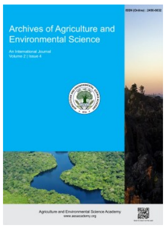
Archives of Agriculture and Environmental Science 9(4): 667-675 (2024)
https://doi.org/10.26832/24566632.2024.090405

e-ISSN: 2456-6632

This content is available online at AESA

Archives of Agriculture and Environmental Science

Journal homepage: journals.aesacademy.org/index.php/aaes



ORIGINAL RESEARCH ARTICLE

CrossMark

Assessment of biochar quality and agronomic efficiency produced from rice-husk and saw-dust at different temperature regimes

Purnika Aryal[1*], Shree Prasad Vista[2], Rabindra Dhakal[3], Bidhika Basnet[1], Purnesh Chand[1], Sapana Gyawali[1] and Naba Raj Pandit[4]

[1]Himalayan College of Agricultural Sciences and Technology (HICAST), Kirtipur, Kathmandu, Nepal
[2]Nepal Agricultural Research Council (NARC), National Soil Science Research Center, Lalitpur, Nepal
[3]Nepal Academy of Science and Technology (NAST), Lalitpur, Nepal
[4]International Maize and Wheat Improvement Center (CIMMYT), Lalitpur, Nepal
[*]Corresponding author's E-mail: purnika.aryal@gmail.com

ARTICLE HISTORY

Received: 13 September 2024
Revised received: 01 November 2024
Accepted: 12 November 2024

Keywords

Biochar
Pyrolysis temperature
FTIR
Productivity

ABSTRACT

Declining soil fertility and the limited use of sustainable soil organic amendments has resulted in reduced crop productivity in Nepal. This study assessed biochar produced from rice husk and sawdust at three different pyrolysis temperatures (200°C, 400°C, and 600°C), characterized their properties and applied them as soil amendments to test their agronomic effect on kidney bean production. The highest biochar yields were achieved at lower pyrolysis temperatures (200°C) for both rice husk (40%) and sawdust (38.4%). Ash content was significantly higher in rice husk (33.6%) compared to sawdust biochar (5.8%) across all temperatures. Sawdust biochar had higher volatile matter (91%) than in rice husk biochar (61.5%). The fixed carbon content was greater at 200°C and 400°C for both rice husk and sawdust biochar. FT-IR result showed significant loss of aromatic groups with increasing temperature. Biochar from all three temperatures was then used in a pot experiment to grow kidney beans and assess their agronomic effects. Seven treatments were used: control (CK), rice husk biochar at 200°C (RH200), 400°C (RH400), and 600°C (RH600), sawdust at 200°C (SD200), 400°C (SD400), and 600°C (SD600) following a completely randomized design with 3 replications per treatment. Cattle manure was applied uniformly (25 t ha^{-1}) across all treatments, including the control. Over 50 days, SD400 resulted in the tallest plants, SD600 produced the thickest stem and RH600 had the highest number of leaves. Biochar applications showed significantly higher fruit weight and counts, which was on average 24 % higher than the control, with no significant differences between rice husk and saw dust biochar at three different temperatures. The study suggests that high quality biochar can be produced from both rice husk and saw dust and its application boost legume yields, which is crucial for enhancing country's nutritional and food security.

Citation of this article: Aryal, P., Vista, S. P., Dhakal, R., Basnet, B., Chand, P., Gyawali, S., & Pandit, N. R. (2024). Assessment of biochar quality and agronomic efficiency produced from rice-husk and saw-dust at different temperature regimes. *Archives of Agriculture and Environmental Science*, *9*(4), 667-675, https://dx.doi.org/10.26832/24566632.2024.090405

INTRODUCTION

Biochar is a fine-grained, carbon-rich material produced through the pyrolysis of biomass in an oxygen-limited environment. Biochar's recalcitrant nature allows it to remain stable in soil for hundreds to thousands of years, making it an effective carbon (C) sequestration method to combat climate changes (Lehmann *et al*., 2006; Kumari *et al*., 2022). Several studies have documented the significant improvement of soil physicochemical and biological properties upon biochar addition such as increased porosity, surface area, pH, cation exchange capacity (CEC), organic carbon, plant available water (PAW), plant available nutrients such as nitrogen (N), phosphorous (P), potassium (K) and microbial activities (Elkhlifi *et al.*, 2023). The production process of biochar is significantly influenced by factors such as temperature, pressure, and the composition of feedstocks, resulting in varied yield percentages depending on the specific thermochemical process (Chi *et al.*, 2021). Pyrolysis can be categorized into three main types based on thermo-chemical process conditions: slow, flash, and fast pyrolysis (Adekanye *et al.*, 2022). Slow pyrolysis operates at lower temperature (250 to 500 °C) with a low heating rate and longer residence time (Adekanye *et al.*, 2022; Manyà, 2012). In contrast, flash and fast pyrolysis occur at moderate to higher temperatures with high heating rates and short residence times (Adekanye *et al.*, 2022). Low temperature pyrolysis (300 to 500 °C) results in higher biochar yield and carbon content, while high temperature pyrolysis (> 500 °C) produces lower yields but higher surface area with greater adsorption capacities for various compounds (Manyà, 2012). As the charring temperature increases, the alkalinity of biochar also increases. (Ahmee & Yakob, 2021).

Different pyrolysis temperature and feedstocks produce biochar with different qualities and distinct functional groups such as hydroxyl, carboxyl, carbonyl, aldehyde or ketone, aliphatic and aromatic groups (Janu *et al.*, 2021; Pandit *et al.*, 2017). During pyrolysis, biochar undergoes thermochemical conversion, altering its carbon constituent to form a compound that is depleted of hydrogen and oxygen (Küçükbayrak & Kadioğlu, 1989; Pariyar *et al.*, 2020). This process results in the formation of an aromatic carbon structure with both crystalline phase (condensed polyaromatic sheets) and amorphous phase (randomly organized aromatic rings) (Pariyar *et al.*, 2020; Wiedemeier *et al.*, 2015). Lower pyrolysis temperature can retain more oxygenated functional groups, while higher temperature enhance aromatic structures and reduce oxygen content, influencing the stability and reactivity of biochar (Song & Guo, 2012). Biochar having high oxygen content (27–34%) primarily in the form of phenolic and carboxylic acid groups, along with sulfonic group, improves its catalytic activity and molecular absorption on the catalyst surface (Chi *et al.*, 2021). Functional groups are crucial in determining surface complexation, adsorption-desorption mechanism, physicochemical properties of soil and carbon sequestration (Janu *et al.*, 2021; Kul *et al.*, 2021). Morphological characteristics (pores, surface area) and the appearance of the functional groups can be derived from Fourier-transform-infrared spectroscopy (FTIR) and scanning electron microscope (SEM) (Janu *et al.*, 2021; Zaitun *et al.*, 2022).

