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Effect of Pyrolysis Temperature on Characteristics of Biochar Derived from Rice Straw and its Influence on Growth of Sunflower

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ABSTRACT

The management of large volumes of agro-waste such as rice straw is a big challenge as the burning of such waste leads to air pollution. The currenst study was proposed to evaluate the pyrolysis temperature effect on the characteristics of rice straw derived biochar and its implementations to improve the growth of sunflower (*Helianthus annuus* L.). In this study, biochar was prepared at three numerous temperatures viz; 400, 600, and 800 °C. The results of fourier transform infrared spectroscopy (FTIR) and x-ray diffraction (XRD) showed the existence of various functional groups viz; hydrogen bonded hydroxal groups, carboxylic groups, and crystalline structure of biochar, respectively. The proximate and CHNS analysis results, showed enhancement in ash and carbon content, while a reduction was seen in volatile content (VC), nitrogen (N), hydrogen (H) and H/C values, under the rising pyrolysis temperature, thus significantly improving plant growth. The pot trial was conducted with each treatment having four replicates. Application of rice straw derived biochar in potted soil at 2%, 4%, and 6% (w/w) significantly increased soil pH, electrical conductivity (EC_e), and water holding capacity (WHC), while reduced the bulk density (BD) of soil which strongly affect the bioavailability of macro and micro-nutrients in soil for plant. Biochar treatment(RSBC 600°C) at 4% application rate showed significantly higher difference in plant height (153.07cm), SPAD (60.8) and seed yield (12.6 g) of plant as compared to control. The results clearly showed that 4% biochar treatment (RS-BC2) gives beneficial outcomes with greater improvements in growth parameters. Hence, biochar derived from such potential waste is eco-friendly and can serve as a partial substitute for inorganic fertilizer.

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INTRODUCTION

Nowadays, the utilization of agricultural waste has become widespread in current years. About 9% of global energy is derived from biomass and around one billion tons of agricultural waste are produced. The solid waste generated on farms mainly constitutes of 80% organic matter (Akhter *et al.*, 2021). Rice (*Oryza sativa*) production ranks among the world's largest agricultural activities, although it trails behind commodities such as sugarcane and corn. Consequently, the production of derivative products, including rice husks (RHs) and rice straw, has also increased (Bisht *et al.*, 2020; Hussain *et al.*, 2021).

Rice straw was burned in the fields to banish which adversely affects the environmental quality standards by the outrush of toxic gases i.e., greenhouse gases, nitrogen oxides, and carbon monoxide, etc. into the climate surroundings. These gases lead to the formation of smog and cause hazardous impacts on human health (Chandio, *et al.*, 2020). The commercial method of biochar production through pyrolysis seems a suitable method that leads to control of the massive amount of field residue as well as rice straw. Pyrolysis is a thermochemical process that contributes to the degradation of organic matter in oxygen free environment, in this process, raw material is subjected to pyrolysis temperatures ranging from 300-600 °C (Sakhiya *et al*., 2021).

Allohverdi, Mohanty *et al*. (2021) studied that pyrolysis is the thermal reduction of substantial biomass under no or limited oxygen by supplying temperatures ranging from 300-800 °C. The products obtained were biochar, syngas, and bio-oil. The yield of the reaction is directly affected by changing temperature and processing time (Wang *et al*., 2020). The working ability of biochar is directly affected by the process parameters such as pressure, temperature, reactor setups, and the presence of catalysts and feedstock quality (Hossain *et al*., 2020). The ability of biochar to retain nutrients depends upon its porosity and surface charge, including both cation and anion exchange capacities (Adeleke and Babalola 2020). The application of biochar retards the leaching of nitrogen (N), phosphorus (P), and potassium (K), as well as the emission of nitrogen through nitrous oxide (Tsai *et al*., 2021).

Sunflower is an oilseed crop local to North America. Sunflower belongs to the Compositae family which comprises one of the largest groups of flowering plants with 23,000 species distributed among 1600 genera. It is considered a significant source of biomass (Nguyen *et al*., 2021). Soni and Ojha (2021) reported the potential use of biochar as a soil enhancer because it exhibits remarkable aggregate stability due to elevated carbon levels, also rich nutrients support a thriving microbial population. (Jatav *et al*., 2021) reviewed that biochar is a cost-effective product that can also be applicable as a fertilizer. The utilization of biochar initially enhances the physical condition of the soil, which through various indirect mechanisms, can subsequently influence other bio-chemical properties of the soil (Haider *et al*., 2022).

The application of biochar at various doses resulted in a notable rise in pH, electrical conductivity, sodium, carbon, phosphorus, and base saturation levels in the soil. On the contrary, there was a decrease in potential acidity and soil cation exchange capacity, collectively contributing to the enhancement of soil fertility (Leng *et al*., 2022). The efficiency of biochar as a soil amendment is greatly influenced by both the feedstock used and the production conditions employed. Biochar products that effectively support long-term soil health possess high levels of stable organic carbon (OC) and exhibit strong water and nutrient-holding capacities (Brtnicky *et al*., 2021).

Biochar recycles most of the nutrients in soil that have been removed due to the harvesting. It influences seed germination, plant development, disease resistance, and acclimatization to abiotic conditions in terms, of how well plants function (Yang, *et al*., 2020). According to several studies, biochar amendments in soil enhance the plant yield from 10 to 40%. The amendment of soil with biochar increases the nutrient uptake as a result plant yield also increases. Biochar can be used as organic fertilizer, as an alternative to commercial fertilizer, and reduces the demand of synthetic fertilizers (Yang *et al*., 2021).

