



# Poultry litter-derived biochar for sustainable agriculture: implications for rice yield and soil fertility enhancement

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## Abstract

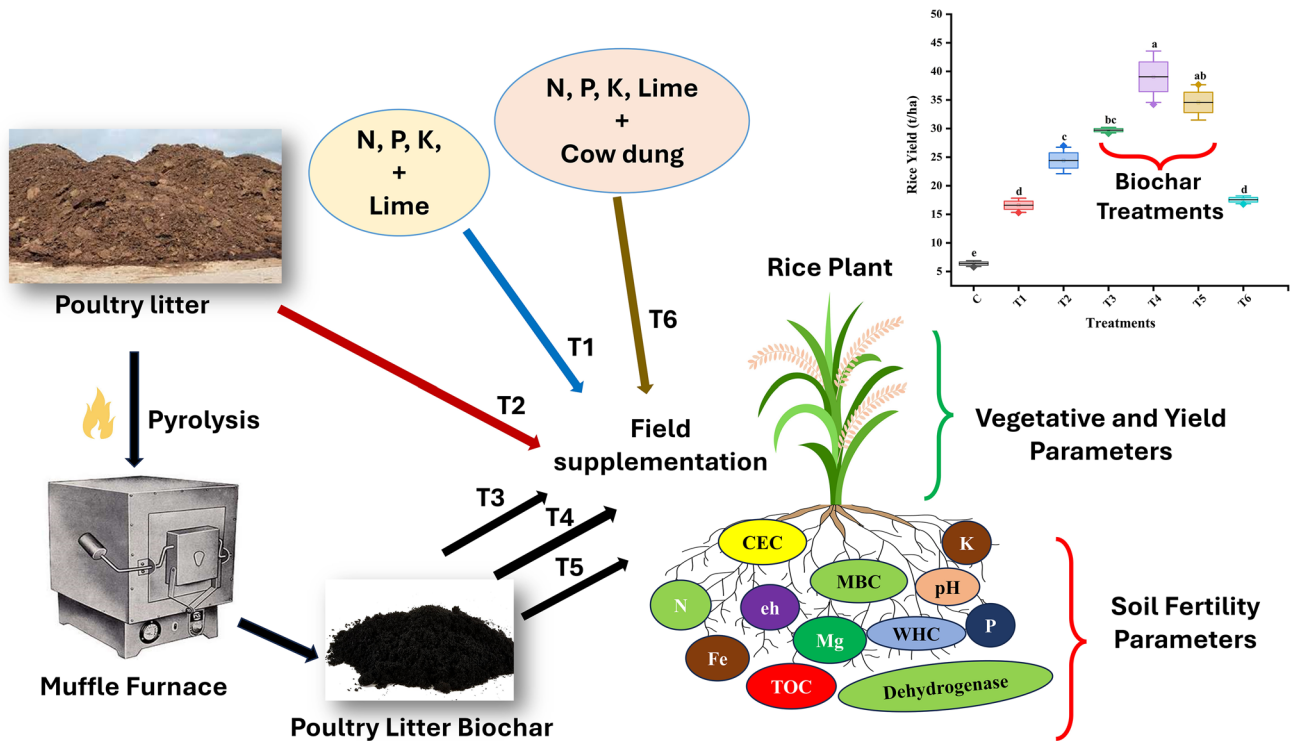
The application of poultry litter in fields and excessive use of synthetic fertilizers in paddy wetlands are common in the State of Kerala. The study compared the effects of bio-amendments, like poultry litter and poultry litter-derived biochar (PLB), mineral fertilizers, and current farming practices that use fertilizers, lime, and cow dung on soil fertility, growth, and yield of rice plants. The research was conducted from November 2022 to March 2023 in the Vayalkkara East paddy field of Kunukara village in Kerala State, India. Six treatments and controls were replicated three times and arranged in a complete randomized block design. A noticeable improvement was observed in the physicochemical properties of the soil under biochar treatments. The vegetative growth and rice yield were significantly higher for biochar treatments. Specifically, rice yield from treatment No. 4, where biochar was prepared at 300 °C with a 60-minutes residence time (PLB300-60), reached 39.06 t/ha, which is six times higher than the control (6.4 t/ha), twice that of mineral fertilizer application (16.6 t/ha), and current farming practices (17.5 t/ha), and 1.5 times greater than feedstock poultry litter (24.4 t/ha). The study strongly recommends using biochar made from waste materials like poultry litter to enhance soil fertility, rice growth, and yield. This approach supports a circular bio-economy through sustainable waste management and good agricultural practices that protect the paddy wetlands and the surrounding ecosystem.

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## Graphical abstract



**Keywords** Paddy wetlands · Mineral fertilizers · Bio-amendments · Sustainable waste management · Soil fertility

## Introduction

The poultry sector is among the rapidly expanding agricultural sectors in India, boasting a typical annual growth rate of 8 to 15%. Since the late seventies, the Indian poultry sector has experienced remarkable growth (Muduli et al. 2019). According to FAOSTAT production data website year (2006), India ranks third in global egg production, contributing 4.54% of the world's total. Rather than egg production, the mass of poultry litter generated in a medium-scale farm depends on various factors like litter (with bedding material) management, intake, and feed digestibility. Livestock manure is a nutrient-rich, valuable source of nitrogen (N) and phosphorus (P) and is commonly used on croplands to enhance soil fertility. Poultry litter (PL) is one of a kind, widely supplemented in cultivable soil as a top dressing material. Technically, poultry litter consists of excreta, spilled feed, feathers, and bedding materials (sawdust and wood chips) in poultry operations. Poultry litter contains enough nutrients and other excreted substances, such as pathogens, hormones, antibiotics, pesticides, and heavy metals (Steinfeld et al. 2006). Based on dry matter digestibility of 87.5%, a bird

aged 35 and 49 days can produce between 0.34 kg and 0.63 kg of litter (Leytem et al. 2007), with total manure production estimated to be around 4 to 6 kg. The amount of nutrients excreted in the litter will be the difference between the nutrients in the feed and those absorbed. Studies estimated that broiler chickens excrete about 55% of the total nitrogen (N), 70% of the phosphorus (P), and 80% of the total potassium (K) that consumed through feed; the mass of spilled feed can also influence the nutrient content in the litter (Leytem et al. 2007).

Additionally, poultry farming presents several challenges to human health and the environment, notably as a source of infectious diseases and a contributor to antimicrobial resistance; it has contributed to environmental impact by contaminating natural resources. Although the sector is commonly seen as efficient in converting natural resources into consumable products, it demands substantial amounts of land, water, and nutrients for feed production. This contributes to climate change and environmental pollution, including air and water. The direct application of poultry litter to fields gradually causes environmental damage, including the deterioration of groundwater and surface water due to nutrient leaching, surface runoff,

and soil contamination from accumulating heavy metals (Steinfeld et al. 2006). A suitable waste management strategy for PL must be implemented to eliminate associated environmental issues (Petersen et al. 2019). Poultry farms have faced criticism because of the environmental impacts they cause. Massive waste generation, disposal issues, and associated environmental damages are the challenges. A recent study on poultry waste management in Kerala has reported that 83.3% of the waste was sold for different purposes. Out of the total waste sold, 66.7% was utilized as fertilizer, 30% as fish feed, 23.3% as biogas, 16.7% as pig feed, and 3.3% as dog feed, and some ended up in landfills (Bashir et al. 2019). Dry rendering is the latest scientific disposal method for producing value-added products using poultry farm and slaughterhouse wastes (Abraham et al. 2015). The literature cited that converting poultry litter to biochar is a sustainable practice from a waste management perspective. The pyrolysis of poultry litter transforms the nutrients into less soluble forms within the poultry litter biochar (PLB) (Lehmann and Joseph, 2015).

Biochar technology has already been established as a soil management practice in developed countries, while it has yet to gain similar recognition in developing nations (Fagbenro and Onawumi, 2013). Biochar is the thermal decomposition product obtained from biomass pyrolysis under a limited oxygen supply (Lehmann and Joseph, 2015). The benefits of biochar are substantial once it is added to the soil. Biochar can retain soil nutrients and make it bioavailable, act as a microhabitat for the soil microbial community, maintain pH, sequester CO<sub>2</sub> in soil, and reduce the emission of greenhouse gases (Thies and Rillig, 2009; Mensah and Frimpong, 2018). This technology is quite new to developing countries like India. In India, farmers prefer the slash-and-burn method over the slash-and-char method. Biochar is widely accepted as a powerful soil amendment due to its multifunctional role in improving soil health and enhancing agricultural productivity (Khan et al. 2024). One of its primary benefits is the improvement of soil structure and aeration. The recent interest in biochar is due to its high organic Carbon content and capacity to hold nutrients. Most biochar amendment studies were conducted as pot trials in a greenhouse setup for the short term (Fagbenro et al. 2013; Yusif et al. 2018; Olakayode et al. 2019). A few studies reported on carbon and greenhouse gas dynamics of wetland rice soils after biochar addition (Shanthi et al. 2017), the impact of addition of different mulches and combination of biochar and sawdust ash on soil permeability (Joy, 2017), the application of biochar derived from water hyacinth in an integrated paddy and fish culture systems of the State of Kerala (Namjudeen et al. 2019), the potential of biochar from *Eichhornia crassipes* and *Phragmites karka* (prominent invasive wetland weeds) for use as a soil amendment to the possible soil fertility enhancement and carbon management

(Viswanathan et al. 2020), the influence of tender coconut husk derived biochar on nutrient use efficiency, yield and economics of banana (*Musa spp.*) (Sainath et al. 2020), the implications of *amarindus indica* shell biochar's capacity to absorb chromium (Cr), copper (Cu), and lead (Pb) from aqueous medium (Rajakumar et al. 2022), and the effect of invasive wetland weeds derived biochar on soil organic carbon (SOC) dynamics and stability of tropical Ultisol soil (Viswanathan et al. 2023).

While biochar provides several environmental and economic benefits, its application comes with challenges. The variability in biochar quality becomes a barrier to widespread adoption and application in agriculture and environmental management, primarily due to inconsistent composition and lack of standardization (Adhikari et al. 2024, Köves et al. 2024). Moreover, the absence of regulatory frameworks for biochar use raises concerns about improper application and misuse, highlighting the need for clear guidelines to ensure its safe and effective deployment. Furthermore, the production and application of biochar face several significant challenges related to energy requirements, environmental risks, and agronomic issues (Patel and Panwar, 2023). The pyrolysis process is employed for biochar production, which demands energy inputs, particularly at elevated temperatures. Regarding biochar yield and quality, various technologies (slow pyrolysis, fast pyrolysis, intermediate pyrolysis, torrefaction, microwaves, gasification, flash carbonization, and hydrothermal carbonization) have been implemented (Kumar and Sharma 2017; Bindar et al. 2023). Among the thermochemical conversion technologies, slow pyrolysis is reliable for high-yield biochar production, which yields 30-50% and can reach over 60-70% depending on the feedstock, reactor type, and operating conditions (Chaudhary et al. 2024, Gabhane et al. 2020; Song and Guo, 2012). Fast pyrolysis results in greater bio-oil yields (50-70%), while biochar yields are typically 10% of the total feedstock. Regardless of the method, biochar production must be carefully managed to ensure the quality and consistency of the material (Jayakumar et al. 2023; Chaudhary et al. 2024).

Rice is a staple food in Kerala, which is cultivated seasonally by following conventional farming practices specific to the region. According to the economic review 2023 published by the Kerala State Planning Board, during 2022-23, the area under rice cultivation (wetland) decreased to 1.9 lakh ha, showing a decrease of 1.9% compared to 2021-22 (Economic Review, 2023). However, the production and productivity of rice recorded an increase to 5.9 lakh tons and 3117 kg per ha, respectively (Economic Review, 2023). Paddy soils constitute the most extensive anthropogenic wetlands (Kogel-Knabner et al. 2010). These anthrosols are unique and modified by specific paddy cultivation operations such as submergence and drainage, plowing and puddling, organic manuring, charring, liming, and fertilization.

Ensuring nutrition and food security is one of the major challenges outlined by the United Nations' Sustainable Development Goals (SDGs). The projected world population will be more than 9.7 billion by 2050 (Programme et al. 2024; van Dijk et al. 2021), making a specific demand for food by 35–56% between 2010 and 2050. In order to obtain the highest yield, farmers must exploit paddy soils for the inadequate and imbalanced supply of fertilizers (Dwivedi and Meshram, 2014). However, the excessive use of fertilizers and pesticides has led to a decline in soil fertility, heavy metal and pesticide contamination, structural damage, and soil acidification (Masmoudi et al. 2023; Pawlak and Kolodziejczak, 2020); more than 40% of cultivable land has been affected due to these factors (Singh et al. 2022). In addition, abiotic stresses like heat waves, drought, floods, and nutrient scarcity tend to cause low crop yield and quality (Ali et al. 2017; Hasnain et al. 2023; Radha et al. 2023). Therefore, effective and sustainable soil management is necessary to meet the needs of current and future generations.

Most of the paddy fields in Kerala are highly weathered laterite soils, which are relatively infertile, acidic, and gravely clay, depleted of basic cations, and have low water and nutrient retention capacity (Babu et al. 2024). The acidic soils in the paddy fields of Kerala require the best organic supplement to improve the topsoil fertility and health and to achieve maximum rice yield. The present study examined the field supplementation effects of poultry litter (PL) and poultry litter biochar (PLB) on soil fertility, growth, and yield of UMA MO-16 rice variety compared to conventional farming practices over a cultivating season. The present study is expected to promote sustainable waste management and good agricultural practices in the State of Kerala. The majority of the existing studies showcased the input of biochar on soil matrix in a nutshell, based on short-term (less than a month) pot trials only. The actual benefits of biochar on soil fertility, crop vegetative growth, and yield can be attained from long-term field amendment studies. The present study explores the impact of biochar under field conditions on the soil rhizosphere, nutrient dynamics, and the vegetative growth and yield parameters of rice plants throughout a cultivation season.

## Materials and methods

### Collection and characterization of poultry litter (PL)

Raw poultry litter was collected at the beginning of the summer season in Kerala. Poultry litter (PL) of 45-day-old broilers was collected from a small-scale poultry farm in the Ernakulam District of Kerala (Babu et al. 2021). Animal husbandry and diet practices are similar among the small-scale farms in this region. The feed supplementation continued  $24 \times 7$ ,

varied with the size and age of the poultry. The feed supplement for poultry was categorized as pre-starter (powder form) for 10 days aged chickens at the dosage of 30 g/day/chicken, starter (powder form) for 10–27 days aged chickens at the dosage of 71 g/day/chicken, and finisher (pellets) for 27–45 days aged chickens at the dosage of 154 g/day/chicken. A flock size of 500 numbers (1 chicken/1.2 square feet) generated 430.85 kg of poultry litter over 45-day intervals, quantifying 3494.6 kg/year from the poultry farm selected for the feedstock collection. Representative samples were collected using a stratified random sampling method, in which samples were taken from four corners and the center of the farm. Later, the contents were thoroughly mixed and packed in sterile polythene bags. The poultry litter was air-dried for two days to remove the excess moisture content, ground to pass through a 2-mm sieve, and subjected to proximate and ultimate analysis per the ASTM D-5142 methods (Sugumaran and Seshadri, 2009). The physicochemical properties like pH, electrical conductivity (EC), redox potential, and temperature ( $^{\circ}\text{C}$ ) of collected poultry litter samples were analyzed. Brunauer–Emmett–Teller (BET) analysis for surface area and pore volume and scanning electron microscope-energy-dispersive X-ray analysis (SEM-EDAX) determined raw poultry litter feedstock's surface morphology and chemical composition. C, H, N, and S elemental analysis was performed using an Elementar Vario-EL-III analyzer.

### Synthesis and characterization of poultry litter biochar (PLB)

The feedstock poultry litter was slow pyrolyzed at 250  $^{\circ}\text{C}$  for 30 minutes (min), 300  $^{\circ}\text{C}$  for 60 min, and 350  $^{\circ}\text{C}$  for 30 min of residence time at a heating rate of 10  $^{\circ}\text{C}/\text{min}$ , respectively, in a laboratory-grade muffle furnace (model no. MF 3 Labline). The selection of slow pyrolysis temperatures (250, 300, and 350  $^{\circ}\text{C}$ ) and residence time (30 and 60 min) for biochar synthesis was randomly selected from the literature (Lehmann and Joseph, 2015) and confirmed through the characterization study, which yielded maximum biochar and physicochemical properties suitable for soil amendment purposes. The biochar was cooled and ground to pass through a 2-mm mesh. It was then used for proximate and ultimate analyses using the ASTM D-5142 methods (Rajkovich et al. 2012). The proximate analysis includes the physical entities of materials: moisture content, bulk density, volatile matter, ash content, fixed carbon, yield, and liming potential (Helrich, 1990). The bulk density ( $\text{gcm}^{-3}$ ) has been identified by the methodology described by Masulili et al. (2016), based on the Eq. (1) as follows:

$$\text{Bulk density}(\text{g}/\text{cm}^3) = \frac{\text{Weight of oven dried biochar}(\text{g})}{\text{The volume of the packed materials}(\text{cm}^3)} \quad (1)$$

The presence of moisture content in the biochar was measured following the methods described by Masulili (2010), and the Eq. (2) for calculating the moisture content is as follows,

$$\text{Moisture Content (\%)} = \frac{\text{Initial weight of biochar (g)} - \text{Oven dry weight of biochar (g)} \times 100}{\text{Oven dry weight of biochar (g)}} \quad (2)$$

The volatile matter emitted from the feedstock during the pyrolysis has been identified based on the methodology described by Zhang et al. (2017). The formula (3) for calculating the volatile matter (%) is given as follows.

$$\text{Volatile Matter (\%)} = \frac{W_1(\text{g}) - W_2(\text{g}) \times 100}{W_3(\text{g})} \quad (3)$$

where,

$W_1$  = weight of sample and crucible before heating (g).

$W_2$  = weight of a given sample (g).

$W_3$  = weight of sample and crucible after heating

$$\text{Yield (\%)} = \frac{\text{Mass of biochar (g)} \times 100}{\text{Oven dried mass of feedstock (g)}} \quad (4)$$

The biochar yield was analyzed using a method from Sadaka et al. (2014). The Eq. (4) for calculating the yield (%) is as follows:

The fixed carbon content in the biochar samples was determined by the formula (5) mentioned by Novak et al. (2009).

$$\text{Fixed Carbon (\%)} = 100 - (\text{Ash content (\%)} + \text{Volatile Matter (\%)}) \quad (5)$$

The moisture content of prepared biochar material was analyzed using the methodology described by Maiti (2003). The ultimate analysis includes the chemical properties such as pH, EC, Eh, C, H, N, S, H/C, and C/N ratio. A titrimetric analysis determined the liming potential of biochar by adding 10 mL of 1 M HCl into a powdered biochar sample taken in a polypropylene tube, shaken for 2 h at 25 °C on a reciprocating shaker, and letting the mixture stand overnight (16 h). The pH of the suspension was adjusted using 0.5 M NaOH until it reached neutral (pH 7). The volume of NaOH used was recorded. Parallely, a blank without biochar and a reference sample of CaCO<sub>3</sub> powder should be included in the batch. The liming potential of biochar samples was calculated using the following formula (6):

$$\text{Percentage CaCO}_3 \text{ equivalent} = (M(b - a) \times 10^{-3} \times 100.09 \times 100) / 2 \times W \quad (6)$$

where  $M$  = standardized molarity of NaOH (mol/L).

$b$  = volume of NaOH consumed by blank (mL).

$a$  = volume of NaOH consumed by the biochar (mL).

$W$  = mass of biochar (g).

The ultimate analysis was done for chemical entities of biochar material such as pH, electrical conductivity (EC),

redox potential (Eh), H/C, and C/N ratio. The elemental composition was analyzed using an ELEMENTAR Vario-EL-III CHNS analyzer, and surface morphology was identified by scanning electron microscopy (SEM). The proximate and ultimate analyses of biochar are performed to evaluate its composition, quality, and suitability for carbon sequestration, adsorption, soil remediation, agriculture, energy production, and environmental management. These analyses provide essential insights into the chemical and physical characteristics of biochar.

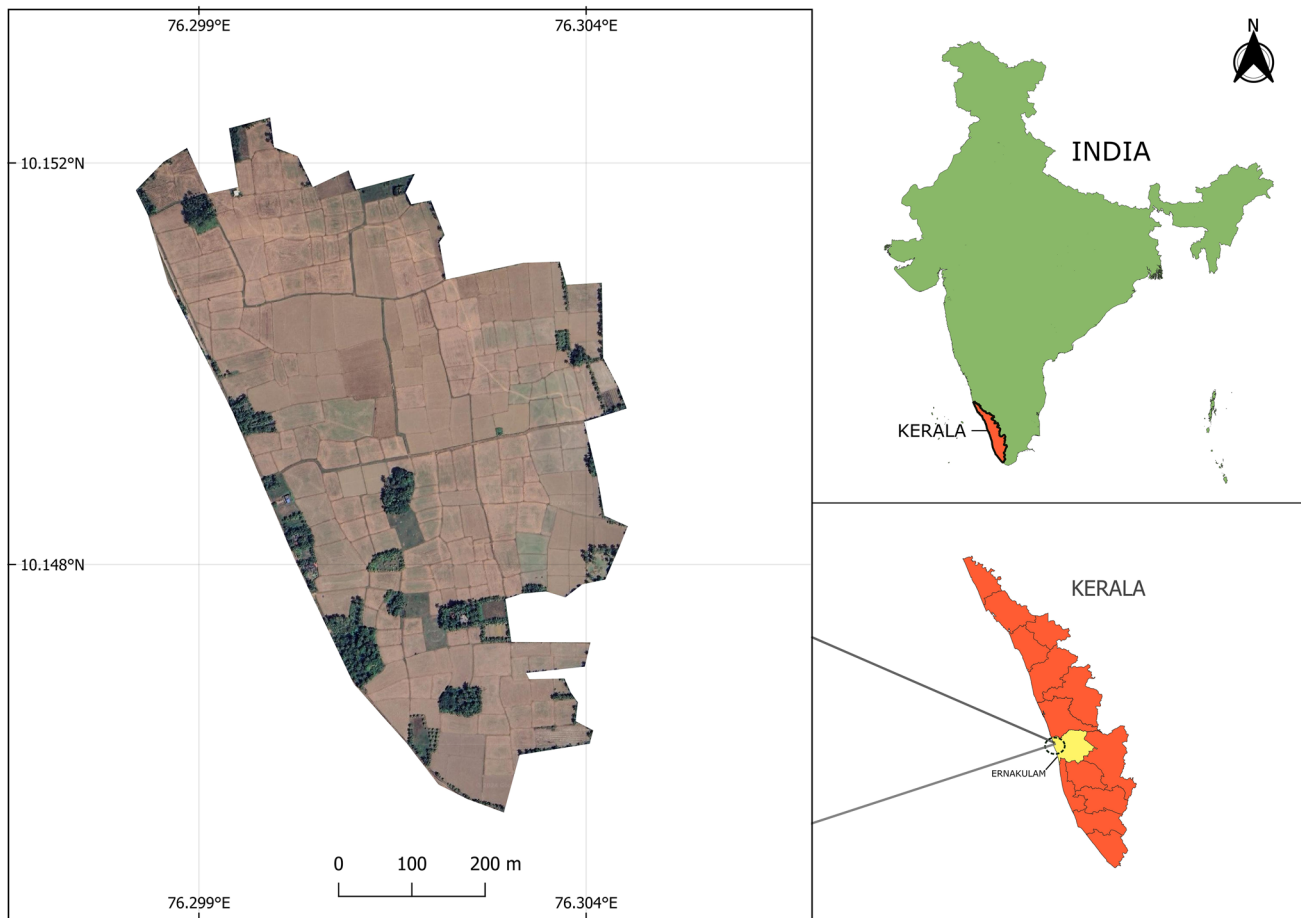
## Experimental design and treatments

The experiment was conducted at lowland, acidic paddy fields at Vayalkkara East Nellupadashekham (Paddy field) of Kunnukara village, Kerala, South India (Fig. 1). The study area belongs to south central laterite agroecological units of Kerala. The Vayalkkara East paddy field covers the maximum cultivating area near the banks of the river Periyar (10° 14' 792" N and 76° 30'030" E). The test materials used in the field trial are given in Table 1. The field experiment

was started in November 2022 after amending all the test materials on topsoil (0–15 cm). Each treatment is replicated thrice and arranged in a complete randomized block design. Each experimental plot consisted of a 2 × 2 m<sup>2</sup> area and was placed 1 m apart (Fig. 2). A rice bed was made following the traditional method using healthy rice seeds of UMA MO-16. After 10 days of seed germination, seedlings reach 3–5 inches in height, and 3–4 leaves are ready for transplantation. Forty-eight rice seedlings were transplanted into each experimental plot in a 3 × 4 × 4 pattern similar to the pattern followed by the native farmers of the Vayalkkara East Paddy Field of Kunnukara Village. Proper seedling transplantation is necessary for strong root development and better yield.

## Sampling

Every 10 days, the vegetative growth measurements of rice plants were taken in triplicates from each experimental plot by a destructive sampling method (Gomez and Gomez,



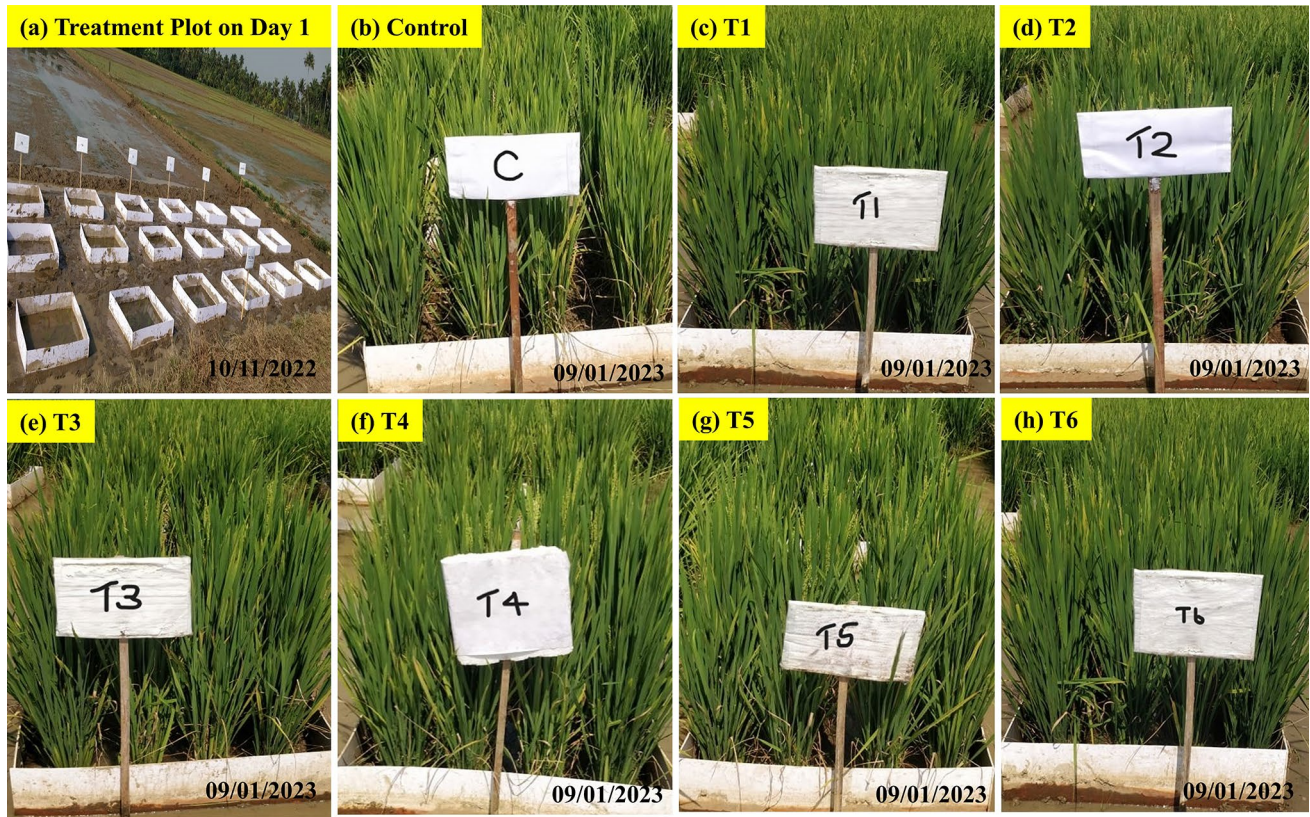
**Fig. 1** Map of Vayalkkara East Paddy Field at Kunnukara village, Kerala State, India

**Table 1** List of treatments used for field trial

Sl.No	Treatments	Treatment code
1	Control (paddy soil at the study site before fertigation)	C
2	Soil + Mineral fertilizers (urea (N)-0.78 g/kg, Factamfos (P)-1.95 g/kg, potash (K)-0.78 g/kg, and lime, 1.8 g/kg)	T1
3	Soil + Poultry Litter @ 1% application rate, i.e., 10 g/kg	T2
4	Soil + PLB250-30 (PLB pyrolyzed at 250°C for 30 min @ 1% application rate, i.e., 10 g/kg)	T3
5	Soil + PLB300-60 (PLB pyrolyzed at 300°C for 60 min @ 1% application rate, i.e., 10 g/kg)	T4
6	Soil + PLB350-30 (PLB pyrolyzed at 350 °C for 30 min @ 1% application rate, i.e., 10 g/kg)	T5
7	Soil + Current farming practices (mineral fertilizers (N-0.78 g/kg: P-1.95 g/kg: K-0.78 g/kg, and lime-1.8 g/kg) + cow dung-1.8 g/kg)	T6

1984). The vegetative growth parameters, such as crop height, root length, shoot length, number of leaves, and root and shoot dry weight, were monitored throughout the rice cultivation period. The rice yield parameters were monitored once at the harvest stage (Gomez and Gomez, 1984). A couple of yield parameters such as the number of tillers/

hill, number of productive tillers, number of panicles, length, and density of panicles, grains/panicles, number of filled grains, percentage filled grains, the weight of 1000 grains, Kerner weight, number of spikelets, rice yield, straw yield, seed setting rate, and the harvest index were identified at the end of 120 days of the field experiment (Gomez and Gomez,



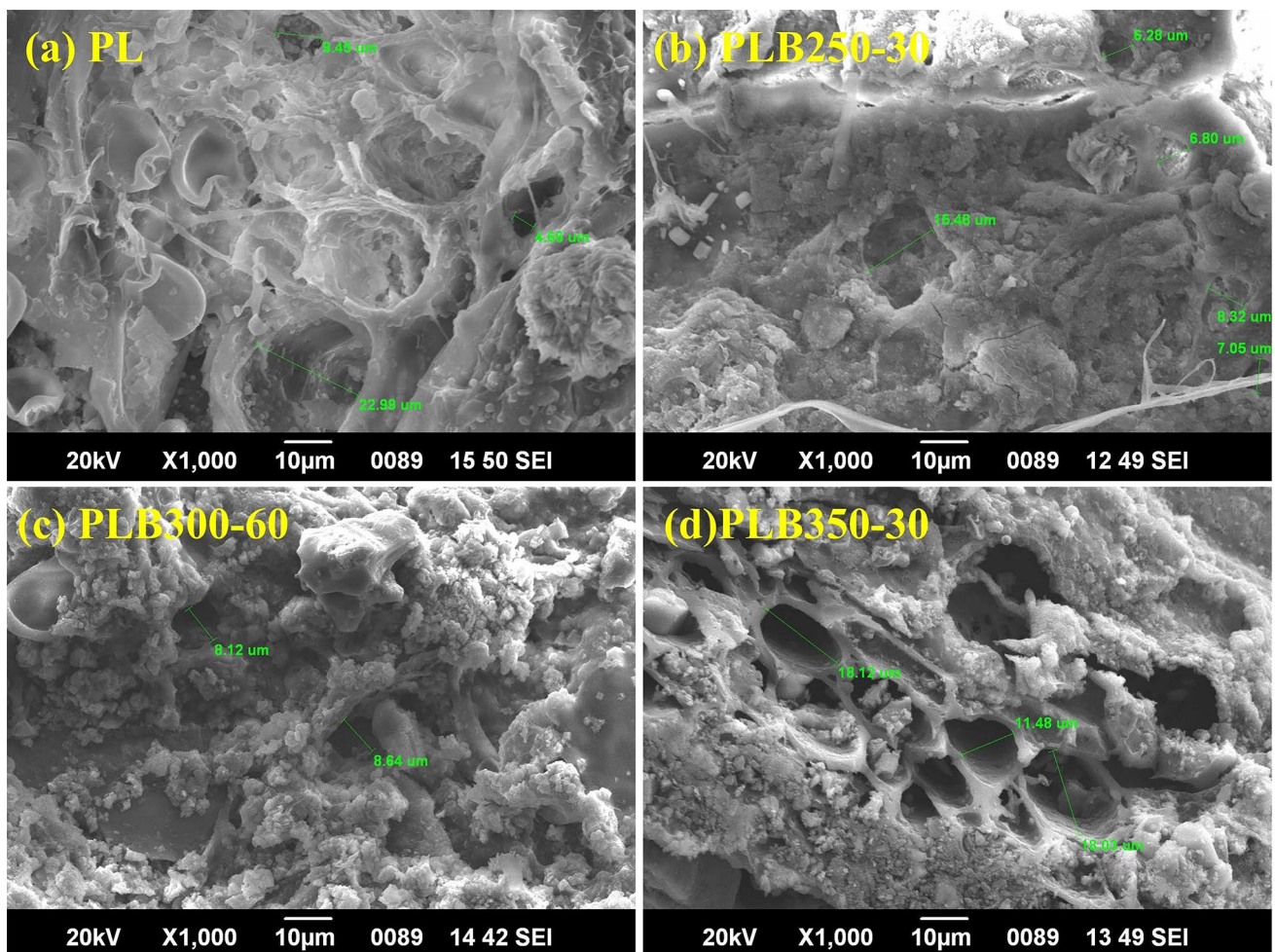
**Fig. 2** Field experimental plot on day 1 (a), control plot on day 60 (b), T1 on day 60 (c), T2 plot on day 60 (d), T3 plot on day 60 (e), T4 plot on day 60 (f), T5 plot on day 60 (g), and T6 plot on day 60 (h)

1984). Soil profile samples (i.e., topsoil 0-15 cm and subsoil 15-30 cm) were collected during the pre-cultivation/before transplanting stage (day 1), jointing and booting stage (day

60), and post-harvest stage (day 120) from each experimental plot randomly by manual coring following the cooping-coning method (Maiti 2003), with diagonal sampling to

**Table 2** Proximate and ultimate analysis of raw poultry litter and biochar

Properties	PL	PLB250-30	PLB300-60	PL350-30
<b>Proximate Analysis</b>				
Volatile matter (%)	72.3±0.4	66.5±0.9	61.3±0.6	46.3±1.3
Ash content (%)	19.4±0.2	29.4±0.2	35.8±0.06	38.5±0.6
Fixed carbon (%)	–	4.2±0.77	2.4±0.04	15.2±1.5
Moisture content (%)	17.6±0.02	1.9±0.08	4.1±0.03	2.5±0.23
Yield (%)	–	54.9±1.7	39.3±0.5	44.8±0.6
Yield (kg)	–	0.549±0.001	0.392±0.005	0.447±0.006
Bulk density (g/cm <sup>3</sup> )	0.188±0.03	0.533±0.002	0.441±0.008	0.543±0.004
Liming potential	–	–9.9±0.1	0.87±0.3	0.64±0.4
<b>Ultimate analysis</b>				
pH	7.6±0.03	7.2±0.04	8.1±0.02	8.7±0.05
EC (mS/cm)	8.97±0.41	15.4±0.42	17.6±0.52	16.7±0.22
Eh (relative)	–101±0.01	–13.5±0.02	–45.67±0.02	–108±0.04
C (%)	28.1±0.21	28.5±0.11	35.1±0.41	34±0.32
H (%)	3.3±0.01	1.9±0.04	0.32±0.02	2.1±0.03
N (%)	3.2±0.01	2.4±0.01	3.1±0.02	2.2±0.01
S (%)	0.70±0.003	0.3±0.002	0.33±0.001	0.58±0.002



**Fig. 3** Scanning electron microscopic images of PL (a), PLB250-30 (b), PLB300-60 (c), and PLB350-30 (d)

guarantee representativeness. A large volume of soil collected from the field was thoroughly mixed on a flat, clean surface to ensure uniformity. The soil is poured into a conical heap and is flattened, and the soil is divided into four equal parts (quarters). The two opposite quarters are discarded, while the remaining two quarters are remixed. The coning and quartering (cooping) process is repeated until the desired sample size is obtained (Maiti 2003). The composite samples were then freeze-dried using a Lark Penguin Classic freeze dryer at  $-80^{\circ}\text{C}$ , filtered through a 2-mm mesh, and stored at room temperature. Further analysis was carried out using each sample in three replications; data were presented as mean value  $\pm$  standard deviation. Separate wet samples were taken to analyze soil dehydrogenase enzyme and microbial biomass carbon.

### Fundamental soil quality parameters

Soil quality parameters were determined based on Maiti (2003) and Rajkovich et al. (2011). Soil organic matter and

organic carbon were quantified using wet oxidation followed by back titration, according to the method outlined by Walkley and Black (1934). The water-holding capacity was determined using the Keen-Raczkowski box method (Keen and Raczkowski, 1921). Chemical parameters such as pH, electrical conductivity (EC), and redox potential (Eh) were measured by the electrochemical method and cation exchange capacity via the spectrophotometric method (Rajkovich et al. 2011). The indole-phenol Blue method using a spectrophotometric procedure was followed to determine the soil's cation exchange capacity (CEC) (Santoni et al. 2001). Soil nutrients such as available nitrogen (Kjeldahl method), phosphorus (Bray's No.1 method), potassium (flame photometry), iron and magnesium (atomic absorption spectrophotometry) were analyzed (Maiti, 2003). Soil microbial health was assessed through microbial biomass carbon (MBC) (Jenkinson and Powlson, 1976) and dehydrogenase enzyme activity (Klein et al. 1971).

## Statistical analysis

A two-way analysis of variance (ANOVA) and Tukey honestly significant difference (HSD) test were applied at the 0.05 level to assess and analyze significant differences in the measured indices across various treatments and soil depths. “Two-way ANOVA” is a statistical test used to examine how two independent variables affect a dependent variable simultaneously, while “Tukey HSD” (Tukey’s honestly significant difference) is a post hoc test often used after a two-way ANOVA to identify which specific groups within the analysis have significantly different means from each other. Pearson correlation analysis was conducted at significance levels of  $p \leq 0.05$ , 0.01, and 0.001. Data analysis and graphing were performed using Origin 2023b software.

## Results and discussion

### Characteristics of poultry litter and biochar

The proximate analysis results for poultry litter (PL) showed moisture content at  $17.6 \pm 0.02\%$ , bulk density at  $0.188 \pm 0.03 \text{ g/cm}^3$ , ash content at  $19.4 \pm 0.2\%$ , and volatile matter at  $72.3 \pm 0.4\%$ , as detailed in Table 2. It was found that the biochar prepared at low temperatures (PLB250-30) possesses a high amount of volatile matter ( $66.5 \pm 0.9\%$ ) and low ash content ( $29.4 \pm 0.2\%$ ); at the same time, due to enhanced carbonization reaction, PLB350-30 has the highest fixed carbon ( $15.2 \pm 1.5\%$ ). As read, Jindo et al. (2014) observed increased ash content and fixed carbon with increased pyrolysis temperature. The slow pyrolysis temperatures (250, 300, and 350 °C) and residence time (30 and 60 min) were selected through an optimization study conducted previously for biochar synthesis, which yielded maximum biochar and optimum physicochemical properties suitable for soil amendment purposes. It was found that poultry litter biochar with high residence time (PLB300-60) exhibited high moisture content ( $4.06 \pm 0.03\%$ ), contributed by the macropores over the biochar surface able to adsorb moisture from the surroundings compared to that of biochar with low residence time. The yield was found to be decreased in the order PLB250-30 ( $54.9 \pm 1.7\%$ ) > PLB350-30 ( $44.8 \pm 0.6\%$ ) > PLB300-60 ( $39.3 \pm 0.5\%$ ). At high temperatures and residence time, the rate of carbonization and ash formation will be much higher, which might result in a reduction of biochar yield (Lehmann and Joseph (2015)). The bulk density varied between  $0.441 \pm 0.008$  and  $0.543 \pm 0.004 \text{ g/cm}^3$ . The liming potential was found to be high for PLB300-60 ( $0.876 \pm 0.3$ ), followed by PLB350-30 ( $0.645 \pm 0.4$ ) and PLB250-30 ( $-9.91 \pm 0.1$ ). Biochar prepared at low temperatures exhibited the lowest liming potential due to the minimum ash content present, while the biochar

prepared at high temperatures contains more ash, which imparts a significantly alkaline nature.

All data represented in mean value  $\pm$  standard deviation calculated from triplicate analysis. The “-” mark indicates no data available.

According to the pore size distribution given by IUPAC, particles < 2 nm diameter are microporous, 2-50  $\mu\text{m}$  mesoporous, and > 50 nm are macroporous. On examination under a scanning electron microscope, the external surface of PL was found to be irregular, rough texture with macropores of uneven size distribution; at the same time, in PLB, the macropores are distributed uniformly with a size range from 6.3-15.5  $\mu\text{m}$ ; PLB250-30, 8.1-8.6  $\mu\text{m}$ ; PLB300-60, and in 11.5-18.1  $\mu\text{m}$  in PLB350-30 (Fig. 3a, b, c, d). The biochar PLB350-30 exhibits a more significant number of macropores on its surface compared to the poultry litter feedstock and low-temperature biochars like PLB250-30 and PLB300-60, which is attributable to enhanced carbonization reactions that occurred at the specific temperature (350 °C) (Ghani et al. 2022). The porous nature of biochar enhances the soil’s aeration, promoting healthy root growth and stimulating microbial activity (Zhu et al. 2017, Khan et al. 2024). Poultry litter was slightly alkaline ( $7.6 \pm 0.03$ ) in nature, and the conductivity was found to be  $8.97 \pm 0.41 \text{ mS/cm}$ . In addition, it has a negative redox potential ( $-101 \pm 0.01 \text{ mV}$ ), indicating the fact that the material is anoxic (Table 2). The carbon content of poultry litter ( $28.1 \pm 0.2\%$ ) was remarkably high compared to lower levels of hydrogen ( $3.3 \pm 0.01\%$ ), nitrogen ( $3.2 \pm 0.01\%$ ), and sulfur ( $0.70 \pm 0.003\%$ ). The pH values of the poultry litter biochar samples ranged from  $7.2 \pm 0.04$  to  $8.7 \pm 0.5$ , indicating its alkaline nature, whereas the PLB350-30 had notably high alkalinity ( $8.7 \pm 0.5$ ) due to the increased ash content. The electrical conductivity was high in PLB300-60 ( $17.55 \pm 0.5 \text{ mS/cm}$ ). Similar to PL, biochar samples had negative redox potential. The percentage composition of total C was decreasing in the order PLB300-60 ( $35.1 \pm 0.4\%$ ) > PLB350-30 ( $34.01 \pm 0.3\%$ ) > PLB250-30 ( $28.5 \pm 0.1\%$ ). The composition of H ( $2.05 \pm 0.03\%$ ) and S ( $0.58 \pm 0.002\%$ ) was highest in PLB350-30, while N in PLB300-60 ( $3.06 \pm 0.02\%$ ).

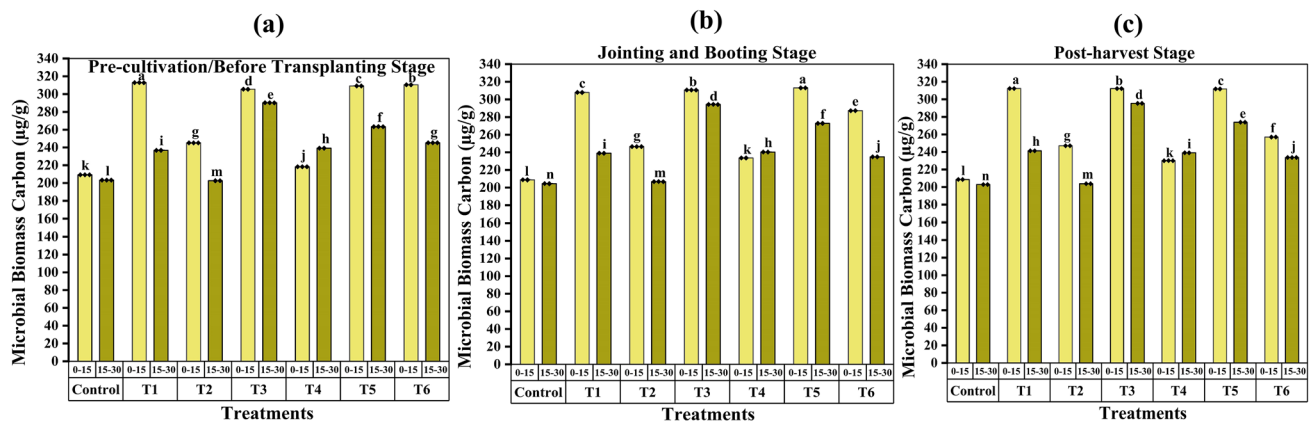
### Soil physicochemical properties

The fundamental soil properties are given in Table 3. The soil remained acidic in all treatments from pre-cultivation (day 1) to the post-harvest period (day 120). The electrical conductivity was high in the subsoil of T5 during pre-cultivation ( $1902 \pm 0.87 \mu\text{S/cm}$ ). In all treatments, organic matter was significantly high in the topsoil (0-15 cm). Compared to the jointing-booting (day 60) and post-harvest (day 120) stages, the organic matter composition was less in the pre-cultivation soil (Table 3). The total organic carbon (TOC) was not significantly different in treatments in the pre-cultivation

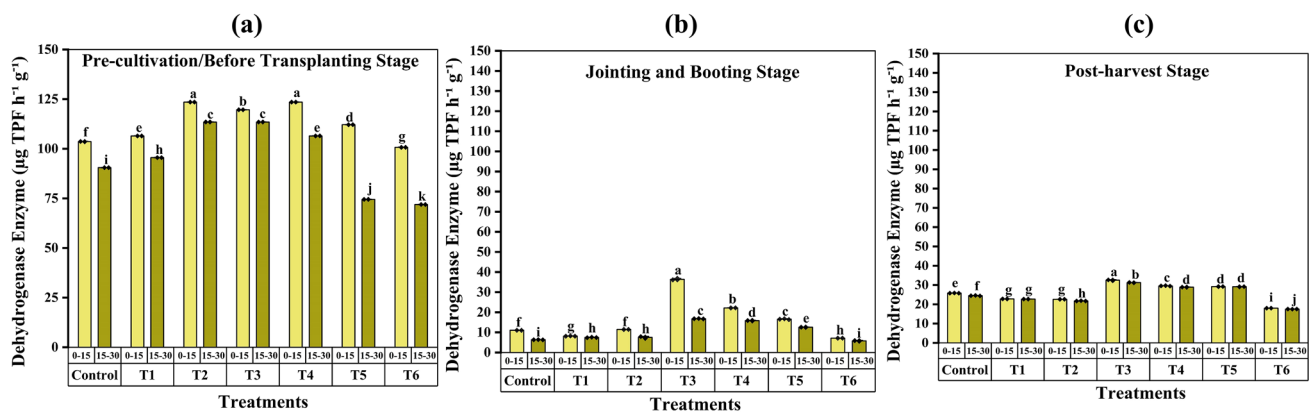
**Table 3** Soil fundamental properties in the pre-cultivation stage (day 1), jointing and booting stage (day 60), and postharvest stage (day 120)

Sampling stage	Treatments	Soil Depth (cm)	pH	EC ( $\mu\text{S}/\text{cm}$ )	Eh (mV)	TOC (%)	OM (%)	CEC in $\text{NH}_4/\text{L}$ (cmolc/kg)	WHC (%)	
Pre-cultivation stage (day 1)	C	0–15	5.7 $\pm$ 0.01	77.1 $\pm$ 0.01	78 $\pm$ 0.1	1.5 $\pm$ 0.05	2.6 $\pm$ 0.11	20.3 $\pm$ 0.21	46 $\pm$ 0.25	
		15–30	5.8 $\pm$ 0.02	24.1 $\pm$ 0.2	79 $\pm$ 0.2	1.2 $\pm$ 0.1	2.06 $\pm$ 0.23	19.5 $\pm$ 0.32	47.2 $\pm$ 0.2	
	T1	0–15	6.5 $\pm$ 0.1	448 $\pm$ 0.12	29 $\pm$ 0.1	1.4 $\pm$ 0.04	2.5 $\pm$ 0.21	21.9 $\pm$ 0.41	56.4 $\pm$ 0.1	
		15–30	6.5 $\pm$ 0.03	398 $\pm$ 0.21	30 $\pm$ 0.2	1.2 $\pm$ 0.2	2.1 $\pm$ 0.02	21.1 $\pm$ 0.31	56.8 $\pm$ 0.2	
	T2	0–15	6.9 $\pm$ 0.02	340 $\pm$ 0.32	19 $\pm$ 0.1	1.4 $\pm$ 0.22	2.5 $\pm$ 0.32	22.7 $\pm$ 0.43	67.2 $\pm$ 0.1	
		15–30	6.5 $\pm$ 0.01	301 $\pm$ 0.41	38 $\pm$ 0.3	1.2 $\pm$ 0.1	2.1 $\pm$ 0.02	20.3 $\pm$ 0.21	66.4 $\pm$ 0.2	
	T3	0–15	6.7 $\pm$ 0.01	599 $\pm$ 0.31	32 $\pm$ 0.2	1.5 $\pm$ 0.44	2.5 $\pm$ 0.42	21.9 $\pm$ 0.43	68.8 $\pm$ 0.3	
		15–30	6.7 $\pm$ 0.03	1620 $\pm$ 0.33	20 $\pm$ 0.1	1.1 $\pm$ 0.18	2.0 $\pm$ 0.08	21.1 $\pm$ 0.09	67.2 $\pm$ 0.2	
	T4	0–15	6.6 $\pm$ 0.02	901 $\pm$ 0.25	30 $\pm$ 0.4	1.8 $\pm$ 0.21	3.2 $\pm$ 0.22	23.6 $\pm$ 0.32	71.2 $\pm$ 0.1	
		15–30	6.6 $\pm$ 0.04	592 $\pm$ 0.66	29 $\pm$ 0.2	1.3 $\pm$ 0.31	2.3 $\pm$ 0.12	21.9 $\pm$ 0.33	70.4 $\pm$ 0.1	
	T5	0–15	6.8 $\pm$ 0.01	540 $\pm$ 0.21	19 $\pm$ 0.1	1.3 $\pm$ 0.22	2.3 $\pm$ 0.13	25.2 $\pm$ 0.21	80 $\pm$ 0.15	
		15–30	6.5 $\pm$ 0.03	1902 $\pm$ 0.87	40 $\pm$ 0.5	1.1 $\pm$ 0.11	1.9 $\pm$ 0.14	24.4 $\pm$ 0.05	79.2 $\pm$ 0.1	
	T6	0–15	6.1 $\pm$ 0.2	80.2 $\pm$ 0.11	38 $\pm$ 0.6	1.3 $\pm$ 0.13	2.2 $\pm$ 0.03	23.6 $\pm$ 0.22	49.6 $\pm$ 0.1	
		15–30	6.2 $\pm$ 0.1	98.7 $\pm$ 0.21	46 $\pm$ 0.3	1.1 $\pm$ 0.04	2.0 $\pm$ 0.01	22.7 $\pm$ 0.33	48.8 $\pm$ 0.3	
	Jointing and Booting stage (day 60)	C	0–15	5.8 $\pm$ 0.01	120 $\pm$ 0.57	80 $\pm$ 0.57	1.6 $\pm$ 0.11	2.9 $\pm$ 0.22	21.1 $\pm$ 0.22	44.4 $\pm$ 0.1
			15–30	6.1 $\pm$ 0.1	130 $\pm$ 0.57	88 $\pm$ 0.58	2.4 $\pm$ 0.21	4.3 $\pm$ 0.31	20.3 $\pm$ 0.23	45.6 $\pm$ 0.1
		T1	0–15	5.9 $\pm$ 0.01	140 $\pm$ 5.47	58 $\pm$ 6.57	2.5 $\pm$ 0.02	4.3 $\pm$ 0.12	23.6 $\pm$ 0.12	56.4 $\pm$ 0.1
			15–30	6.7 $\pm$ 0.1	130 $\pm$ 0.57	70 $\pm$ 6.57	3.3 $\pm$ 0.31	5.8 $\pm$ 0.21	22.7 $\pm$ 0.32	56.4 $\pm$ 0.1
T2		0–15	6.1 $\pm$ 0.01	120 $\pm$ 10.7	76 $\pm$ 5.47	1.6 $\pm$ 0.2	2.8 $\pm$ 0.04	25.2 $\pm$ 0.23	65.6 $\pm$ 0.1	
		15–30	6.5 $\pm$ 0.2	140 $\pm$ 10.7	86 $\pm$ 5.47	1.4 $\pm$ 0.1	2.4 $\pm$ 0.06	24.4 $\pm$ 0.43	66 $\pm$ 0.57	
T3		0–15	6.1 $\pm$ 0.01	130 $\pm$ 5.47	90 $\pm$ 4.38	2.2 $\pm$ 0.03	3.8 $\pm$ 0.12	26.8 $\pm$ 0.25	68 $\pm$ 0.36	
		15–30	6.5 $\pm$ 0.06	140 $\pm$ 5.47	98 $\pm$ 4.38	1.8 $\pm$ 0.05	3.2 $\pm$ 0.04	25.2 $\pm$ 0.18	67.2 $\pm$ 0.1	
T4		0–15	6.2 $\pm$ 0.16	110 $\pm$ 5.47	91 $\pm$ 2.73	0.92 $\pm$ 0.01	1.6 $\pm$ 0.04	28.4 $\pm$ 0.22	70.4 $\pm$ 0.1	
		15–30	6.5 $\pm$ 0.01	120 $\pm$ 5.47	96 $\pm$ 2.73	1.8 $\pm$ 0.11	3.2 $\pm$ 0.02	26.8 $\pm$ 0.16	69.6 $\pm$ 0.1	
T5		0–15	6.5 $\pm$ 0.01	120 $\pm$ 0.01	88 $\pm$ 5.47	2.9 $\pm$ 0.21	4.9 $\pm$ 0.11	30.04 $\pm$ 0.41	74 $\pm$ 0.25	
		15–30	6.6 $\pm$ 0.06	120 $\pm$ 0.01	98 $\pm$ 5.47	1.7 $\pm$ 0.1	2.9 $\pm$ 0.03	28.4 $\pm$ 0.66	72.8 $\pm$ 0.2	
T6		0–15	6.2 $\pm$ 0.1	122 $\pm$ 1.09	88 $\pm$ 0.54	1.5 $\pm$ 0.04	2.5 $\pm$ 0.11	27.6 $\pm$ 0.33	48.4 $\pm$ 0.1	
		15–30	6.1 $\pm$ 0.01	120 $\pm$ 1.09	89 $\pm$ 0.54	1.5 $\pm$ 0.03	2.5 $\pm$ 0.21	25.2 $\pm$ 0.23	48 $\pm$ 0.32	
Post-harvest stage (day 120)		C	0–15	4.9 $\pm$ 0.07	283 $\pm$ 97.49	107 $\pm$ 2.19	2.6 $\pm$ 0.11	4.6 $\pm$ 0.32	9.7 $\pm$ 0.81	44 $\pm$ 0.76
			15–30	5.1 $\pm$ 0.07	105 $\pm$ 97.49	103 $\pm$ 2.19	2.04 $\pm$ 0.07	3.5 $\pm$ 0.22	7.3 $\pm$ 0.32	48 $\pm$ 0.36
		T1	0–15	5.2 $\pm$ 0.01	104 $\pm$ 0.54	98 $\pm$ 5.47	3.6 $\pm$ 0.12	6.3 $\pm$ 0.22	13.8 $\pm$ 0.1	56 $\pm$ 0.25
			15–30	5.2 $\pm$ 0.01	105 $\pm$ 0.54	108 $\pm$ 5.47	2.04 $\pm$ 0.18	3.5 $\pm$ 0.11	12.2 $\pm$ 0.22	56 $\pm$ 0.1
	T2	0–15	5.3 $\pm$ 0.08	108 $\pm$ 83.25	107 $\pm$ 4.92	2.8 $\pm$ 0.13	4.9 $\pm$ 0.11	12.9 $\pm$ 0.22	60 $\pm$ 0.1	
		15–30	5.4 $\pm$ 0.08	260 $\pm$ 83.25	98 $\pm$ 4.92	2.2 $\pm$ 0.11	3.9 $\pm$ 0.22	11.4 $\pm$ 0.21	64 $\pm$ 0.1	
	T3	0–15	5.4 $\pm$ 0.07	150 $\pm$ 5.47	106 $\pm$ 7.12	2.8 $\pm$ 0.43	4.9 $\pm$ 0.31	15.4 $\pm$ 0.21	60 $\pm$ 0.05	
		15–30	5.3 $\pm$ 0.07	140 $\pm$ 5.47	111 $\pm$ 7.12	2.5 $\pm$ 0.21	4.2 $\pm$ 0.08	14.6 $\pm$ 0.22	60 $\pm$ 0.11	
	T4	0–15	5.5 $\pm$ 0.03	140 $\pm$ 10.95	104 $\pm$ 5.47	2.1 $\pm$ 0.07	3.6 $\pm$ 0.21	17.9 $\pm$ 0.11	64 $\pm$ 0.1	
		15–30	5.6 $\pm$ 0.03	120 $\pm$ 10.95	91 $\pm$ 5.47	2.3 $\pm$ 0.04	3.9 $\pm$ 0.2	15.4 $\pm$ 0.14	64 $\pm$ 0.1	
	T5	0–15	5.6 $\pm$ 0.21	120 $\pm$ 10.95	103 $\pm$ 5.47	1.7 $\pm$ 0.04	2.9 $\pm$ 0.11	20.3 $\pm$ 0.23	72 $\pm$ 0.1	
		15–30	5.9 $\pm$ 0.21	110 $\pm$ 10.95	93 $\pm$ 5.47	2.5 $\pm$ 0.14	4.4 $\pm$ 0.32	18.7 $\pm$ 0.21	72 $\pm$ 0.25	
	T6	0–15	5.6 $\pm$ 0.08	60 $\pm$ 27.38	92 $\pm$ 1.09	2.2 $\pm$ 0.12	3.9 $\pm$ 0.17	14.6 $\pm$ 0.14	44 $\pm$ 0.3	
		15–30	5.7 $\pm$ 0.08	110 $\pm$ 27.38	94 $\pm$ 1.09	2.4 $\pm$ 0.13	4.2 $\pm$ 0.06	13.8 $\pm$ 0.09	48 $\pm$ 0.32	

All data represented in mean value  $\pm$  standard deviation calculated from triplicate analysis



**Fig. 4** Microbial biomass carbon (MBC) in the soil during the cultivation periods. The alphabets indicate the significant difference ( $p < 0.05$ ) among treatments. The alphabet shares different letters are significantly different



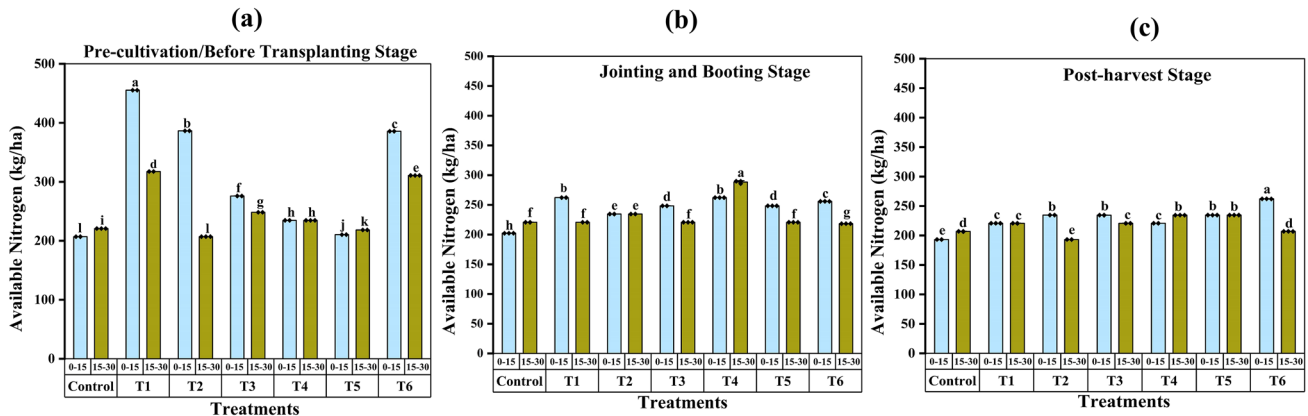
**Fig. 5** Soil dehydrogenase enzyme during the cultivation periods. The alphabets indicate the significant difference ( $p < 0.05$ ) among treatments. The alphabet shares different letters are significantly different

period, except T4, which exhibits significantly higher TOC ( $1.8 \pm 0.21\%$ ) in the topsoil. Meanwhile, T5 exhibits the highest water-holding capacity (WHC) during pre-cultivation (day 1) ( $80 \pm 0.15$ – $79 \pm 0.1\%$ ), jointing-booting ( $74 \pm 0.25$ – $72 \pm 0.2\%$ ), and post-harvest ( $72 \pm 0.25\%$ ) periods up to soil depths 0–15 cm and 15–30 cm. Cation exchange capacity (CEC) measures negative charges within the soil matrix. T5 showed the highest CEC during the jointing and booting stage ( $30.04 \pm 0.41$ – $28.4 \pm 0.66 \text{ cmolc/kg}$ ) and decreased gradually during the post-harvest period.

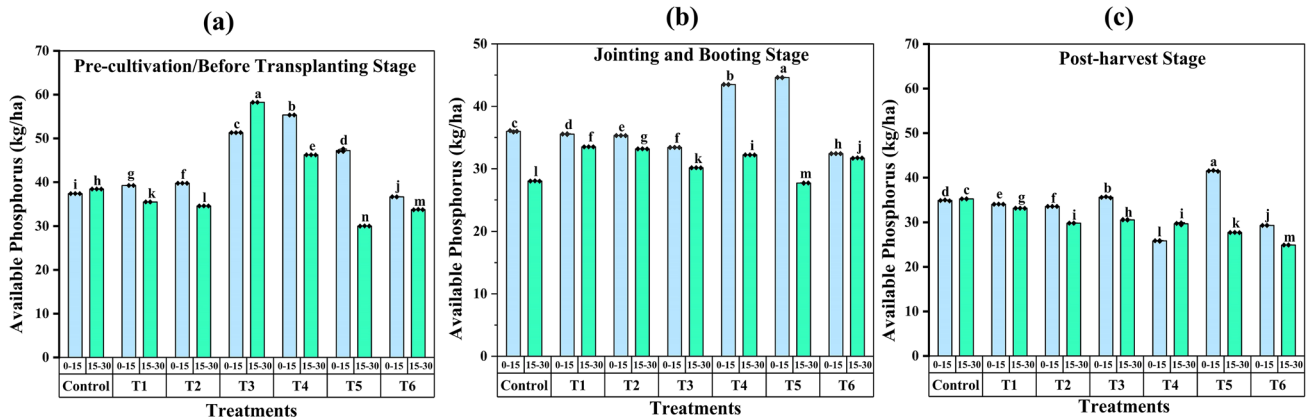
### Microbial biomass carbon and dehydrogenase enzyme activity in soil

The microbial biomass carbon (MBC), one of the soil microbial properties, was recorded higher for T1, T2, and T6 treatments including control except biochar (T3, T4, and

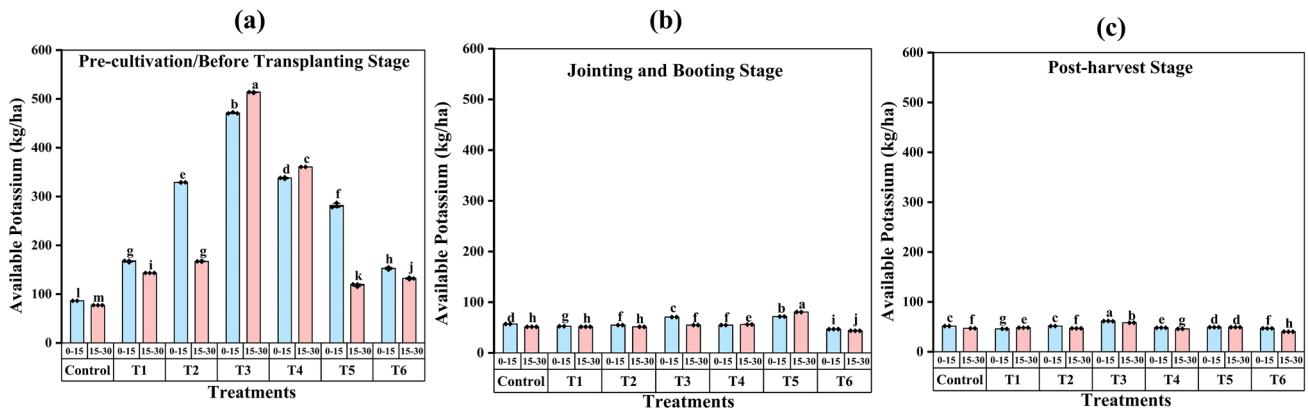
T5) in the pre-cultivation period (day 1) than in jointing and booting (day 60) and post-harvest soil (day 120). The treatments of T1 ( $312.9 \mu\text{g/g}$ ), followed by T6 ( $310.5 \mu\text{g/g}$ ), exhibited significantly high MBC in the top soils (Fig. 4a) collected from the pre-cultivation soil, whereas the biochar treatments T3 ( $310.6$ – $294.4 \mu\text{g/g}$ ), T4 ( $233.7$ – $240.3 \mu\text{g/g}$ ), and T5 ( $313.08$ – $272.9 \mu\text{g/g}$ ) recorded a significant increase in MBC during the jointing and booting stage, on day 60 compared to pre-cultivation (on day 1) and post-harvest (on day 120) periods. Microbial biomass carbon is a quantifiable labile soil carbon used to measure biological activity. The addition of poultry litter biochar facilitated the mineralization of soil organic matter and labile carbon fractions in the paddy soil, thereby enhancing the microbial biomass carbon (Lehman and Joseph, 2015). The biochar-amended soil improved its structure, nutrient availability, moisture retention, and pH stabilization and enhanced microbial habitats.



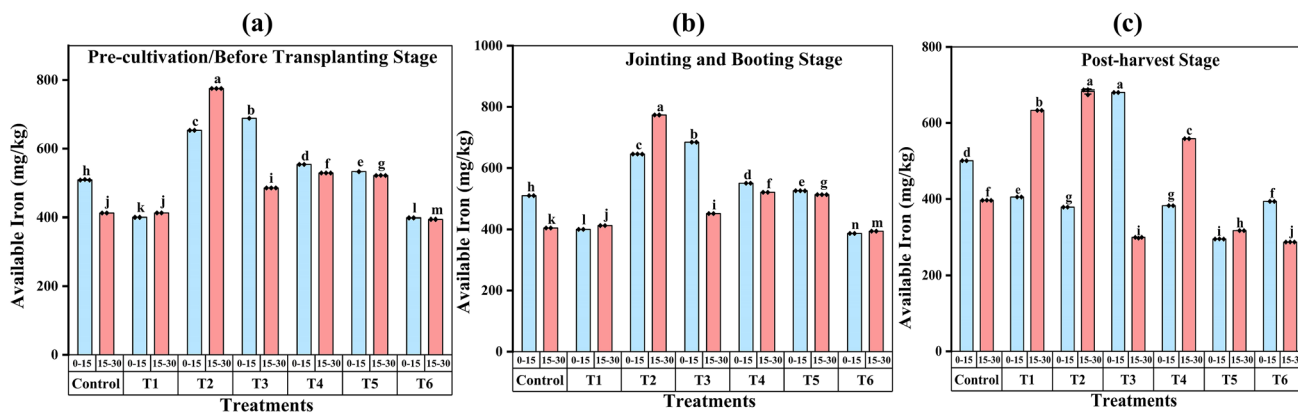
**Fig. 6** Available nitrogen (mg/kg) content in the soil. The alphabets indicate the significant difference ( $p < 0.05$ ) among treatments. The alphabet shares different letters is significantly different