The effect of biochar on soil properties is greatly influenced by the types of biochar produced from various feedstocks and pyrolysis conditions, as well as its interaction with the soil, including re-dox reactions, adsorption-desorption, and precipitation-dissolution and climatic conditions (Bruun *et al.*, 2008; Küçükbayrak & Kadioğlu, 1989; Pariyar *et al.*, 2020). In low fertile soil, biochar has shown improved physicochemical properties like porosity, pH, OC and CEC (Cornelissen *et al.*, 2013; Martinsen *et al.*, 2014; Obia *et al.*, 2016). Due to its highly porous structure, large surface area and high CEC, biochar has a strong sorption capacity, which enhances nutrient availability, retention capacity and nutrient use efficiency (NUE) (Pandit *et al.*, 2024; Puga *et al.*, 2020). Several previous studies have reported increased crop productivity upon biochar addition primarily due to improved soil physicochemical and biological properties and enhanced Nitrogen Use efficiency (Cornelissen *et al.*, 2013; Kapoor *et al.*, 2022; Pandit *et al.*, 2021). In Nepal, most research is carried on assessing the effect of biochar on cereal crops such as maize and rice, as well as commercial vegetables like cauliflower, potato, tomato, okra, and radish while studies on legumes particularly kidney beans are limited. Moreover, most Nepalese soils are acidic in nature, with around 67% cultivated areas having low pH and contain low to medium level of organic matter and essential soil nutrients such as nitrogen, phosphorous and potassium. Applying biochar in these low fertility soils could be a promising nourisher for enhancing soil fertility and yields in Nepal (Kumari *et al.*, 2022). Kidney beans, a variety of the common bean, Phaseolus vulgaris, are herbaceous annual plants grown extensively worldwide for their edible dry seeds or unripe fruit (Nasiri *et al.*, 2024). Kidney beans belonging to family leguminous are native to the central America and Mexico. Kidney beans are known for their ability to improve soil fertility and enhance nitrogen enrichment through biological nitrogen fixation (BNF) (Etminani *et al.*, 2021). The addition of biochar in soil has been shown to increase the levels of biological nitrogen fixation (BNF) and nodulation in legume crops such as white clover (Trifolium repens) (Rillig *et al.*, 2010), soyabean (Glycine max) and alfalfa (Medicago sativa) (George *et al.*, 2012; Rillig *et al.*, 2010).

Although various studies have documented the positive agronomic effects of biochar on crop productivity, their remains a lack of mechanistic explanations (Cornelissen *et al.*, 2018; Pandit *et al.*, 2024). It is crucial to evaluate the properties and structure of biochar produced from various feedstocks and pyrolysis temperatures, as well as their mechanistic effects on crop growth and development in controlled environments. In this study, biochar produced from two different feedstocks (sawdust and rice husk) pyrolyzed at three temperature levels (200°C, 400°C and 600°C) underwent proximate analysis to determine moisture content, volatile matter, and fixed carbon content. In addition, the chemical composition and functional groups of the biochar produced from both rice husk and saw dust at these three temperatures were assessed using Fourier-transform infrared spectroscopy (FTIR). There are few, if any, studies on the characterization of biochar using FTIR in Nepal. A comprehensive study covering aspects from biochar yield, proximate analysis, FT-IR analysis to its application as a soil amendment has been lacking in Nepal, highlighting the necessity of such research. Therefore, the study aims to assess the properties of biochar produced from two different feedstocks at three different pyrolysis temperatures and examine their agronomic effect on kidney bean production.

MATERIALS AND METHODS

Biochar production

Rice husk and sawdust were used as feedstock for biochar production. Rice husks were collected from Bhawani Mill located in Patan, Lalitpur. Saw Dusts were collected from Anand Kasta Furniture Udyog located in Sanepa Road, Lalitpur. Collected rice husks and saw dust were kept in a dry storage room before biochar production. Pyrolysis of feedstocks was conducted at three different temperature levels 200°C, 400°C and 600°C to assess the properties and composition of the resulting biochar prepared from the drum method as well as its impact on the growth of kidney beans. The locally available drum along with temperature gun was used for the thermo-conversion process.

Yield and proximate analysis

The biochar yields were calculated based on the mass difference before and after charring (Equation 1). A sampling weight of 500 g was used for each type of biochar.

Yield (%) = Mass of biochar (g) (1)

Moisture content was determined by drying 2 g of soil sample in a crucible at 105°C. Volatile matter contents (% dry weight basis) were determined by burning 2 g of biochar in a covered crucible at 950°C for 11 minutes. The ash content (dry weight basis) was determined by burning the sample in an uncovered crucible at 750°C for two hours. Fixed carbon content was calculated using the formula mentioned in equation 2 (Adeniyi *et al*., 2022).

Fixed carbon content (%) =100- (%moisture + %ash + %volatile matter) (2)

FT-IR

Fourier transform infrared (FTIR) spectra of biochar produced from both sawdust and rice husk feedstocks were collected to assess their composition and structure. The FTIR spectrophotometer used for the specific measurements was 'Shimadzu IR Tracer-100'; a high-precision equipment with excellent measurement speed, sample sensitivity, and the spectral resolution with analytical software (Marahatta *et al*., 2024). After measuring the IR spectra of each of these biochar sample specimens, the spectrophotometer was calibrated at ambient air conditioning, and it's in-built functions were standardized. As soon as the instrument reached the fully-functional states, a trace amount of every sample was injected into its sample compartment, and the concerned interferograms (intensity of IR over time) were recorded. Each sample of 10 milligrams was kept in an FT-IR machine, in which sample absorbed varying amounts of infrared (IR) energy from the source depending on its functional groups. All samples were ground into powders prior to spectral acquisition. spectrum data was used for bond analysis.

Experimental design and cultivation practices

A pot experiment was conducted from 30th July 2023 to 23rd September 2023 in Kathmandu district, Nepal (27.4415° North and 85.1918° East). Seven treatments with three replications including 1) Control (CK), 2) rice husk biochar produced at 200 °C mixed with manure (RH200), 3) rice husk biochar produced at 400 °C mixed with manure (RH400), 4) rice husk biochar produced at 600 °C mixed with manure (RH600), 5) sawdust biochar produced at 200 °C mixed with manure (SD200), 6) sawdust biochar produced at 400 °C mixed with manure (SD400), and 7) sawdust biochar produced at 600 °C mixed with manure (SD600) were arranged in Completely Randomized Design (CRD). In each pot except the control, 0.8 g of biochar (2 t ha^{-1}) and 10 g of manure (25 t ha^{-1}) substrate are mixed well and applied in respective pots. An earthen pot with a diameter of 12 inches and a height of 23 cm was used in the experiment. The soil was collected from the nearby agriculture land used for production of vegetables like chilies, brinjal etc. and unwanted foreign materials like weeds, roots, and pebbles were removed and 4 kg of soil was filled in each treatment pot. Each pot was filled with pebbles at the bottom to support the aeration. Kidney bean (ITALY-38) seeds were soaked overnight in water and the next morning, two seeds were sown 3-4 cm below the soil surface in each pot. After sowing, light irrigation was provided uniformly to all the pots using watering canes. Each pot was irrigated on alternative days thereafter. After two weeks, the smaller and least robust plants were removed, leaving the healthier plants in each pot. Staking was provided for the plant support in all the pots after 10 days of sowing. The manual weeding was carried out at an interval of 6 days. The diameter or girth of the plant stem, plant height, number of leaves was measured with the help of a vernier caliper at 10 DAS, 20 DAS, 30 DAS up to 50 DAS. The total days for harvesting and number of fruits per pot was listed manually and average fruit weight was determined by calculating the average weight per pot.