The research study aimed at derivation of biochar from rice straw at three various temperatures viz; 400, 600, and 800°C and characterization of each prepared biochar through Fourier Transform Infrared Spectroscopy and X-ray Diffraction Spectroscopy. Pot trial was conducted to assess the influence of each prepared biochar on soil properties and growth parameters of sunflower.

MATERIALS AND METHODS

Collection of raw material

The feedstock (rice straw) was collected from three randomly selected locations within a pre-irrigated field area at the University of the Punjab Lahore, Pakistan (Locations: N 31°30. 078' E 074° 18. 139; N 31°30. 081' E 074° 18. 154'; N 31°30. 100' E 074° 18. 158') as shown in Figure 1.

Preparation of raw material

The collected rice straw biomass was placed in the open air to dry for 5-6 days. Rice straw was chopped into small pieces of uniform size (about 2 cm) using a machine like a straw chopper or shredder. This helps reduce moisture content and prepare the straw for further processing. The uniformly sized prepared feedstock was utilized for pyrolysis.

Preparation of biochar

The chopped rice straw feedstock was subjected to pyrolysis, a process of heating organic material in the absence of oxygen. That process was done in a specialized pyrolysis unit. Rice straw-derived biochar was prepared at various temperatures viz: 400, 600, and

800°C for a residence time of 25 min under an extremely limited supply of oxygen i.e., by achieving 0.001 Torr pressure in the feedstock chamber of a semi-automatic pyrolyzer with ramp rate of 30 °C min^{-1}. Before utilization for further analyses, each batch of prepared biochar was stored in separate polythene bags.

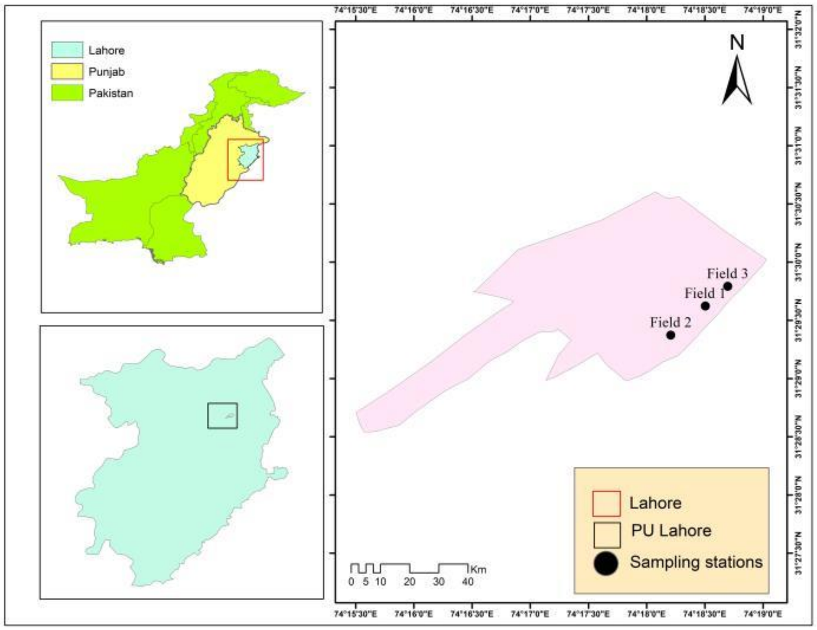

Figure 1. Geographical sampling sites.

Surface characterization of biochar

The Fourier Transform Infrared Spectroscopy (FTIR) absorbance spectra were acquired using a spectrometer (IR-Prestige-21, Tokyo, Japan), scanning across wave numbers ranging from 4000 to 400 cm^{-1}. FTIR study were used to detect the presence of various functional groups and biochemical composition of rice straw derived biochar. X-ray Diffraction (XRD) technique was employed to analyze the atomic structure along the crystallinity of the biochar by using (Thermo tm scientific ARL Equinox 300).

Proximate and ultimate analysis

The proximate analysis of the prepared rice straw biochar was performed to determine the moisture content (MC), volatile content (VC), ash content (AC) and fixed carbon (FC) by using following formula:

$$\text{Moisture Content (\%)} = \frac{W_1 - W_2}{W_1} \times 100$$

$$\text{Volatile Content (\%)} = \frac{W_2 - W_3}{W_2} \times 100$$

$$\text{Ash Content (\%)} = \frac{W_3 - W_4}{W_3} \times 100$$

Where W_1 is the initial weight of air-dried sample, W_2 is the weight of the dried sample for 24 h at 105 °C, W_3 is the weight of the dried sample to find VC for 7 min at 950 °C, W_4 is the weight of dried sample for 5-6 h at 750 °C to determine the ash content. However, Fixed Carbon (%) = 100-weight % (MC + VC +AC).

Physicochemical analysis

The prepared biochar underwent a comprehensive set of analyses, encompassing pH, electrical conductivity (EC_e) of the prepared biochar were determined by adding a twenty gram of the sample (biochar) in 100 mL of distilled water. The mixture was left for 2-4 h, mixed and filtered the solution and determined the pH and electrical conductivity. (Zhang *et al*., 2021) suggested that the bulk density (BD) was measured by using 100 cm^3 container filled with biochar after tapping for 3-4 times to settle down the biochar and make sure the consistency of volume by using formula

Bulk Density (BD) = Prepared ground biochar/stuffed volume of biochar

(Ippolito *et al*., 2015) given the protocol of cation exchange capacity (CEC) of rice straw derived biochar was determined by using a barium acetate solution. Water holding capacity of biochar sample was measured by observed the procedure given by (Yang *et al*., 2021).

