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RESEARCH ARTICLE

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The impact of water hyacinth biochar on maize growth and soil properties: The influence of pyrolysis temperature

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Abstract

Introduction: Options for managing water hyacinths (WHs) include converting the biomass into biochar for soil amendment. However, less has been known about the impact of WH-based biochar developed in varying pyrolysis temperatures on plant growth and soil qualities.

Materials and Methods: A pot experiment was undertaken in a factorial combination of WH biochars (WHBs) developed at three temperatures (350°C, 550°C and 750°C) and two application rates (5 and 20 t ha^{-1}), plus a control without biochar. Maize was grown as a test crop for 2 months under natural conditions.

Results: Our study showed that applying WHB developed between 350°C and 750°C at 20 t ha^{-1} increased maize shoot and root dry biomass by 47.7% to 17.6% and 78.4% to 54.1%, respectively. Nevertheless, raising the biochar pyrolysis temperature decreased maize growth, whereas increasing the application rate displayed a positive effect. The application of WHB generated at 350°C and 550°C at 20 t ha^{-1} resulted in significant improvements in soil total nitrogen (17.9% to 25%), cation exchange capacity (27.3% to 20.2%), and ammonium-nitrogen (60.7% to 59.6%), respectively, over the control. Additionally, applying WHB produced from 350°C to 750°C at 20 t ha^{-1} enhanced soil carbon by 38.5%–56.3%, compared to the control. Conversely, applying biochar produced at 750°C resulted in higher soil pH (6.3 ± 0.103), electrical conductivity (0.23 ± 0.01 dS m^{-1}) and available phosphorus (21.8 ± 2.53 mg kg^{-1}).

Conclusion: WHBs developed at temperatures of 350°C and 550°C with an application rate of 20 t ha^{-1} were found to be optimal for growing maize and improving soil characteristics. Our study concludes that pyrolysis temperature significantly governs the effectiveness of biochar produced from a specific biomass source.

KEYWORDS
biochar, productivity, soil amendment, thermal conversion, weed management

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1 | INTRODUCTION

Water hyacinth (WH) (*Eichhornia crassipes*), recognized as among the top 10 worst weeds in the world (Patel, 2012), has troubled the waterways of tropical countries for over a century (Djihouessi et al., 2023). Notably, the WH invasion of Lake Tana, Ethiopia's largest lake where the Blue Nile originates, began in 2011 (Nega et al., 2021) and poses a threat to the area's aquatic environment, tourism, water transportation, fisheries, power plants, agriculture and social and economic conditions (Dersseh et al., 2019). The extensive invasion of WH in Lake Tana resulted in a minimum of US$3.2 million in direct economic losses (Enyew et al., 2020). Excessive eutrophication, shallow depth of the lake and favourable environmental conditions are the fundamental causes of the WH proliferation at Lake Tana (Damtie et al., 2022). The infestation of WH in Lake Tana has progressed to the point that adaptation is unavoidable and proved that removal is expensive, technically challenging and frequently unattainable (Van Oijstaeijen et al., 2020). Moreover, eradication of WHs from waterways was reported to be extremely difficult (Priya & Selvan, 2017). On the other hand, the biomass of WH is an inexpensive and relatively unexplored resource for value-added products that have favourable socioeconomic and environmental effects (Nega et al., 2021). Invasive plants can be efficiently exploited by using them as raw material for biochar production (Feng et al., 2021). Thus, a valuable resource for soil carbon sequestration and enhancing soil fertility can be achieved by converting WH biomass into biochar and applying it to the soil as an amendment (Masto et al., 2013).

For thousands of years, people have developed and used biochar, the solid product of biomass pyrolysis in limited air conditions, most often known as charcoal (Weber & Quicker, 2018). Thermal processing is applied to the feedstocks at temperatures ranging from 300°C to 800°C to produce biochar (Novak et al., 2019). A carbon-rich biochar offers several advantages for improving soil fertility, storing soil nutrients and water and lowering greenhouse gas emissions (Chen et al., 2023; Zhao et al., 2014). Due to several attributes, such as improved nutrient availability, soil microbial biomass, soil pH and cation exchange capacity (CEC), applying biochar can positively impact crop yield and soil health (Muñoz et al., 2016; Vijay et al., 2021) and boosts the sequestration of carbon in the soil (Ding et al., 2023). There is a significant chance that biochar will improve the soil's nutrient availability by reducing leaching and enhancing soil quality (Agegnehu et al., 2017). Additionally, biochar by itself can supply nutrients necessary for plant growth (DeLuca et al., 2015) particularly, when applied to acidic and low-nutrient soils, biochar can help increase crop yield (Jeffery et al., 2017).