Statistical analysis

Data management and analysis was performed in excel. One-way linear ANOVA was performed for proximate analysis of biochar and to assess the effect of biochar treatments on plant growth parameters and yield using GenStat Version 15.0. Tukey's HSD (honest significant difference) test was performed at a 5% level of significance to compare the mean between different treatments. The difference between the treatments was significant at $p < 0.05$ unless stated otherwise.

RESULTS AND DISCUSSION

Biochar yield and proximate analysis

The biochar yield and results from proximate analysis, including moisture, ash, volatile matter, and carbon content are presented in Table 1. Biochar yield was observed highest at the lower pyrolysis temperatures of 200 °C, achieving 40% for rice husk and 38.4% for sawdust (Table 1). The highest yield was observed for RH200, followed by RH400 and SD200. Our findings

Table 1. Yield and proximate analysis of biochar produced from saw dust and rice husk at three pyrolysis temperatures.

Source	Yield (%)	Moisture content	Ash content	Volatile matter content	Fixed carbon content
RH200	40	1.82 ± 1.84a	32.50 ± 4.72a	62.45 ± 5.58a	3.24
RH400	39.2	0.83 ± 0.94a	35.32 ± 4.45a	60.43 ± 4.36a	3.42
RH600	37.2	2.14 ± 0.23a	33.99 ± 9.45a	63.19 ± 3.08a	2.86
SD200	38.4	1.59 ± 0.72a	4.15 ± 0.16b	95.2 ± 2.47b	1.21
SD400	26	4.04 ± 0.77b	6.18 ± 0.13c	86.02 ±7.33b	4.32
SD600	24.4	2.16 ± 0.79a	7.25 ± 1.48c	92.49 ± 5.79b	1.11

Letters in the table denotes significant difference between the treatments at 5% probability level (post hoc Tukey test, $p < 0.05$).

showed that biochar yield was higher for rice husk compared to saw dust, aligning with Jindo *et al.* (2014) who reported a 34% yield for rice husk biochar and Rutherford *et al.* (2012) who observed yields of 20-28% for saw dust biochar. At pyrolysis temperatures of 400°C and 600°C, the average biochar yield was 25.2%, illustrating a 34% reduction compared to the 38.4% yield at 200 °C for saw dust. Biochar yield is significantly influenced by pyrolysis temperature, with higher yields achieved at lower temperatures and vice versa (Cornelissen *et al.*, 2016; Song & Guo, 2012). This aligns with our findings, where the highest biochar yield was obtained at a lower pyrolysis temperature (200 °C) for both rice husk (40%) and saw dust (38.4%) biochar, followed by yields at 400 °C and 600 °C (Table 1). The highest moisture content (4.04%) was found in SD400 among all biochars. At low pyrolysis temperature, minimal thermal decomposition occurs, resulting in a larger portion of the feedstock remaining as solid carbon (Cornelissen *et al.*, 2016). Conversely, at medium and high temperatures, most of the feedstock is converted into liquid and gases, leaving less solid carbon (Chen *et al.*, 2015; Cornelissen *et al.*, 2016; Crombie *et al.*, 2013). No significant differences in moisture content were observed among the other biochars, with values ranging from 0.83% to 2.16%. Saw dust biochar exhibited significantly higher volatile matter, ranging from 92% to 95%, compared to rice husk biochar, which ranged from 60% to 63% across all three pyrolysis temperatures (Table 1). High volatile-matter content was observed in saw dust biochars at relatively low temperatures due to the presence of lignin in woody feedstocks, which partially resists pyrolytic decomposition at 400 °C, but not at higher temperatures (above 950 °C, used for ash content analysis). In a study by (Jindo *et al.*, 2014), sawdust biochar (SD) showed a more significant changes in volatile content from 200 to 800 °C compared to rice husk biochar (RH). In contrast, rice husk biochars showed high ash content at all temperature levels, possibly due to interactions between organic and inorganic constituents during pyrolysis, resulting in ash content exceeding 20 % (Jindo *et al.*, 2014; Rutherford *et al.*, 2012). The fixed carbon content was highest at 400 °C for both rice husk and saw dust biochars.

According to Dume *et al.* (2015), biochar with ash content greater than 35% will have a fixed carbon content below 30%, which aligns with our findings (Table 1). In proximate analysis by (Ronsse *et al.*, 2013), it was found that fixed carbon content in biochar samples strongly depends on the intensity of the thermal treatment, justifying the highest carbon content in RH400 and SD400. The moisture contents of input materials were