Elemental analysis (%)

The elemental structure of carbon, hydrogen, nitrogen and sulphur was determined by using pre-calibrated elemental analysing system (GmbH, Varo MICRO cube V1.9.4). The complete oxygen was calculated by using formula: Oxygen (%) =100-C-H-N-S-ash

Setting of pot experiment

The experiment was conducted in pots to observe the influence of rice straw derived biochar on growth of sunflower.

Collection of soil

Soil was collected from the Botanical Garden,University of the Punjab, Quaid-e-Azam Campus, Lahore, Pakistan. Soil was air dried on polythene sheets under sunlight. Large aggregates were broken down into small pieces; the extraneous material was removed from the soil and soil was sieved through the sieve of mesh size 2mm^2.

Experimental design

The pot experiment was conducted in the greenhouse having a transparent glass roof in Botanical Garden, University of the Punjab, Quaid-e-Azam Campus, Lahore, Pakistan, in "Completely Randomized Block Design" with four replicates per treatment. The plastic middle-sized pots of 15 cm length and 2 kg capacity were used for experimentation. Seeds were sown under depth of 1 cm layer of soil. Seeds were covered with a thick layer of soil and followed by watering with a sprinkler. The treatments accompanied by;

- Control treatment soil (no amendment of biochar and no fertilizer)
- Derived biochar prepared at 400°C (at application rates of 2%, 4%, and 6% (w/w))
- Derived biochar prepared at 600°C (at application rates of 2%, 4%, and 6% (w/w))
- Derived biochar prepared at 800°C (at application rates of 2%, 4%, and 6% (w/w))
- Addition of commercial fertilizer into soil (urea, NPK)

Potted soil amended with biochar, it was placed in the glasshouse to keeping moistened for 15 days of pre-incubation period to build up the biochemical activities in the biochar and soil. In conducted experiment, the sunflower (*H. annuus*) being used as a experimental plant due to its higher production of biomass and expeditious flowering. Three germinating seeds were shifted into pots. After germination, thinning was performed to retain one seedling in each pot. Regular watering was carried out for growth of plant during the growth period of plants.

Soil characterization

Physico-chemical analysis of 15 days incubation of pre-planting and post-harvesting soil was performed. Soil samples was collected from each pot in polythene bags, air dried, crushed and sieved through mesh size 2.5 mm^2. The physical-chemical properties i.e., pH, electrical conductivity (EC_e) was measured by preparing soil extract (1:5). Bulk density of soil was measured by same protocol used for biochar. Loss of ignition method was used for measuring total organic matter of the soil samples by using (Bushra and Remya 2024) method. (Tomczyk *et al*., 2020)given the protocol for measuring the cation exchange capacity (CEC) of the soil samples. Pot soil retains water and the measurement of water holding capacity was followed by using the procedure given by (Yang *et al*., 2021).

Growth parameters

Different concentrations of prepared biochar along with control and commercial fertilizer treatments affected the whole plant length, plant fresh weight, plant dry weight, Soil Plant and Analysis Development (SPAD), and seed yield were measured after the harvest of 65 days old plants.

Statistical analysis

All collected data were analyzed by using Analysis of Variance (one way system). The significant differences between mean values were observed by applying Least Significant Difference Test (LSD) at $p \leq 0.05$, performed by using SPSS version 23.

RESULTS AND DISCUSSION

FTIR Characterization of rice straw derived biochar

FTIR of rice straw biochar was used to analyze different functional groups on the exterior of biochar as shown in figure 2. at wavelengths ranging from 4000-400 cm^{-1}. For rice straw derived biochar prepared at three different temperatures i.e., 400, 600, and 800 °C. The surface of rice straw biochar showed various oxygen containing functional groups. The adsorption peaks ranging from 547- 785 cm^{-1} among all pyrolytic temperatures indicated the existence of SiO_2, this band can be visible in all biochar derived from rice materials (Deka, Medhi *et al*., 2018). The intense peaks were broad around 1030-1060 cm^{-1} with the temperature rise, which showed CO–O–CO stretches, representing the existence of anhydride groups revealed by (Foong, Chan *et al*., 2022). (Xu *et al*., 2021) reported that peaks appeared between 1500-1565 cm^{-1} linked to —COOH vibration or C=O and C=C. The vibration stretch at peak ranges 2304 cm^{-1} corresponding to O=C=O group caused by existence of CO_2, which was not observed in high temperature biochar similar to the findings of (Viswanathan *et al*., 2022). The vibration of bands between 2730 and 3055 cm^{-1} showing aliphatic C-H stretch vibration in all prepared biochar. (Venkatesh *et al*., 2022) reported that around wavelength of 3250-3587 cm^{-1} indicates the phenolic O-H group. The findings of (Singh *et al*., 2020) showed that when pyrolysis temperature accelerated from 400 to 800 °C, the intensity of peaks declined moderately such as aromatic groups and hydroxyl groups caused by the process of de-polymerization and dehydration. Other works (Shukla *et al*., 2022) described that various bands showed functional groups present in prepared biochar at (400-600°C) and are not present in high-temperature derived biochar.