The various agricultural advantages of adding biochar to soils are reliant upon the specific biochar's feedstock biomass, application rate, and pyrolysis temperature (Kavitha et al., 2018). Research indicates that pH, specific surface area (SSA), pore volume, total carbon (TC) and ash content increase as the pyrolysis temperature rises, while CEC and volatile matter drop (Tomczyk et al., 2020). Furthermore, the pyrolysis process modifies the nutritional composition and potentially the availability of nutrients in the resultant biochar (Naeem et al., 2015). Pyrolysis temperature positively correlates with the available phosphorus (P_{av}) and potassium (K) contents of biochar (Hossain et al., 2021) whereas total nitrogen (TN) had a negative correlation (Ye et al., 2020). Considering this fact, all kinds of biochar will not provide the intended impact (Brassard et al., 2019). Thus, careful selection of biochar characteristics before applying to a particular soil will increase the effective use of biochar (Dai et al., 2020).

Several studies demonstrated that biochar produced at lower temperatures promotes plant growth better than the respective higher pyrolysis temperature biochar in different pH soils (Alotaibi & Schoenau, 2019; Butnan et al., 2015; Deng et al., 2022; Gunes et al., 2015; Luo et al., 2014; Nelissen et al., 2014). Whereas, soil properties including pH (Hagner et al., 2016; Luo et al., 2014), electrical conductivity (EC), P_{av} (Abrishamkesh et al., 2015) and organic matter (Tang et al., 2020) increased while CEC decreased (Fachini et al., 2021) with the application of high pyrolysis temperature biochar. Yet, it is not clear how biochar produced at different pyrolysis temperatures affects plant growth and soil properties. Clarifying these relationships will contribute to a more comprehensive understanding of biochar application in agriculture and facilitate the development of targeted strategies for optimizing its benefits.

A study conducted by Masto et al. (2013) and Hammam et al. (2022) showed the effects of applying WH biochar (WHB) generated at 300°C on the development of maize and barley, respectively, and soil properties. However, there is a notable absence of sufficient studies examining the potential of WHB produced at different temperatures for enhancing plant growth and ameliorating soil. This highlights the need for further research to fill this knowledge gap and provide insights into the effectiveness of biochar derived from WH at various pyrolysis temperatures. Additionally, utilizing WH biomass which is highly proliferating in Lake Tana, Ethiopia, could be an alternative weed management option that has not been studied so far. Consequently, it is crucial to conduct further research on the effects of WHB on plant growth and soil properties, considering the impact of biochar pyrolysis temperature and application rate. This could be essential to grasp the effects of pyrolysis temperature and application rates of WHB to identify the optimal production temperature to generate the most effective biochar from WH and recommendations for wider field applications. Therefore, this study aimed to elucidate how WHB prepared at diverse temperatures and applied at varying rates influence maize growth and selected soil chemical characteristics.

2 | MATERIALS AND METHODS

2.1 | Biochar preparation and analysis

The biochar used in the experiment was derived from an invasive aquatic weed called water hyacinth (WH). The WH biomass was collected from two primary infestation locations at Lake Tana, *Wusha Tires* (12°07′09″ N, 37°36′55″ E) and *Sheha Gomenge* (12°12′52″ N, 37°33′51″ E) in the Amhara Regional State, Ethiopia. The WH biomass was washed, chopped and dried overnight in an oven at 105°C. Dried WH biomass was kept in stainless still cups, and pyrolyzed using a muffle furnace (LT 40/12; Nabertherm GmbH) at temperatures of 350°C (WHB350), 550°C (WHB550) and 750°C (WHB750) at a heating rate of 5°C per minute and a retention time of 2 h. The basis for selecting the 350–750°C pyrolysis temperature range was the recommended range of slow pyrolysis temperature (350–800°C) for biochar by Tomczyk et al. (2020).