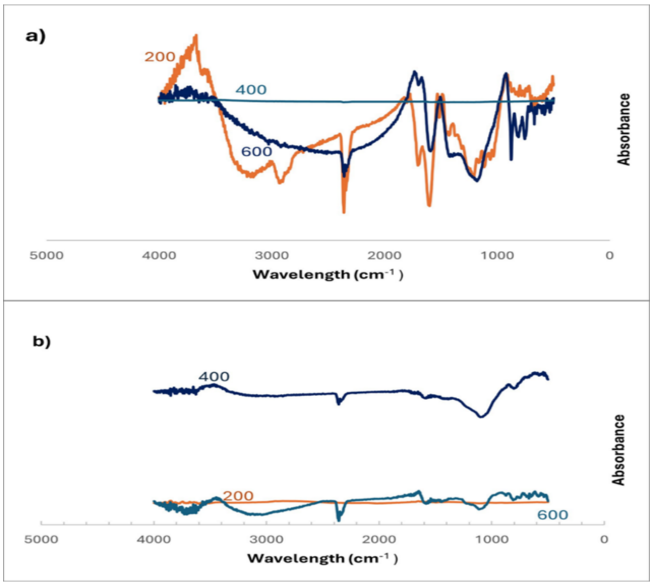


Figure 1. *FTIR spectra of biochar formed with sawdust (a) and rice husk (b).*

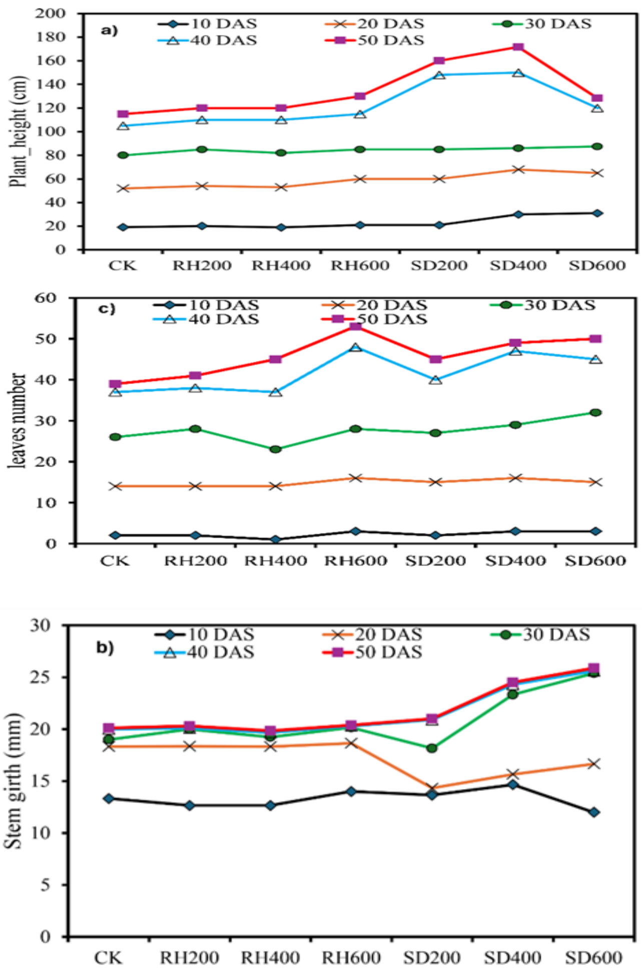


Figure 2. *Effect of treatments on plant height (a), stem girth (b) and leaves number (c) measured at 10 days interval until 50 DAS.*

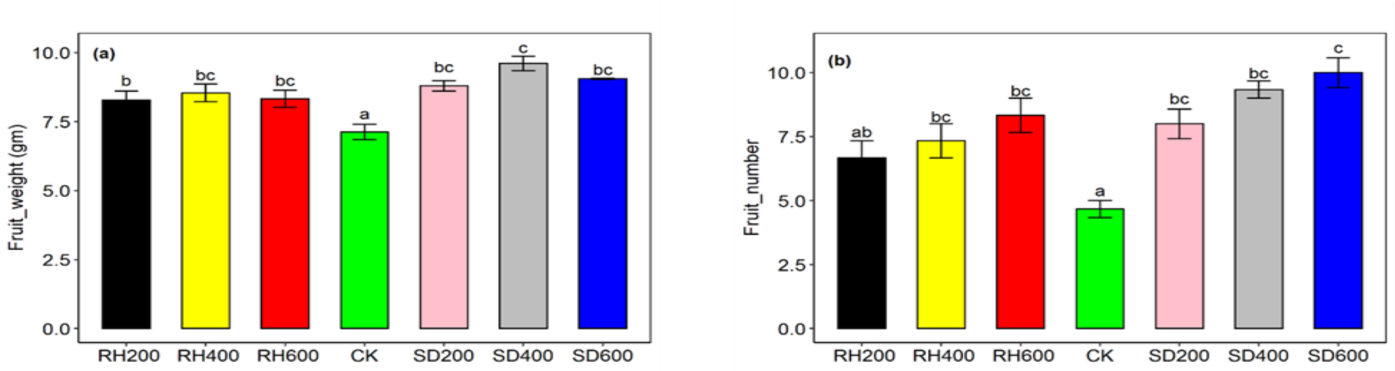


Figure 3. *Effect of saw dust and rice husk biochar produced at three pyrolysis temperature on average fruit pod yield (a) and pod number (b); Different letters inside the graph denote significant differences between the treatments at 5% probability level (post hoc Tukey test, p < 0.05).*

found to be 5.84%, 7.99%, 31.64%, and 5.32 wt.% for wood, straw, green waste, and algae, respectively, (Ronsse *et al*., 2013) and corroborated by our findings (Table 1). The relative ash content of biochar samples significantly increased with higher pyrolysis severity, as expected, because ash remains in the solid fraction while organic matter undergoes thermal decomposition, resulting in weight loss in the carbon-containing fraction. Moreover, temperature influences ash composition, with higher pyrolysis temperatures leading to increased ash content due to volatile matter release (Dume *et al*., 2015).

FT-IR

FTIR spectra of biochar produced from rice husk and saw dust at three different pyrolysis temperatures are presented in Figure 1. In the higher temperature range of 600 °C, the spectra shows a continuous loss of aromatic groups (Liu *et al*., 2015), as illustrated in Figure 1 (a and b). Figure 1 (a) showed significant changes in chemical and structural compositions of biochar as the temperature increases. Similarly, Figure 1 (b) indicates that the chemical and structural compositions vary with increasing temperature. Furthermore, as the pyrolysis temperature increases from 200 to 600 °C, there is a noticeable decrease in several characteristic bands (Figure 1a). At the higher temperature of 600 °C, the spectra showed a continuous loss of triple bonds and various compounds. The material at this temperature contained ketones-related components and no double or triple bonds. The minimal presence of functional groups in the biochar prepared at 600°C suggests that bonds are breaking as the temperature rises. The spectra in Figure 1(a and b) clearly show the presence of the aldehyde groups, oxygen-related groups (phenol), and aromatic rings (Nandiyanto *et al*., 2019). As the heating temperature increases to 350°C, the breaking of C=O bonds may also increase (Armynah *et al*., 2018), as observed in Figure 1a and b.

Effect on plant growth and yield parameters

Biochar produced from both saw dust and rice husk at 200 °C, 400 °C and 600 °C and mixed with organic manures showed beneficial effects on kidney beans production, including plant height, stem diameter, leaves number, fruit number and pod yield (Figures 1-3). No significant differences were observed in kidney bean production between rice husk biochar produced at three different temperatures (Figure 3). A similar trend was observed for saw dust biochar. This is in line with the study by Pandit *et al.* (2017), where biochar produced from slow and fast pyrolysis temperatures (ranging from 250 to 700 °C) using seven different kiln types from Eupatorium adeophorum (locally named "banmara") feedstock did not show significant variation in maize production in Nepal. Our experiment shows that SD400 resulted in the tallest plant, reaching 170 cm, compared to other treatments, which ranged from 118 to 155 cm. Similarly, SD400 (24.2 mm) and SD600 (25 mm) had higher stem girth than other treatments, which ranged from 20 mm to 20.5 mm, and the highest number of leaves was observed at RH600 (53) indicates that the good quality biochar can be produced from rice husks and saw dust at pyrolysis temperature ranging from 200 to 600 °C (Table 1) to achieve significant yield effects in kidney beans. Previous studies reported significant positive effects of biochar-based fertilizers produced from rice husk and saw dust in improving crop growth parameters such as plant height (Syahrinudin *et al*., 2019; Zhao *et al*., 2022), stem girth (Acharya *et al*., 2023; Rahayu *et al*., 2022), leaf number (Akhtar *et al*., 2014), which aligns with our findings (Figures 2 and 3).