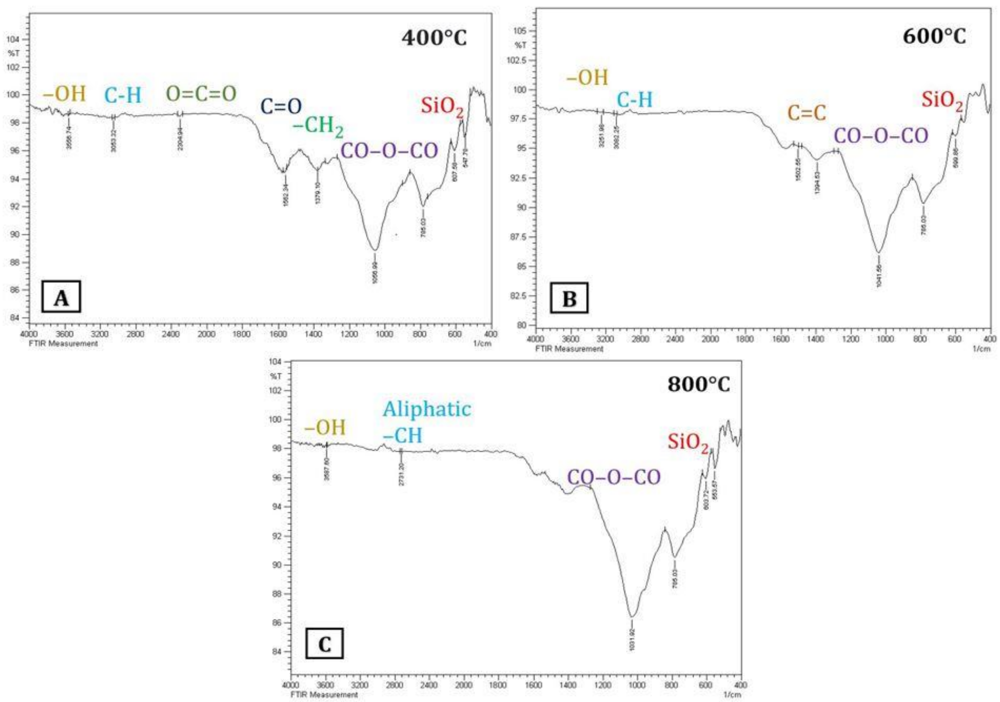

Figure 2. Fourier transform infrared spectra of derived biochar at different temperatures i.e.; A= 400 °C, B=600 °C and C=800 °C.

X-ray diffraction (XRD) characterization of rice straw derived biochar

The XRD pattern of biochar is shown in Figure 3. The results were close to preceding studies of XRD analysis of prepared biochar at three different temperatures. Similar results were shown by a previous study (Getahun *et al*., 2020) at a temperature of 400°C, the existence of well-crystallized mineral quartz was demonstrated by the medium peak observed at 2θ=60.01°. (Bera *et al*., 2018) reported that another mineral sylvite, also known as potassium chloride (KCl) was present at peaks ranging from 2θ=27.14° and a small peak 2θ=40.60°. Biochar prepared at 600°C temperature showed additional bands at 2θ=26.14°and 2θ=50.24° which were assigned to the appearance of quartz (SiO_2) and calcite ($CaCO_3$). Furthermore, a sharp diffraction peak at 2θ=22.04° corresponds to phagioclase which can more exist in biochar prepared (600 °C) than in biochar prepared at 400°C (Ma *et al*., 2022). No previous studies of XRD analysis were observed at biochar prepared at 800 °C. The results supported those peaks nearby 2θ=23.18° indicating the presence of graphite that led to diminishing the amorphous structure of biochar (Yakout, 2017). On the other hand, crystalline crystobalite (SiO_2) and mullite ($3Al_2O_3 \cdot 2SiO_2$) were present at strongly intense peaks 2θ=60.14° and 2θ=*50*.04°.

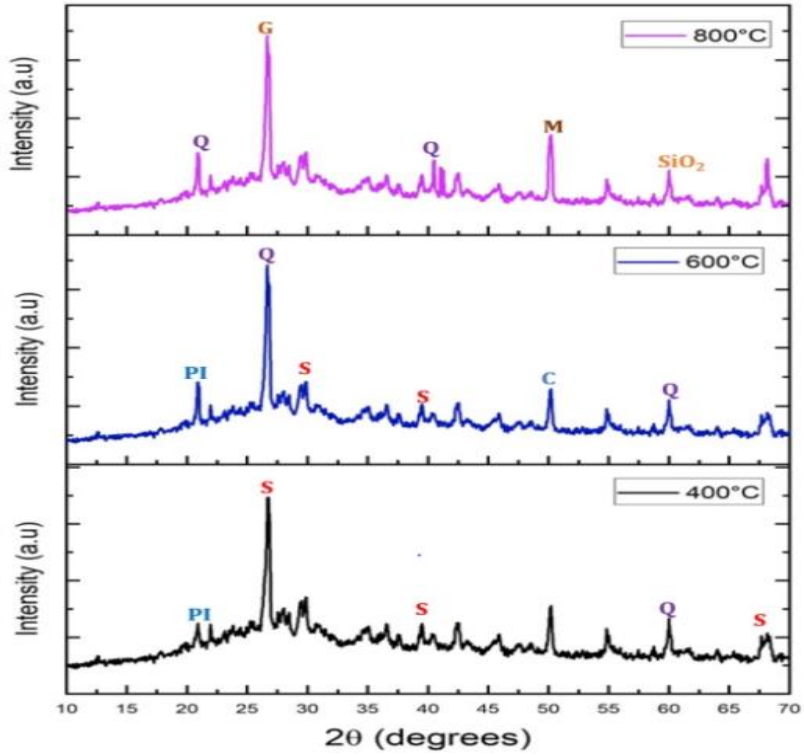

Figure 3. X-ray diffraction patterns of derived biochar at different temperatures i.e; A= 400 °C, B= 600 °C and C= 800°C. *Q* quartz, *S* sylvite, *C* calcite, *PI* phagioclase, *G* graphite, *M* mullite.