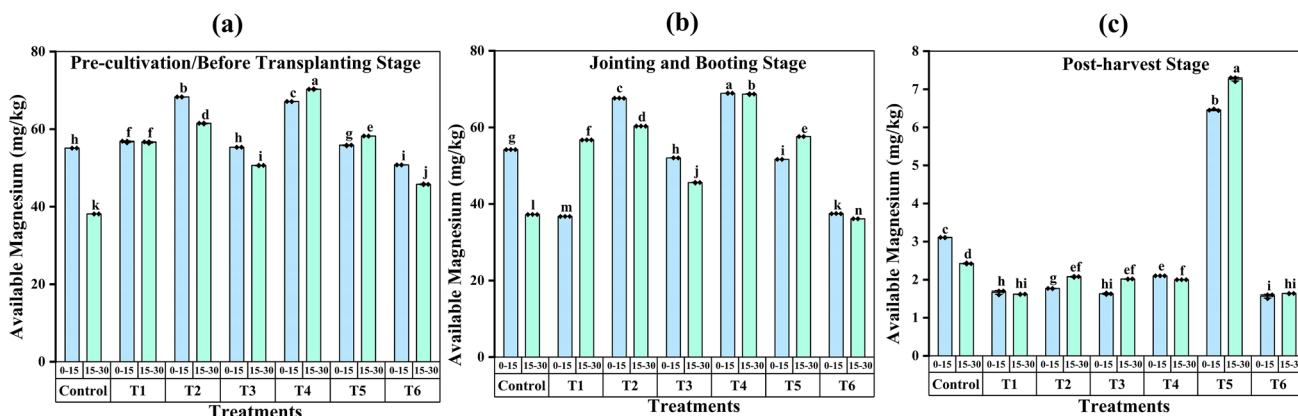
**Fig. 7** Available phosphorus (mg/kg) content in the soil. The alphabets indicate the significant difference ( $p < 0.05$ ) among treatments. The alphabet shares different letters is significantly different



**Fig. 8** Available potassium (mg/kg) content in the soil. The alphabets indicate the significant difference ( $p < 0.05$ ) among treatments. The alphabet shares different letters are significantly different



**Fig. 9** Available iron (mg/kg) content in the soil. The alphabets indicate the significant difference ( $p < 0.05$ ) among treatments. The alphabet shares different letters are significantly different



**Fig. 10** Available magnesium (mg/kg) content in the soil. The alphabets indicate the significant difference ( $p < 0.05$ ) among treatments. The alphabet shares different letters that are significantly different

**Table 4** Standard range of nutrients, fertility level, and nutrient index for paddy soil (Parker 1951)

TOC (%)	Avl N (kg/ha)	Avl P (kg/ha)	Avl K (kg/ha)	Avl Mg (mg/kg)	Fertility Level	Range	Nutrient Index
<0.5	<272	<9.8	<120	<50	Low	<1.70	I
0.5–0.75	272–544	9.8–24.5	120–280	50–100	Medium	1.71–2.33	II
>0.75	>544	>24.5	>280	>100	High	>2.33	III

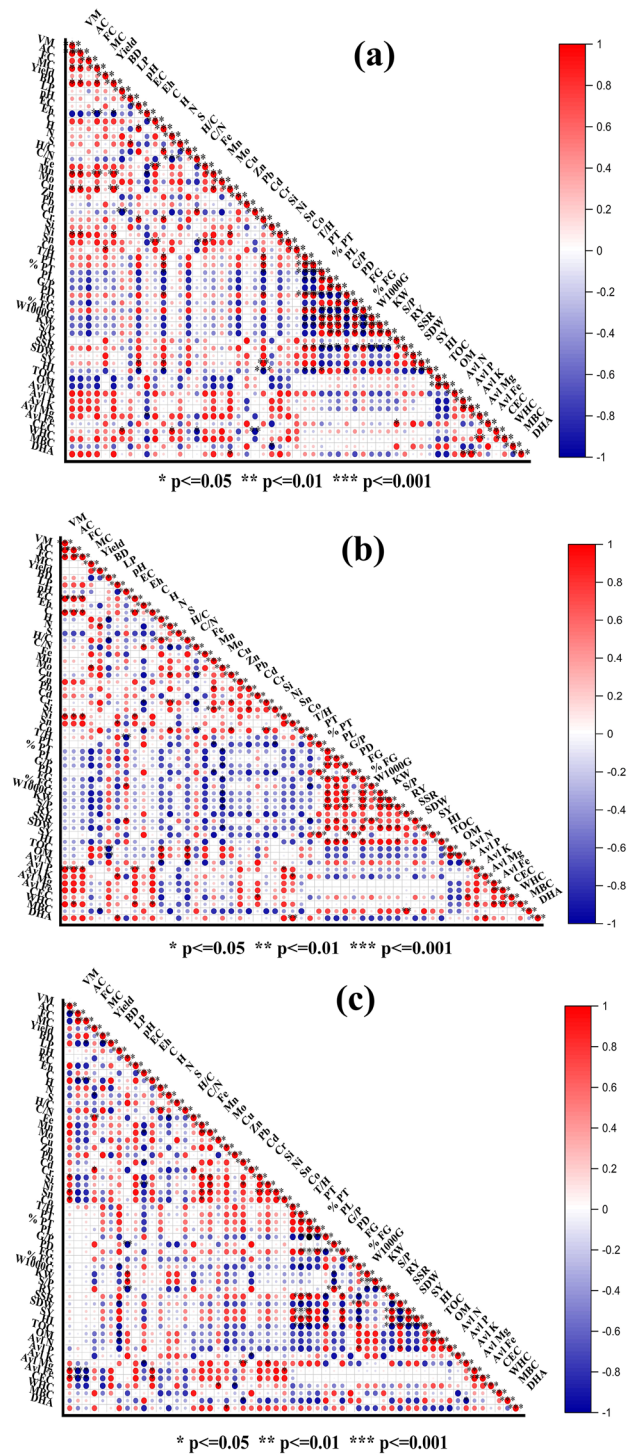
**Table 5** Nutrient index and fertility level of soil under different treatments

Treatments	Sampling stage	Depth	Nutrient Index				
			TOC	Avl N	Avl P	Avl K	Avl Mg
Control	Pre-cultivation stage (day 1)	0-30 cm	III	I	III	I	I
T1	Jointing-booting stage (day 60)		III	I	III	I	I
T2	Post-harvest stage (day 120)		III	I	III	I	I
T3			III	I	III	I	I
T4			III	I	III	I	I
T5			III	I	III	I	I
T6			III	I	III	I	I
Fertility level			High	Low	High	Low	Low

All these factors combined to create a more favorable habitat for microorganisms, thereby increasing microbial biomass carbon and contributing to overall soil health and fertility. Soil dehydrogenase is a respiratory enzyme that aids in the biological oxidation of organic matter. This enzyme activity is considered an oxidative activity of microorganisms. Hence, it is a good indicator of microbial activity (Masto et al. 2007; Nannipieri et al. 2017). Soil dehydrogenase activity (DHA) was found to be high in topsoils (0-15 cm) of T4 (123.51  $\mu\text{g/g}$ ), followed by T3 (113.48  $\mu\text{g/g}$ ), T5 (112.15  $\mu\text{g/g}$ ), and T2 (106.5  $\mu\text{g/g}$ ), during pre-cultivation (Fig. 5a). In the jointing-booting stage (day 60), T3 exhibited high dehydrogenase concentration (36.16  $\mu\text{g/g}$ ), followed by T4 (22.2  $\mu\text{g/g}$ ) and T5 (16.8  $\mu\text{g/g}$ ). Similarly, T3 (32.7  $\mu\text{g/g}$ ), T4 (29.7  $\mu\text{g/g}$ ), and T5 (29.02  $\mu\text{g/g}$ ) exhibited the highest DHA during the post-harvest stage (day 120) also (Fig. 5c). Parihar et al. (2016) concluded that dehydrogenase activity in the soil was positively correlated with microbial biomass carbon. Meanwhile, successive elevations in soil fertility levels generally decrease dehydrogenase activity (Mohan et al. 2019). Xiang et al. (2008) observed that DHA was roughly 4 times higher on the surface (0-20 cm) than in the subsoil (40-60 cm).

### Soil nutrient properties

The nutrient, available nitrogen (Avl N), was found to be significantly high in the topsoil of T1 (455.4 kg/ha), which is the treatment plot that follows the current farming practice (CFP) (Fig. 6a). Similarly, T6 is a reference plot maintained by farmers that follows CFP, also exhibited a high concentration of available N in the pre-cultivation soil (day 1). The trend occurred because of the intermittent addition of synthetic N fertilizers like urea to the topsoil during cultivation. However, the available N under all treatments except the biochar treatments, such as T3, T4, and T5, were significantly reduced in the jointing-booting (day 60) and the post-harvest soils (day 120) compared to pre-cultivation (Fig. 6b, c). The instantaneous decrease in the available N concentration in the treatment plots of CFP, such as T1 and T6, and poultry litter (T2) toward the end of the cultivation is primarily due to nutrient leaching and surface runoff from the field. Meanwhile, the available phosphorus (Avl P) was significantly higher in T3 (51.3-58.2 kg/ha), T4 (55.3-46.2 kg/ha), and T5 (47-30 kg/ha) in the pre-cultivation soil (Fig. 7a). Similarly, the concentration of phosphorus found to be decreased in the topsoil toward the end of cultivation under all treatments (Fig. 7b, c). The distribution of available potassium (Avl K) was decreased in the order T3 (472.6-514.7 kg/ha) > T4 (339.4-360.6 kg/ha) > T2 (329.3-168 kg/ha) > T5 (280-119.8 kg/ha) > T1 (168-143.4 kg/ha) > T6 (152.9-133.9 kg/ha) > control (86.2-77.3 kg/ha) respectively up to 0-30 cm depth during pre-cultivation (Fig. 8a, b, c). The available



**Fig. 11** Pearson Correlation Heat Map of physico-chemical properties of poultry litter biochar vs Soil fertility attributes during the pre-cultivation period on day 1. PLB250-30 (a), PLB300-60 (b), and PLB350-30 (c)

iron (Avl Fe) was observed maximum in the T2 (653.4-775.2 mg/kg) soil and minimum in T6 (398.6-394.6 mg/kg) during the pre-cultivation. Compared to topsoil, subsoils