At slow pyrolysis temperatures (200 to 400 °C), biochar retains more volatile compounds and oxygen containing functional groups such as hydroxyl, carboxyl, carbonyl etc., and less stable carbon, enhancing microbial activity and nutrient availability (Bruun *et al*., 2012; Song & Guo, 2012; Tomczyk *et al*., 2020). These oxygenated functional groups enhance cation exchange capacity (CEC) and nutrient retention, thereby improving soil fertility and crop yields. In our study, as the pyrolysis temperature increased to 600 °C, there was a continuous loss of aromatic rings and a decline in oxygen containing functional groups (Figure 1).

Consequently, the biochar became more hydrophobic and became less reactive due to the reduction of these functional groups. At higher pyrolysis temperature, biochar exhibits highly hydrophobic in nature with more stable carbon, greater surface area and increased porosity, providing habitat for microbes and enhancing microbial activity (Tomczyk *et al*., 2020). The hydrophobic nature of biochar induces water repellency, reduce waterlogging and nutrient leaching (Adhikari *et al*., 2022), thereby making these nutrients available to the plants. Rice husk biochar can release significant amount of silica, which synergistically enhances the uptake of other essential nutrients such as phosphorus, potassium and calcium, benefitting the crop growth and development (Zhang *et al.*, 2017; Zhu *et al.*, 2004). Moreover, Ndor *et al.* (2016) found that biochar produced from saw dust and rice husk enhanced the uptake of N, P and K in maize, which in turn, significantly increased crop height, leaf area and biomass.

In our study, biochar produced at 200, 400 and 600°C from saw dust increased kidney bean yield by an average of 28.6% and from rice husk by an average of 19.1% compared to the control (Figure 1a). The treatment that resulted in the quickest first harvest was SD200 (45 d) followed by RH600 (46 d) and RH400 (48 d) (data not shown). These treatments showed significant differences compared to the control. The maximum harvesting period observed during research was observed in RH600 (19.33 d) followed by SD400 (16 d), and SD200(16 d). Average pod weight was significantly higher in all the biochar treatments compared to the control (Figure 3a). The treatments SD200, SD400, SD600, RH200, RH400 and RH600 increased pod weight by 23.5%, 34.9%, 27.10%, 16.15%, 19.94% and 16.93% respectively, compared to the control (Figure 3a). SD400 had the highest average pod weight among all treatments. Previous studies have documented positive yield effects of biochar produced from both slow and fast pyrolysis temperature ranging from 200 to above 700 °C (Azeem *et al.*, 2019; Farhangi-Abriz *et al.*, 2021; Pandit *et al.*, 2017; Schmidt *et al.*, 2015). In accordance with this, Azeem *et al.* (2019) reported an increase in mash bean biomass and grain yield by 24% and 7%, respectively, upon biochar addition produced at 350 °C pyrolysis temperature. Similarly, biochar produced at a pyrolysis temperature from 550-700 °C and mixed with organic fertilizers increased radish yield by 320 % (Dahal *et al.*, 2021) and pumpkin yield by 300% (Schmidt *et al.*, 2015) compared to the control. These results suggest that crop yield can be improved across a wide range of pyrolysis temperatures, which have varied physiochemical characteristics influencing crop growth parameters and yields. However, previous studies have highlighted that the yield effect is much stronger with biochar produced at slow pyrolysis temperature below 550 °C (Farhangi-Abriz *et al.*, 2021; Li *et al.*, 2019), which aligns with our study where biochar from saw dust produced at 400 °C (SD400) stood out and produced the highest kidney bean production (Figure 3).

When mixed with organic manures, biochar forms an organic coating on its surface, allowing nutrient adsorption and retention in its pores and nano pores for prolonged period (Hagemann *et al.*, 2017; Joseph *et al.*, 2018) and acting as a slow-release mechanism for nutrients (Schmidt *et al.*, 2015). Akhtar *et al.* (2014) reported enhanced plant growth by improving nutrient retention capacity and supplying nutrients as and when required by the crops. Moreover, Kammann *et al.* (2015) reported increased nutrient retention, supply and uptake of nitrate and phosphate in biochar-based organic fertilizers, which correlated with crop production. The slow-release mechanism ensures plants have a steady supply of essential nutrients during critical crop growth periods, enabling synchrony between soil nutrient supply and plant demand, leading to improved crop growth and higher yields. Microbial activity and nutrient release were significantly higher during the grain-filling period in biochar-treated treatments compared to control (Ali *et al.*, 2020). Moreover, the slow release of nutrients improves nutrient use efficiency and reduces nutrient losses to the environment through leaching and emissions of greenhouse gases (N_2O and NO), contributing to mitigating environmental pollution and climate change (Zhang *et al.*, 2015).

Applying biochar improves soil physicochemical properties such as pH, soil structure and porosity, creating an enabling environment for increasing microbial biomass and promoting the symbiotic relationship between legumes and nitrogen fixing bacteria, supplying more nitrogen in the soil for plant uptake, thereby increasing crop production (Rondon *et al.*, 2007; Steiner *et al.*, 2007; Van Zwieten *et al.*, 2010). Biochar addition increased nodulation, microbial and nitrogenase activity, nitrogen fixation and plant N content (Rondon *et al.*, 2007). Biochar application improved fresh and dry biomass yields of cowpea and sesbania, which belong to Leguminosae family, compared to non-biochar plots (Jalal *et al.*, 2018). This can be correlated with our study where the mutual effect between biochar and legumes could have made more N available, increasing the kidney bean yields.

Conclusion

Biochar produced from different sources at varying temperatures showed significant differences in yield, chemical composition, and impacts on plant growth. Our study found that adding biochar at all three pyrolysis temperatures enhanced plant growth and fruit yields, with sawdust biochar produced at 400°C showing the most positive agronomic effects. These findings suggest that high-quality biochar can be produced from sawdust and rice husks, making it a viable option for agricultural use. Our results indicated that kidney beans treated with biochar outperformed the control, suggesting potential benefits for other crops as well. However, further research is needed to evaluate its effectiveness across diverse agro-ecological zones, soil types, and crops. Farmers can utilize crop residues and other organic waste materials to produce biochar and apply them in agricultural field to improve soil physicochemical and biological properties (microbial activity) thereby enhancing the crop productivity. Biochar can reduce the need for fertilizer inputs, enabling farmers to potentially reduce fertilizer costs while improving crop yields, leading to better economic benefits with minimal environmental impact.

DECLARATIONS

Authors contributions

Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization: P.A., SP.V., R.D.; Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization; Writing – review & editing, Resources, Methodology: B.B. P.C., S.G.; Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization: N.R.P.

Ethics approval: Not applicable.

Consent for publication: All authors have given their consent for the publication.

Data availability: Data will be made available on request.

Supplementary data: Not available.

Funding statement: The research received no external funding.

Additional information: No additional information is available for this paper.