Proximate and ultimate analysis

The results of proximate analysis of biochar were shown in Figure 4 illustrating that rice straw biochar originally had higher moisture and volatile content while these contents decreased with rise in temperature because of thermal degradation of hydrophillic functional groups and organic compounds in consistence with the findings of (Tao *et al*., 2020). Whereas ash content and fixed carbon increases as the temperature rises from 400 to 800°C. This could be assigned due to substantial degradation of organic material leaving behind a high proportion of ash content (Cabriga *et al*., 2021). The results of (Wang *et al*., 2020) described that high fixed carbon content at high temperatures might be due to the existence of recalcitrant carbon.

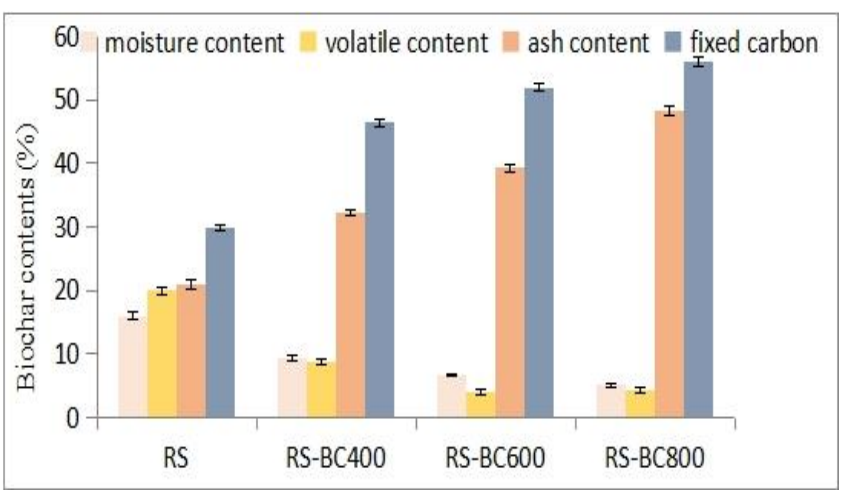

Figure 4. Proximate analysis of derived biochar at different temperatures.

The results of ultimate analysis of biochar shown in Table 1, illustrated that the biochar yield of rice straw biochar significantly decreased 39.23 % to 33.05 % with the rise in temperature. As actual fact, it was suggested that reduction of yield was caused due to thermal decomposition of various hydrocarbons (Nazir *et al*., 2021). The carbon content in rice straw biochar enhanced with the rise in temperature than the raw biomass by 44.25 % to 53.5 % due to high rate of carbonization as well as the formation of aromatic carbon structures. Whereas nitrogen content (3.32 % to 1.37 %) and hydrogen content (6.01 % to 1.92 %) reduced than the raw biomass. The studies (Ortiz *et al*., 2020) reported that reduction of nitrogen might be due to elimination of volatile compounds such as nitrogenous gases, ammonia (NH_3) and hydrogen cyanide (HCN). In other findings of (Saffari *et al*., 2020) reported that the decreased amount of hydrogen content caused due to removal of water vapors during pyrolysis which emitted hydrogen atoms from biochar surface. Similarly, high temperature biochar showed low oxygen content (31.49 % to 12.78 %) due to thermal decay of organic matter (Nepal *et al*., 2023). In another study (Haque *et al*., 2022). It was claimed that the aromaticity, hydrophilicity, and polarity of biochar structure represent the H/C and C/N atomic ratios of organic components in biochar. The studies reported by (Muzyka *et al*., 2023). The C/N ratio of biochar substantially increased (28 to 48.6) as compared to feedstock (4.64) due to partial loss of nitrogen compounds and increased level of carbonization process. However, ratio of H/C of organic components decreases with the rising temperature due to thermal breakdown of hydrogen bonds.

Table 1. Ultimate analysis of rice straw feedstock and its derived biochar produced at different temperatures viz; 400, 600 and 800 °C.

Index	Units	RS	RS-BC400	RS-BC600	RS-BC800	LSD
BY	%	-	39.25±2.16	37±1.87	33.05±1.55	47.1409
C	(wt.%)	43.55±1.99	44.25±2.16	49.05±2.22	53.5±2.29	11.8817
N		3.32±0.39	2.12±0.02	1.65±0.29	1.37±0.26	2.20849
H		6.02±1.25	4.07±0.69	2.26±0.43	1.92±0.37	4.81426
O		31.49±2.28	24.42±1.89	16.95±1.78	12.78±1.31	21.183
C/N	-	4.64±0.03	28.0±1.81	36.75±2.20	48.6±2.29	47.6697
H/C		0.22±0.04	0.017±0.019	0.014±0.01	0.009±0.006	0.2748

Key. BY -biochar yield; C -carbon; H -hydrogen; N -nitrogen; O -oxygen, RS-BC=rice straw derived biochar. Values are means of four replicates ± SD, LSD =least significant difference.