The biochar samples were milled and screened through a 2-mm sieve for analysis and the pot experiment application. The biochar's pH and EC were measured from a 1:10 (biochar [g] to deionized water [mL]) mix suspension (Singh et al., 2017). The biochar's ash content was determined according to the ASTM D1762-84 method (Enders et al., 2012). A CHN analyzer (2400 Series II; Perkin Elmer) was used to apply the dry combustion to analyze the total C and N of the biochar. The percentage $CaCO_3$ equivalency was used to express the liming capacity of the biochar samples, which were measured following Singh et al. (2017). Briefly, 0.5 g of ground biochar was combined with 10.0 mL of a 1 M HCl solution, agitated for 2 h, and left to stand for 16 h. Then, the mixture was titrated vigorously while being stirred with a standardized 0.5 M NaOH solution until it achieved a pH of 7. The calculation presented by Singh et al. (2017) was then applied to obtain the percent $CaCO_3$ equivalency. According to Wang et al. (2012), the amount of accessible P in the biochar was determined by using an extraction procedure using a 2% formic acid. In brief, a 0.35 g sample of biochar was shaken for 30 min at 160 rpm with 35 mL of 2% formic acid mixed in. A flow injection autoanalyzer (FIAlyzer-1000, FIAlab Instruments, Inc., Seattle, USA) was used to measure the available P in the filtrate after a 10-min centrifugation period and filtration using Whatman No. 41 filter paper. The Brunauer–Emmett–Teller approach (Brunauer et al., 1938) was used to analyze the SSA and the porosity of biochar using an accelerated surface area and porosimetry (ASAP 2010; Micrometric). The physicochemical properties of the experimental biochars are presented in Table 1. The details of biochar analysis methods and characteristics are found in our previous work (Gezahegn et al., 2024).

2.2 | Soil sample collection and preparation

For this experiment, a surface soil sample classified as Nitisol (Abewa et al., 2020) was collected up to a soil depth of 20 cm from a farmer's training centre (11°37′34.16″ N, 37°27′37.48″ E) in Bahir Dar, Ethiopia, where previously maize was grown. After collecting the soil, large pieces of plant debris, roots and stones were removed and air-dried under a shade for 5 days. Once ground, the soil sample was screened through a 2-mm sieve and thoroughly homogenized for the pot experiment and physicochemical analysis. Selected physical and chemical properties of the test soil before planting are given in Table 1.

TABLE 1 The basic physicochemical characteristics of the experimental soil and water hyacinth biochars developed at various temperatures of pyrolysis.

Biochar properties	WHB350	WHB550	WHB750	Soil[a]
Sand (%)	–	–	–	28
Silt (%)	–	–	–	24
Clay (%)	–	–	–	47
Yield (%)	51.0 ± 1.07	37.9 ± 0.38	33.3 ± 0.30	–
pH (H_2O)	9.24 ± 0.01	11.0 ± 0.01	11.2 ± 0.003	5.61
EC (μS cm^{-1})	28.0 ± 0.45	32.9 ± 1.15	44.7 ± 2.11	0.097
Total carbon (%)	33.9 ± 1.44	33.0 ± 0.44	27.8 ± 0.47	1.72
Total nitrogen (%)	2.14 ± 0.04	1.91 ± 0.02	1.37 ± 0.01	0.26
C/N	15.9 ± 0.62	17.3 ± 0.22	20.3 ± 0.73	–
Ash (%)	33.3 ± 0.3	42.1 ± 0.24	52.4 ± 0.53	–
$CaCO_3$ equivalence (%)	17.7 ± 1.01	24.8 ± 1.75	33.3 ± 1.05	–
Available phosphorus (g kg^{-1})	5.36 ± 1.67	5.95 ± 0.25	6.74 ± 0.22	7.26
CEC ($cmol_+$ kg^{-1})	44.4 ± 0.65	34.6 ± 1.67	2.3 ± 0.14	26.2
Specific surface area (m^2 g^{-1})[a]	1.1	14.6	29.8	–
Total pore volume (cm^3 g^{-1})[a]	4.23×10^{-3}	18.29×10^{-3}	32.63×10^{-3}	–
Micropore volume (cm^3 g^{-1})[a]	1.58×10^{-3}	3.49×10^{-3}	6.01×10^{-3}	–
Average pore width (nm)[a]	15.4	5.01	4.37	–

Abbreviations: C/N, carbon-to-nitrogen ratio; CEC, cation exchange capacity; EC, electrical conductivity; WHB350, WHB550 and WHB750, water hyacinth biochars prepared at 350°C, 550°C and 750°C, respectively.

[a] Values are average of two replicates.

2.3 | Pot experiment

A pot experiment took place at the College of Agriculture and Environmental Sciences campus (11°37′19.04″ N, 37°27′35.94″ E), