. Nutrient management practices involving legume-biochar, legume-compost, and mineral fertilizers show a contrasting effect on soil nutrient dynamics, reflecting in crop growth and yield attributes. Our study revealed that legume-biochar under integrated nutrient management strategy can improve soil organic carbon and outpace all other nutrient management treatments aimed to improve growth and yield in rice crops. Our research also indicates that soil health and long-term fertility indicators vary significantly for biochar and compost treatments; however, the determination of doses in nutrient management strategies is the key to success. Still, the yield response and nutrient uptake were observed the best for low-dose biochar treatment, which might ease the most significant constraint in organic farming regarding the volume of organic fertilizer required to achieve sustainable grain yield in rice. Furthermore, low-dose biochar treatment can have an added benefit over other treatments through economic ferti-fortification and can be an integrated sustainable strategy equally dealing with low soil health, fertility, and profitability issues in paddy cultivation. However, similar analyses with compost indicate that low organic carbon soils may experience a yield loss despite similar nutrient holding capabilities as of biochar. Henceforth, our analyses suggest that legume biochar are beneficial as they can provide a quick return and long-term soil benefits in nutrient management of heavy semi-arid tropical soils. Nevertheless, similar field studies are required to validate these results at a larger scale while targeting food and nutritional security in future climate change scenarios.

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Declarations

Competing Interests The authors declare no competing interests.

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