Physicochemical analysis of rice straw derived biochar is shown in Table 2. The outcomes revealed that values of pH and EC_e at different temperature biochar enhanced as the pyrolytic temperature raised. The pH was found to be highly alkaline than the raw biomass (8.7 to 10.25) due to the dissipation of acidic functional groups. These outcomes were similar to the studies of (Chandra and Bhattacharya 2019). After thermal decay of feedstock, rice straw biochar was found to have higher electrical conductivity by 261 μ S cm^{-1} to 503 μ S cm^{-1}. The results of another study (Griffin *et al*., 2022) explained that the increase of EC_e due to existence of carboxylic group on biochar surface were also decreased because they are non-conductive. The density of prepared biochar was decreased from 0.32 g cm^{-3} to 0.22 g cm^{-3} as the temperature upshifted from 400 to 800 °C due to loss of volatile matter which reduced the biochar mass that causes variation in bulk density reported by (Tang *et al*. 2021). Furthermore, CEC of the biochar was significantly increased by 7.11 $cmol_c$ kg^{-1} to 10.10 $cmol_c$ kg^{-1} by increasing temperature respectively. The results showed that WHC of biochar was significantly enhanced than the raw biomass (34.6 % to 82 %) due to reduction of hydrophilic groups, but this finding opposed the previously described results from another research studies (Murtaza *et al*., 2023) that describes the decrease in water holding capacity of biochar.

Table 2. Physicochemical properties of rice straw derived biochar produced at different temperatures viz; 400, 600 and 800 °C.

Properties	Units	RS	RS-BC400	RS-BC600	RS-BC800	LSD
pH	-	8.7±0.38	8.92±0.24	9.52±0.22	10.25±0.23	1.7777
EC_e	(μ S cm^{-1})	261±1.58	450.7±1.92	481.5±2.06	503±3.81	283.9383
BD	(g cm^{-3})	0.58±0.03	0.32±0.03	0.23±0.02	0.22±0.01	0.426879
CEC	($cmol_c$ kg^{-1})	7.11±0.80	7.40±0.38	8.56±0.36	10.10±0.74	3.481681
WHC	(%)	34.6±1.25	61±1.58	68.5±1.80	82±2.62	51.01723

Key. EC_e -electrical conductivity of extract; BD -bulk density; CEC -cation exchange capacity; WHC -water holding capacity; RS-BC -rice straw derived biochar. Values are means of four replicates ± SD. LSD = least significant difference.

Improvement of soil amended with rice straw derived biochar

After 15 days of incubation period, the results of physicochemical properties of biochar amended soil with different concentration rates are given in Table 3. Values of pH and EC_e significantly enhanced to 8.29 and 134.5 μS cm^{-1}. This study showed that pH was found to be highly alkaline due to loss of acidic functional groups (Hu *et al*., 2020). CEC usually constitutes the existence of cations on biochar surface (Laila, Nazir *et al*., 2022) Additionally, TOM and CEC also raised (3.74 g kg^{-1} to 3.93 g kg^{-1}) and (7.93 $cmol_c$ kg^{-1} to 12.29 $cmol_c$ kg^{-1}) with increasing concentration of biochar and bulk density was slightly reduced due to high porosity and retaining capacity of excessive nutrients and moisture in soil that agreed with the analysis of (Aziz *et al*., 2023). These results are in agreement with the findings of Peng *et al*., (2011) who demonstrated that rice straw biochar produced at a higher temperature significantly elevates the pH of soil and enhances the CEC of soil by more than 17%, Furthermore, biochar addition caused the reduced bulk density of soil revealing the fact that rice straw biochar has high porosity. Moreover, the TOM was found in soil raised with high dosage of biochar sample due to considerable increase in inclusion of nutrients and high C/N ratio in biochar amended soil. The enhancement in microbial activity of soil might be due to modification of physicochemical properties of soil, which facilitates the plant defense mechanism (Qin *et al*., 2016).

Enhancement in post harvested soil analysis

After the harvest of 65 days old sunflower, the biochar amended soil samples were collected from each replicate to reveal the changes in soil properties. The consequences of post harvested analysis are shown in Table 4. The data obtained from post analysis was crucially improved contrary to control and commercial fertilizer applied soil. Rice straw biochar served as sustained release organic fertilizer to the enhancement of the soil quality (Kapoor *et al*., 2022).Rice straw biochar comprised about high silicon content and mineral composition was prepared as reported by findings of (Runkle *et al*., 2021) to improve soil fertility. During experimental assessment (Yuan *et al*., 2023), it was disclosed that biochar amended soil upraised the soil properties thus, EC_e, TOM, CEC improved the soil structure. Moreover, bulk density of soil amended with RS-BC3 was reduced to 1.16 g cm^{-3} as compared to control soil which was found 1.43 g cm^{-3}. Biochar being a rich source of organic matter content, serves as a key binder for soil fertility. Its implementation in soil improves the soil properties and provides a conducive environment for the proliferation of beneficial microbes which ultimately boosts the availability of nutrients in soil (Laila, Huda *et al*., 2024; Chen, Li *et al*., 2019). Our results also showed that biochar addition served as a boost product resulting in extremely alkaline due to uplifted soil pH which gives rise to elevation in EC_e and CEC of biochar amended soil. The alkalinity of biochar interlinked with the cellulose and hemicellulose occurred on the surface of biochar (Hussain *et al*., 2021; Lei *et al*., 2019). On the contrary, few studies demonstrated that biochar produced at higher pyrolysis temperatures has higher pH which may suppress plant growth (Mehmood, Ahmed *et al*., 2022).

Table 3. Physicochemical characteristics of pre-sowing soil amended with rice straw derived biochar at various concentrations of viz; 2, 4, 6% (w/w) after 15 days of incubation.