ACKNOWLEDGMENTS

We would like to thank all the staffs of Nepal Academy of Science and Academy, Khumaltar, Lalitpur who relentlessly provided technical support during the strenuous research work and HICAST for helping in times of needs and difficulties.

REFERENCES

Acharya, N., Vista, S. P., Shrestha, S., Neupane, N., & Pandit, N. R. (2023). Potential of Biochar-Based Organic Fertilizers on Increasing Soil Fertility, Available Nutrients, and Okra Productivity in Slightly Acidic Sandy Loam Soil. *Nitrogen*, *4*(1), Article 1. https://doi.org/10.3390/nitrogen4010001

Adekanye, T., Dada, O., & Kolapo, J. (2022). Pyrolysis of maize cob at different temperatures for biochar production: Proximate, ultimate and spectroscopic characterisation. *Research in Agricultural Engineering*, *68*(1), 27–34. https://doi.org/10.17221/106/2020-RAE

Adeniyi, A. G., Adeyanju, C. A., Emenike, E. C., Otoikhian, S. K., Ogunniyi, S., Iwuozor, K. O., & Raji, A. A. (2022). Thermal energy recovery and valorisation of Delonix regia stem for biochar production. *Environmental Challenges*, *9*, 100630. https://doi.org/10.1016/j.envc.2022.100630

Adhikari, S., Timms, W., & Mahmud, M. A. P. (2022). Optimising water holding capacity and hydrophobicity of biochar for soil amendment – A review. *Science of The Total Environment*, *851*, 158043. https://doi.org/10.1016/j.scitotenv.2022.158043

Ahmee, K., & Yakob, A. (2021). Role of Bio Char on the Amelioration of Soil Acidity. *Agrotechnology*, Vol.10, No: 212.

Akhtar, S. S., Li, G., Andersen, M. N., & Liu, F. (2014). Biochar enhances yield and quality of tomato under reduced irrigation. *Agricultural Water Management*, *138*, 37–44. https://doi.org/10.1016/j.agwat.2014.02.016

Ali, I., Ullah, S., He, L., Zhao, Q., Iqbal, A., Wei, S., Shah, T., Ali, N., Bo, Y., Adnan, M., Amanullah, & Jiang, L. (2020). Combined application of biochar and nitrogen fertilizer improves rice yield, microbial activity and N-metabolism in a pot experiment. *PeerJ*, *8*, e10311. https://doi.org/10.7717/peerj.10311

Armynah, B., Atika, Djafar, Z., Piarah, W. H., & Tahir, D. (2018). Analysis of Chemical and Physical Properties of Biochar from Rice Husk Biomass. *Journal of Physics: Conference Series*, *979*, 012038. https://doi.org/10.1088/1742-6596/979/1/012038

Azeem, M., Hayat, R., Hussain, Q., Ahmed, M., Pan, G., Ibrahim Tahir, M., Imran, M., Irfan, M., & Mehmood-ul-Hassan. (2019). Biochar improves soil quality and N2-fixation and reduces net ecosystem CO2 exchange in a dryland legume-cereal cropping system. *Soil and Tillage Research*, *186*, 172–182. https://doi.org/10.1016/j.still.2018.10.007

Bruun, E. W., Ambus, P., Egsgaard, H., & Hauggaard-Nielsen, H. (2012). Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. *Soil Biology and Biochemistry*, *46*, 73–79. https://doi.org/10.1016/j.soilbio.2011.11.019

Bruun, S., Jensen, E. S., & Jensen, L. S. (2008). Microbial mineralization and assimilation of black carbon: Dependency on degree of thermal alteration. *Organic Geochemistry*, *39*(7), 839–845. https://doi.org/10.1016/j.orggeochem.2008.04.020

Chen, D., Liu, D., Zhang, H., Chen, Y., & Li, Q. (2015). Bamboo pyrolysis using TG–FTIR and a lab-scale reactor: Analysis of pyrolysis behavior, product properties, and carbon and energy yields. *Fuel*, *148*, 79–86. https://doi.org/10.1016/j.fuel.2015.01.092

Chi, N. T. L., Anto, S., Ahamed, T. S., Kumar, S. S., Shanmugam, S., Samuel, M. S., Mathimani, T., Brindhadevi, K., & Pugazhendhi, A. (2021). A review on biochar production techniques and biochar based catalyst for biofuel production from algae. *Fuel*, *287*, 119411. https://doi.org/10.1016/j.fuel.2020.119411

Cornelissen, G., Jubaedah, Nurida, N. L., Hale, S. E., Martinsen, V., Silvani, L., & Mulder, J. (2018). Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. *Science of The Total Environment*, *634*, 561–568. https://doi.org/10.1016/j.scitotenv.2018.03.380

Cornelissen, G., Martinsen, V., Shitumbanuma, V., Alling, V., Breedveld, G., Rutherford, D., Sparrevik, M., Hale, S., Obia, A., & Mulder, J. (2013). Biochar Effect on Maize Yield and Soil Characteristics in Five Conservation Farming Sites in Zambia. *Agronomy*, *3*(2), 256–274. https://doi.org/10.3390/agronomy3020256

Cornelissen, G., Pandit, N. R., Taylor, P., Pandit, B. H., Sparrevik, M., & Schmidt, H. P. (2016). Emissions and Char Quality of Flame-Curtain "Kon Tiki" Kilns for Farmer-Scale Charcoal/Biochar Production. *PLOS ONE*, *11*(5), e0154617. https://doi.org/10.1371/journal.pone.0154617

Crombie, K., Mašek, O., Sohi, S. P., Brownsort, P., & Cross, A. (2013). The effect of pyrolysis conditions on biochar stability as determined by three methods. *GCB Bioenergy*, *5*(2), 122–131. https://doi.org/10.1111/gcbb.12030

Dahal, S., Vista, S. P., Khatri, M., & Pandit, N. R. (2021). Effect of biochar blended organic fertilizers on soil fertility, radish productivity and farm income in Nepal. Archives of Agriculture and Environmental Science, 6(4), 416–425. https://doi.org/10.26832/24566632.2021.060402

Dume, B., Berecha, G., & Tulu, S. (2015). Characterization of Biochar Produced at Different Temperatures and its Effect on Acidic Nitosol of Jimma, Southwest Ethiopia. *International Journal of Soil Science*, *10*(2), 63–73. https://doi.org/10.3923/ijss.2015.63.73

Elkhlifi, Z., Iftikhar, J., Sarraf, M., Ali, B., Saleem, M. H., Ibranshahib, I., Bispo, M. D., Meili, L., Ercisli, S., Torun Kayabasi, E., Alemzadeh Ansari, N., Heged�sová, A., & Chen, Z. (2023). Potential Role of Biochar on Capturing Soil Nutrients, Carbon Sequestration and Managing Environmental Challenges: A Review. *Sustainability*, *15*(3), 2527. https://doi.org/10.3390/su15032527