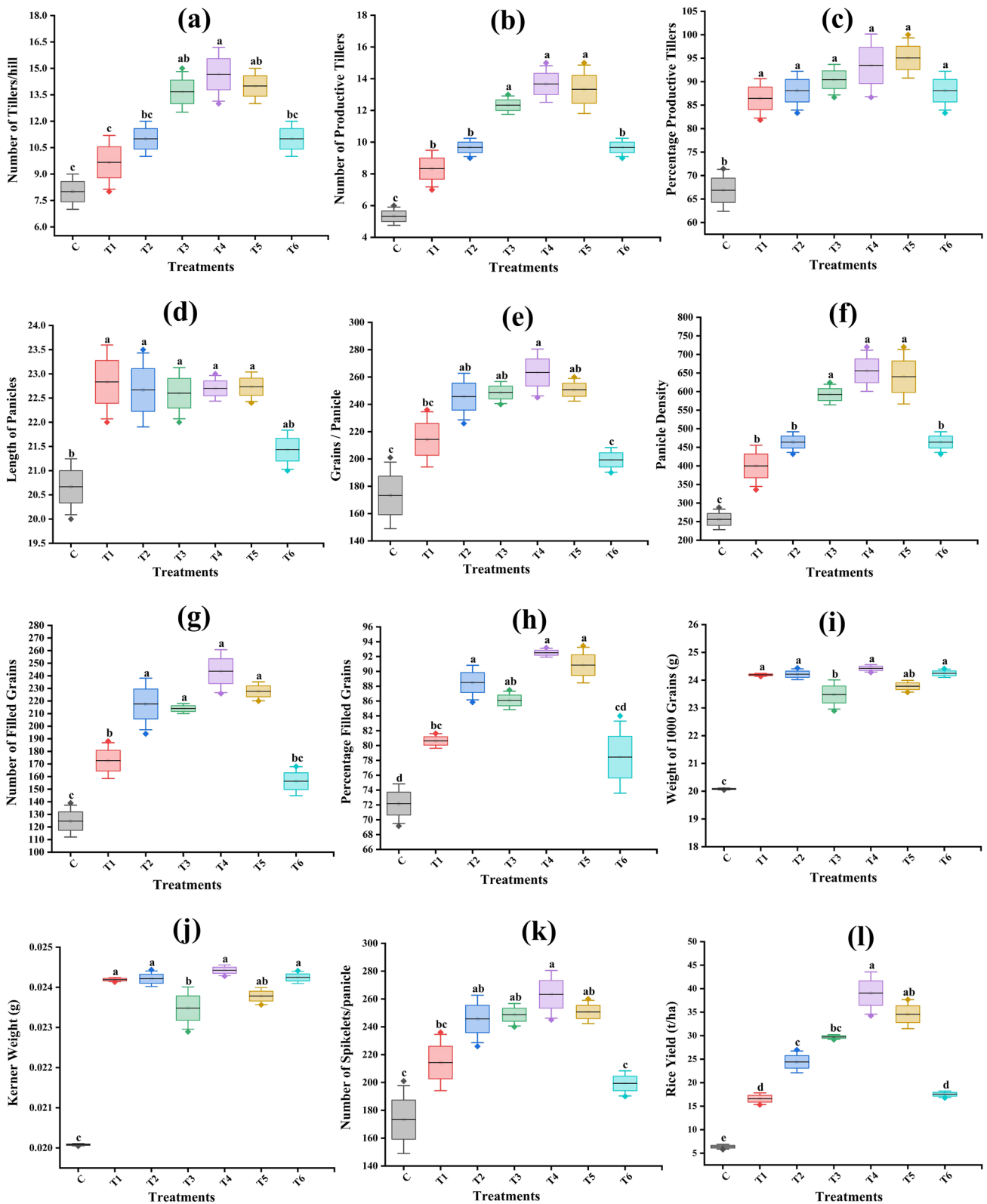
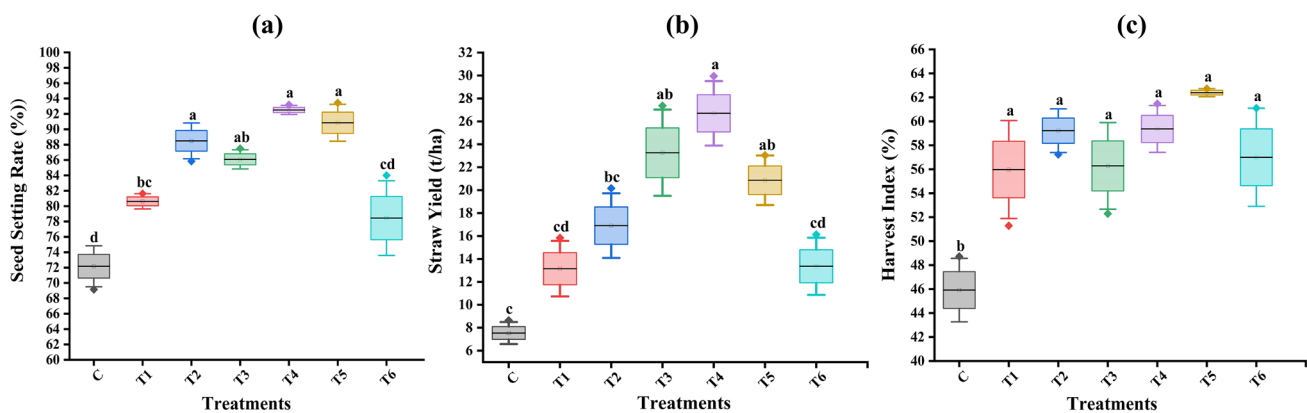


Fig. 13 Yield parameters of UMA MO-16 rice variety after field trial



**Fig. 14** Seed setting rate (a), straw yield (b), and harvest index (c) of UMA MO-16 rice variety after field trial

represented in Fig. 12. It was found that the crop height, root length, and shoot length for T1, T2, T3, T4, and T5 were similar and significantly higher than those of the control and T6 (Fig. 12a, c, d). The crop height was highest in T5 ( $113.3 \pm 2.8$  cm). The root and shoot lengths were highest in T5 ( $24.68$  cm) and T2 ( $29 \pm 0.5$  cm). The number of leaves, root dry weight, and shoot dry weight were found to be high for T5. The number of leaves observed in T5 ( $11 \pm 0.5$ ) was significantly higher than the control (7). Root dry weight and shoot dry weight for biochar treatments such as T5 and T4 were  $0.994 \pm 0.01$  g/plant and  $3.8 \pm 0.26$  g/plant, respectively. Endita and Yoshiyuki (2016) found that rice husk biochar at a 4% application rate significantly affected shoot height, root length, and root diameter from the 6th to the 9th week. In a similar study, Noguera et al. (2010) observed a significant increase in root biomass, length, and diameter after biochar addition to soil. Dong et al. (2015a, b) confirmed that biochar application increased shoot length and rice yield due to the biochar nutrient supply and high electrical conductivity.

#### Effects of PL and biochar on rice yield

The number of tillers per hill is one of the rice yield variables observed highest in T4 (15) and T5 (14), followed by T3 (14), T2 (11), and T6 (11) (Fig. 13a). Treatments T3 (12), T4 (14), and T5 (13) exhibited the highest number of productive tillers (Fig. 13b), and with respect to the percentage of productive tillers, all treatments; T1 (86.4%), T2 (88.08%), T3 (90.4%), T4 (93.5%), T5 (95.05%), and T6 (88.08%) showed significantly higher values than the control (66.9%) (Fig. 13c). The length of the panicles was found to be similar in T1 (22.8 cm), T2 (22.7 cm), T3 (22.6 cm), T4 (22.7 cm), and T5 (22.7 cm), whereas T6 (21.4 cm) and control (20.7 cm) were significantly different (Fig. 13d). Grains per panicle of T4 (263) were significantly higher than those of T2 (246), T3 (249), and T5 (251) (Fig. 13e), whereas T6 (199) and

control (173) were significantly similar but lower than T1 (214). Panicle density of treatments T3 (592), T4 (656), and T5 (640) were similar and significantly higher than that of T1 (400), T2 (464), T6 (640), and control (256) (Fig. 13f). The number of filled grains of T2 (218), T3 (214), T4 (244), and T5 (228) is similar and significantly higher than T1 (173), T6 (156), and control (125), whereas the percentage filled grains found similar and higher in T5 (90.8%), T4 (92.5%), and T2 (88.5%) (Fig. 13g, h). The weight of 1000 grains and the Kerner weight were significantly higher in T1 (24.19 g and 0.024 g), T2 (24.2 g and 0.024 g), T4 (24.4 g and 0.024 g), and T6 (24.2 g and 0.024 g) (Fig. 13i, j). Treatment T4 had the highest number of spikelets per panicle (263), whereas the values of T2 (246), T3 (249), and T5 (251) were significantly similar (Fig. 13k).

The rice yield obtained highest from T4 (39.06 t/ha) and least from control (Fig. 13l). Hence, the present study confirmed that the biochar made from poultry litter at a 1% application rate could improve the rice yield to six fold higher than the control and two fold greater than current farming practiced locally (T6). The seed setting rate of T4 (92.5) and T5 (90.8) was higher (Fig. 14a). The straw yield of T4 (26.7 t/ha) was significantly higher than the rest of the treatments (Fig. 14b). Harvest index was found to be greater in T5 (62.4%), however, significantly similar to T4 (59.4%), T2 (59.2%), T6 (56.9%), T3 (56.3%), and T1 (55.9%), the harvest index was significantly least in control (45.9%) (Fig. 14c). Biochar could enhance plant growth by releasing nutrients (El-Naggar et al. 2019). Previous studies by Lehmann et al. (2003) and Chen et al. (2008) reported that biochar-induced soil pH could maintain soil nutrient bioavailability for crop production. In sub-Saharan Africa, smallholder rice farmers gained large yields by implementing good agricultural practices (GAPs) using organic supplements like biochar and minimum synthetic fertilizers. The yield gains using GAP were achieved through increased panicle number, higher harvest index, and reduced weed

pressure (K. Senthilkumar et al. 2018). Such existing models on good agricultural practices will be evident and substantiate the findings of the present study. Implementing effective agricultural practices with biochar supplementation in paddy wetland systems in Kerala State can transform crop production through a sustainable approach. Rather than intermittently applying mineral fertilizers such as urea, fac-tamfos, potash, and lime, topdressing the paddy soil with poultry litter biochar (PLB300-60), produced at 300 °C with a 60-min residence time, at a 1% application rate during pre-cultivation, can maximize rice yield to 39.06 t/ha, twice that of current practices with minimal effort.

## Conclusion

The present study demonstrated the field supplementation effects of poultry litter and poultry litter-derived biochar in comparison to mineral fertilizers and current farming practices on soil fertility, growth, and yield of UMA MO-16 rice variety. Treatment No. 4, PLB300-60, was the most effective in enhancing soil pH, electrical conductivity, TOC, organic matter, and CEC, making it the recommended choice for soil supplementation. The yield parameters, including rice yield, seed setting rate, straw yield, number of spikelets per panicle, number of filled grains, percentage of filled grains, panicle density, and number of tillers per hill, were also highest in PLB300-60. The rice yield from PLB300-60 (39.06 t/ha) was six times higher than the control (6.4 t/ha), twice that of mineral fertilizer application (T1: 16.6 t/ha) and current farming practice (T6: 17.5 t/ha), and 1.5 times that of feedstock poultry litter (T2: 24.4 t/ha). The study found vegetative growth variables, such as crop height, root and shoot length, number of leaves, and root and shoot dry weight, were remarkably high for treatment No. 5, PLB350-30. All three biochar-amended treatments (T3, T4, and T5) have recorded the highest microbial biomass carbon during the jointing and booting stage (day 60) because of the accelerated carbon mineralization due to biochar-mediated microbial metabolism. Nutrients like N, P, K, Mg, and Fe were found to be more concentrated in the biochar-treated pre-cultivation (on day 1) soils. The fertility levels of the soil were high, as indicated by the TOC and available P concentrations, placing it in nutrient index class III. Furthermore, the study discovered that the proximate and ultimate parameters (elemental and metal compositions) in poultry litter biochar facilitate the long-term retention and availability of nutrients within the soil matrix.

Biochar is a viable approach to sustainable agricultural practices; however, multiple experimental field trials at various cropping seasons need to be performed in order to validate the precision of the study findings. Incorporating poultry litter-derived biochar into current agricultural practices

can boost resilience in paddy wetland ecosystems, ensure food security, and promote sustainability in waste management instead of conventional disposal methods and environmental conservation. Further study needs to consider the synergistic effects of poultry litter biochar with organic fertilizers like cow dung and compost for sustainable farming.

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**Author contributions** Anjali Thaitharanikathil Babu did the sampling, framed the methodology, and wrote the manuscript. Anand Madhavan reviewed and edited the manuscript. Akhilesh Kottikkathara Bhanuvikraman and Umalakshmi Kalayamkudath Subran did the sampling. All authors reviewed the manuscript.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no competing interests.

**Consent for publication** All authors have read and agreed to the publication of the manuscript.

**Ethics approval** This article contains no studies with human participants or animals performed by any of the authors. All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors and are aware that with minor exceptions, no changes can be made to authorship once the paper is submitted.

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