Treatments	Conc.(%)	pH	EC_e ($\mu S\ cm^{-1}$)	BD ($g\ cm^{-3}$)	TOM ($g\ kg^{-1}$)	CEC ($cmol_c\ kg^{-1}$)
C	-	7.81±0.10	104.5±1.80	1.43±0.01	3.74±0.10	7.93±0.05
CF	-	8.29±0.11	125.7±3.59	1.53±0.01	3.75±0.09	8.75±0.13
RSBC-1	2	7.49±0.19	119.5±1.80	1.33±0.01	3.50±0.15	9.46±0.13
	4	7.59±0.10	117.5±1.11	1.34±0.01	3.58±0.09	9.600.21
	6	7.75±0.13	116.25±2.38	1.33±0.01	3.65±0.23	9.48±0.11
RSBC-2	2	7.68±0.16	117.5±1.11	1.26±0.01	3.65±0.23	9.79±0.10
	4	7.66±0.45	119.5±1.80	1.27±0.01	3.78±0.07	10.18±0.30
	6	7.65±0.25	122.3±2.16	1.25±0.01	3.73±0.11	10.19±0.10
RSBC-3	2	8.21±0.14	122.8±2.27	1.24±0.01	3.83±0.22	12.29±0.32
	4	8.24±0.10	127±1.58	1.15±0.01	3.75±0.14	11.81±0.23
	6	8.29±0.15	134.5±1.80	1.16±0.01	3.93±0.21	11.87±0.14
LSD	-	0.692364	28.74477	0.229202	0.300486	3.480974

Key. EC_e= Electrical conductivity of soil extract, TOM-Total organic matter, CEC -cation exchange capacity, BD -bulk density, C -control in which no amendment was made, CF -commercial fertilizer, RSBC-1=biochar produced at 400°C, RSBC-2= biochar produced at 600°C, RSBC-3= biochar produced at 800°C The values are means of four replicates ± SD, LSD =least significant difference.

Table 4. Physicochemical characteristics of post-harvesting soil amended with rice straw derived biochar at various concentrations of viz; 2, 4, 6% (w/w) after harvest 65 days old sunflower.

Treatments	Conc.(%)	pH	EC_e (μScm^{-1})	TOM ($g\ kg^{-1}$)	CEC ($cmol_c kg^{-1}$)	BD ($g\ cm^{-3}$)
C	-	7.80±0.10	115±2.58	3.74±0.10	7.93±0.05	1.39±0.01
CF	-	8.28±0.09	158±2.16	3.75±0.09	8.75±0.13	1.33±0.01
RSBC-1	2	7.56±0.22	129±1.80	3.50±0.15	9.46±0.13	1.22±0.01
	4	7.79±0.10	127±1.11	3.57±0.09	9.60±0.21	1.23±0.01
	6	7.82±0.14	126±2.38	3.65±0.23	9.48±0.11	1.23±0.01
RSBC-2	2	7.73±0.11	127±1.11	3.65±0.23	9.79±0.10	1.15±0.01
	4	7.91±0.38	129±1.80	3.77±0.07	10.1±0.30	1.16±0.00
	6	8.14±0.36	132±2.23	3.72±0.11	10.1±0.10	1.14±0.01
RSBC-3	2	8.23±0.14	132±2.27	3.82±0.22	12.2±0.32	1.13±0.01
	4	8.28±0.13	137±1.58	3.74±0.14	11.8±0.23	1.12±0.01
	6	8.33±0.16	146±1.47	3.93±0.21	11.8±0.14	1.12±0.01
LSD	-	0.69236	28.7448	0.30049	3.48097	0.2292

Key. EC_e=electrical conductivity of soil extract, TOM-total organic matter, CEC= cation exchange capacity; BD=Bulk density, C=control in which no amendment was made, CF=commercial fertilizer, RSBC-1=biochar produced at 400°C, RSBC-2= biochar produced at 600°C, RSBC-3= biochar produced at 800°C. The values are means of four replicates ± SD, LSD =least significant difference.

Improvement in yield and growth attributes of plant

The data attained from crop yield and growth parameters were compared within and along each treatment to certify that different concentrations of biochar at different dosages enhance the cultivated crop yield or not (Figure 5 and 6). Application of all biochar treatments significantly enhanced yield and growth of the growing sunflower. One very interesting finding was that biochar (RS-BC2) amended soil up-shifted the growing plant to reach the flowering stage into 65 days than that of control treatment which showed inflorescence 15 days later. Pyrolysis temperature strongly influenced the biochar surface characterization. The biochar produced at 600℃ temperatures has high functionality and CEC, which ultimately led to high availability of nutrients. The experimental results revealed that biochar application (RS-BC2) significantly raised the plant height, number of leaves and seed yield etc. The increasing trend of various growth attributes were arranged as RSBC-2>RSBC-1>CF> RSBC-3 >C. Biochar acted as a soil conditioner as compared to commercial fertilizer and control treatments. Recent study reported that medium dosage 4% (w/w) showed better growth performance of sunflower. The plant grown in biochar amended soil extensively raised plant height (153 cm) due to high nutrient availability (Diatta *et al*., 2020) as compared to control (87.4 cm) shown in Figure 3 (d). The current study showed in Fig 4 states that the SPAD values (60.8) of the sunflower leaves were significantly increased as the application of biochar in soils in contrast to C and CF 35.5 and 55.02 due to high photosynthetic metabolism which influence the activity rate (Ezz *et al*., 2023). Resultantly, microbial efficiency and bioavailability of essential nutrients improved the plant growth by the application of rice straw biochar (Gupta *et al*., 2020). Rice straw derived biochar improves the soil organic carbon and nutrient use efficiency, which ultimately led to improved crop yield as compared to control (Liu, Jiang *et al*., 2021). Moreover, the enhancement in crop yield might be due to bioavailability of nutrients in combination with improved soil physic-chemical properties influenced by biochar application (El-Naggar, Lee *et al*., 2019; Gosh, Masto *et al*., 2020).

Figure 5. Fluctuation in growth measurements i.e., number of leaves (A); shoot length (B); root length (C); plant length (D). The values are means of four replicates and vertical error bars represents the standard errors with different letters are significantly different from each other. Where, C=control in which no amendment was made,

CF=commercial fertilizer, RSL=rice straw biochar at low dosage (2% w/w), RSM=rice straw biochar at medium dosage (4% w/w), RSH=rice straw biochar at high dosage (6% w/w).

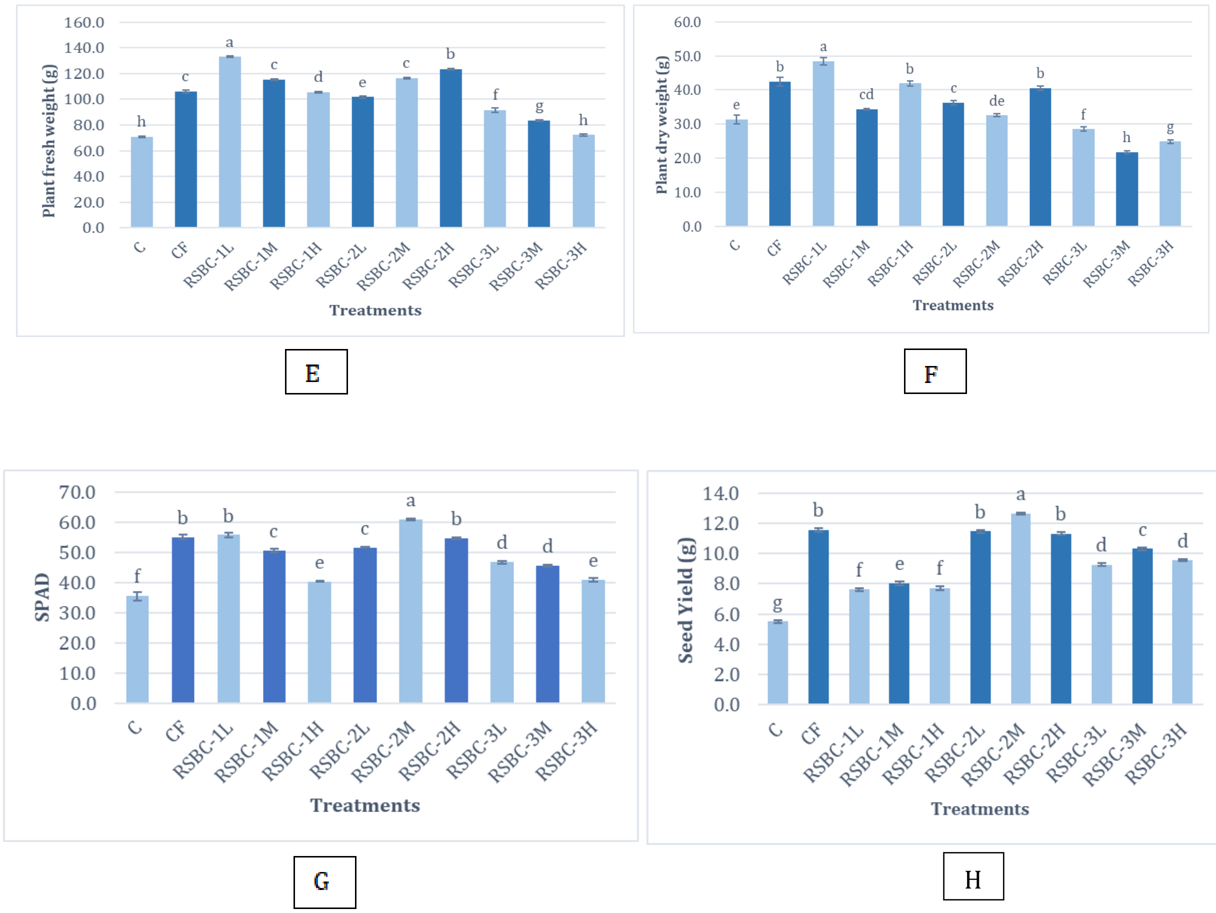

Figure 6. Fluctuation in growth measurement i.e. plant fresh weight (E); plant dry weight (F); SPAD values (G); seed yield (H). The values are means of four replicates and vertical error bars represent the standard errors with different letters are significantly different from each other. Where, C=control in which no amendment was made, CF=commercial fertilizer, RSL=rice straw biochar at low dosage (2% w/w), RSM=rice straw biochar at medium dosage (4% w/w), RSH=rice straw biochar at high dosage (6% w/w).

CONCLUSION

The conversion of rice straw into biochar not only provides the solution for the sustainable management of agricultural waste like rice straw but also provides a value-added product as a soil conditioner. Pyrolysis temperature strongly influenced the functionality, surface morphology, and chemical composition of biochar. The results of fourier transform infrared spectroscopy (FTIR) and x-ray diffraction (XRD) of RS-BC2 revealed the existence of higher functionality and crystalline structure of biochar. The results indicate that increasing application of biochar improves the physicochemical properties of soil as compared to control and commercial fertilizer. From this study, it is concluded that rice straw-derived biochar (RS-BC2) has positive effect on soil edaphic characters and medium concentration (4% biochar treatment) showed pronounced seed yield as compared to control and chemical fertilizer. Future studies can be performed at the field scale for further validation and to evaluate the chemical and biological factors influencing crop yield under biochar treatments.

CONFLICT OF INTEREST

The authors affirm that the research was conducted without any commercial or financial affiliations that could be perceived as potential conflicts of interest.

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