Etminani, A., Mohammadi, K., & Saberali, S. F. (2021). Effect of organic and inorganic amendments on growth indices and seed yield of red kidney bean (*Phaseolus vulgaris*) in competition with *Amaranthus retroflexus*. *Journal of Plant Nutrition*, *44* (3), 421–437. https://doi.org/10.1080/01904167.2020.1822398

Farhangi-Abriz, S., Torabian, S., Qin, R., Noulas, C., Lu, Y., & Gao, S. (2021). Biochar effects on yield of cereal and legume crops using meta-analysis. *Science of The Total Environment*, *775*, 145869. https://doi.org/10.1016/j.scitotenv.2021.145869

George, C., Wagner, M., Kücke, M., & Rillig, M. C. (2012). Divergent consequences of hydrochar in the plant–soil system: Arbuscular mycorrhiza, nodulation, plant growth and soil aggregation effects. *Applied Soil Ecology*, *59*, 68–72. https://doi.org/10.1016/j.apsoil.2012.02.021

Hagemann, N., Joseph, S., Conte, P., Albu, M., Obst, M., Borch, T., Orsetti, S., Subdiaga, E., Behrens, S., & Kappler, A. (2017). *Composting-derived organic coating on biochar enhances its affinity to nitrate*. 10775. EGU General Assembly Conference Abstracts. https://ui.adsabs.harvard.edu/abs/2017EGUGA..1910775H

Jalal, F., Arif, M., Ahmad, I., & Murad, W. (2018). Increasing Farm Productivity and Soil Fertility on Sustainable Basis Through "Summer Gap" Utilization with Biochar and Legumes. *Gesunde Pflanzen*, *70*(1), 45–53. https://doi.org/10.1007/s10343-017-0412-x

Janu, R., Mrlik, V., Ribitsch, D., Hofman, J., Sedláček, P., Bielská, L., & Soja, G. (2021). Biochar surface functional groups as affected by biomass feedstock, biochar composition and pyrolysis temperature. *Carbon Resources Conversion*, *4*, 36–46. https://doi.org/10.1016/j.crcon.2021.01.003

Jindo, K., Mizumoto, H., Sawada, Y., Sanchez-Monedero, M. A., & Sonoki, T. (2014). Physical and chemical characterization of biochars derived from different agricultural residues. *Biogeosciences*, *11*(23), 6613–6621. https://doi.org/10.5194/bg-11-6613-2014

Joseph, S., Kammann, C. I., Shepherd, J. G., Conte, P., Schmidt, H.-P., Hagemann, N., Rich, A. M., Marjo, C. E., Allen, J., Munroe, P., Mitchell, D. R. G., Donne, S., Spokas, K., & Graber, E. R. (2018). Microstructural and associated chemical changes during the composting of a high temperature biochar: Mechanisms for nitrate, phosphate and other nutrient retention and release. *Science of The Total Environment*, *618*, 1210–1223. https://doi.org/10.1016/j.scitotenv.2017.09.200

Kammann, C. I., Schmidt, H.-P., Messerschmidt, N., Linsel, S., Steffens, D., Müller, C., Koyro, H.-W., Conte, P., & Joseph, S. (2015). Plant growth improvement mediated by nitrate capture in co-composted biochar. *Scientific Reports*, *5*(1), 11080. https://doi.org/10.1038/srep11080

Kapoor, A., Sharma, R., Kumar, A., & Sepehya, S. (2022). Biochar as a means to improve soil fertility and crop productivity: A review. *Journal of Plant Nutrition*, *45*(15), 2380–2388. https://doi.org/10.1080/01904167.2022.2027980

Küçükbayrak, S., & Kadioğlu, E. (1989). Effect of pyrolysis on the proximate and ultimate analysis of lignite. *Thermochimica Acta*, *155*, 1–6. https://doi.org/10.1016/0040-6031(89)87131-X

Kul, R., Arjumend, T., Ekinci, M., Yildirim, E., Turan, M., & Argin, S. (2021). Biochar as an organic soil conditioner for mitigating salinity stress in tomato. *Soil Science and Plant Nutrition*, *67*(6), 693–706. https://doi.org/10.1080/00380768.2021.1998924

Kumari, S., Kumar, V., Kothari, R., & Kumar, P. (2022). Effect of supplementing biochar obtained from different wastes on biochemical and yield response of French bean (Phaseolus vulgaris L.): An experimental study. *Biocatalysis and Agricultural Biotechnology*, *43*, 102432. https://doi.org/10.1016/j.bcab.2022.102432

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char Sequestration in Terrestrial Ecosystems – A Review. *Mitigation and Adaptation Strategies for Global Change*, *11*(2), 403–427. https://doi.org/10.1007/s11027-005-9006-5

Li, S., Harris, S., Anandhi, A., & Chen, G. (2019). Predicting biochar properties and functions based on feedstock and pyrolysis temperature: A review and data syntheses. *Journal of Cleaner Production*, *215*, 890–902. https://doi.org/10.1016/j.jclepro.2019.01.106

Liu, Y., He, Z., & Uchimiya, M. (2015). Comparison of Biochar Formation from Various Agricultural By-Products Using FTIR Spectroscopy. *Modern Applied Science*, *9*(4), p246. https://doi.org/10.5539/mas.v9n4p246

Manyà, J. J. (2012). Pyrolysis for Biochar Purposes: A Review to Establish Current Knowledge Gaps and Research Needs. *Environmental Science & Technology*, *46*(15), 7939–7954. https://doi.org/10.1021/es301029g

Marahatta, Prof. Dr. A. B., Baral, G., & Dhital, K. (2024). FTIR Spectroscopic Studies on Hydration Propensities of the Preferentially Selected OPC Cements Manufactured in Nepal. *International Journal of Progressive Sciences and Technologies (IJPSAT)*, *45*(2 July,2024), 1–21.

Martinsen, V., Mulder, J., Shitumbanuma, V., Sparrevik, M., Børresen, T., & Cornelissen, G. (2014). Farmer-led maize biochar trials: Effect on crop yield and soil nutrients under conservation farming. *Journal of Plant Nutrition and Soil Science*, *177*(5), 681–695. https://doi.org/10.1002/jpln.201300590

Nandiyanto, A. B. D., Oktiani, R., & Ragadhita, R. (2019). How to Read and Interpret FTIR Spectroscope of Organic Material. *Indonesian Journal of Science and Technology*, *4*(1), 97. https://doi.org/10.17509/ijost.v4i1.15806

Nasiri, M., Andalibi, B., Khomari, S., Goli, E., Nasiri, S., El-Keblawy, A., & Mastinu, A. (2024). Enhancing salt stress tolerance in kidney beans: The synergistic effects of biochar and salicylic acid in arid and semi-arid regions. *Plant Stress*, *11*, 100423. https://doi.org/10.1016/j.stress.2024.100423

Ndor, E., Jayeoba, J. O., Asadu, C. L. A., & Iheshiulo, E. M.-A. (2016). Growth, Nutrient Uptake and Dry Matter Yield of Maize (Zea Mays L) Grown in Soil Amended with Rice Husk and Sawdust Biochar. *International Journal of Scientific Research in Agricultural Sciences*, *3*(3), 99–103. https://doi.org/10.12983/ijsras-2016-p0099-0103

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., & Børresen, T. (2016). In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. *Soil and Tillage Research*, *155*, 35–44. https://doi.org/10.1016/j.still.2015.08.002

Pandit, N. R., Dahal, S., Shrestha, S., Vista, S. P., & Gautam, D. K. (2021). Biochar as an efficient soil enhancer to improve soil fertility and crop productivity in Nepal. *Nepalese Journal of Agricultural Sciences*, *2021*, *21*.

Pandit, N. R., Mulder, J., Hale, S. E., Schmidt, H. P., & Cornelissen, G. (2017). Biochar from "Kon Tiki" flame curtain and other kilns: Effects of nutrient enrichment and kiln type on crop yield and soil chemistry. *PLOS ONE*, *12*(4), e0176378. https://doi.org/10.1371/journal.pone.0176378

Pandit, N. R., Sipkhan, P., Sharma, S. S., Dawadi, D., Vista, S. P., & Raut, P. (2024). Cattle-Urine-Enriched Biochar Enhances Soil Fertility, Nutrient Uptake, and Yield of Maize in a Low-Productive Soil. *Nitrogen*, *5*(1), 16–27. https://doi.org/10.3390/nitrogen5010002

Pariyar, P., Kumari, K., Jain, M. K., & Jadhao, P. S. (2020). Evaluation of change in biochar properties derived from different feedstock and pyrolysis temperature for environmental and agricultural application. *Science of The Total Environment*, *713*, 136433. https://doi.org/10.1016/j.scitotenv.2019.136433

Puga, A. P., Grutzmacher, P., Cerri, C. E. P., Ribeirinho, V. S., & Andrade, C. A. D. (2020). Biochar-based nitrogen fertilizers: Greenhouse gas emissions, use efficiency, and maize yield in tropical soils. *Science of The Total Environment*, *704*, 135375. https://doi.org/10.1016/j.scitotenv.2019.135375

Rahayu, M., Nurmalasari, A. I., & Aini, N. N. (2022). Effect of various types and doses of biochar on hybrid maize growth. *IOP Conference Series: Earth and Environmental Science*, *1016*(1), 012053. https://doi.org/10.1088/1755-1315/1016/1/012053

Rillig, M. C., Wagner, M., Salem, M., Antunes, P. M., George, C., Ramke, H.-G., Titirici, M.-M., & Antonietti, M. (2010). Material derived from hydrothermal carbonization: Effects on plant growth and arbuscular mycorrhiza. *Applied Soil Ecology*, *45*(3), 238–242. https://doi.org/10.1016/j.apsoil.2010.04.011

Rondon, M. A., Lehmann, J., Ramírez, J., & Hurtado, M. (2007). Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. *Biology and Fertility of Soils*, *43*(6), 699–708. https://doi.org/10.1007/s00374-006-0152-z

Ronsse, F., van Hecke, S., Dickinson, D., & Prins, W. (2013). Production and characterization of slow pyrolysis biochar: Influence of feedstock type and pyrolysis conditions. *GCB Bioenergy*, *5*(2), 104–115. https://doi.org/10.1111/gcbb.12018

Rutherford, D. W., Wershaw, R. L., Rostad, C. E., & Kelly, C. N. (2012). Effect of formation conditions on biochars: Compositional and structural properties of cellulose, lignin, and pine biochars. *Biomass and Bioenergy*, *46*, 693–701. https://doi.org/10.1016/j.biombioe.2012.06.026

Schmidt, H., Pandit, B., Martinsen, V., Cornelissen, G., Conte, P., & Kammann, C. (2015). Fourfold Increase in Pumpkin Yield in Response to Low-Dosage Root Zone Application of Urine-Enhanced Biochar to a Fertile Tropical Soil. *Agriculture*, *5*(3), 723–741. https://doi.org/10.3390/agriculture5030723

Song, W., & Guo, M. (2012). Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of Analytical and Applied Pyrolysis*, *94*, 138–145. https://doi.org/10.1016/j.jaap.2011.11.018

Steiner, C., Teixeira, W. G., Lehmann, J., Nehls, T., De Macêdo, J. L. V., Blum, W. E. H., & Zech, W. (2007). Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil*, *291*(1–2), 275–290. https://doi.org/10.1007/s11104-007-9193-9

Syahrinudin, S., Hartati, W., Sudarmadji, T., Krisdianto, N., & Ibrahim, I. (2019). Biochar enriched with organic fertilizer improves the survival and growth rate of Anthocepalus cadamba seedlings planted on degraded spodosols. *Biodiversitas Journal of Biological Diversity*, *20*(12). https://doi.org/10.13057/biodiv/d201237

Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: Pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, *19*(1), 191–215. https://doi.org/10.1007/s11157-020-09523-3

Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., & Cowie, A. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil*, *327*(1–2), 235–246. https://doi.org/10.1007/s11104-009-0050-x

Wiedemeier, D. B., Abiven, S., Hockaday, W. C., Keiluweit, M., Kleber, M., Masiello, C. A., McBeath, A. V., Nico, P. S., Pyle, L. A., Schneider, M. P. W., Smernik, R. J., Wiesenberg, G. L. B., & Schmidt, M. W. I. (2015). Aromaticity and degree of aromatic condensation of char. *Organic Geochemistry*, *78*, 135–143. https://doi.org/10.1016/j.orggeochem.2014.10.002

Zaitun, Z., Halim, A., Sa'dah, Y., & Cahyadi, R. (2022). Surface morphology properties of biochar feedstock for soil amendment. *IOP Conference Series: Earth and Environmental Science*, *951*(1), 012034. https://doi.org/10.1088/1755-1315/951/1/012034

Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature*, *528*(7580), 51–59. https://doi.org/10.1038/nature15743

Zhang, Y., Ma, Z., Zhang, Q., Wang, J., Ma, Q., Yang, Y., Luo, X., & Zhang, W. (2017). Comparison of the Physicochemical characteristics of bio-char pyrolyzed from moso bamboo and rice husk with different pyrolysis temperatures. *BioResources*, *12*(3), 4652–4669. https://doi.org/10.15376/biores.12.3.4652-4669

Zhao, H., Xie, T., Xiao, H., & Gao, M. (2022). Biochar-Based fertilizer improved crop yields and N utilization efficiency in a maize–Chinese cabbage rotation system. *Agriculture*, *12*(7), Article 7. https://doi.org/10.3390/agriculture12071030

Zhu, Z., Wei, G., Li, J., Qian, Q., & Yu, J. (2004). Silicon alleviates salt stress and increases antioxidant enzymes activity in leaves of salt-stressed cucumber (*Cucumis sativus* L.). *Plant Science*, *167*(3), 527–533. https://doi.org/10.1016/j.plantsci.2004.04.020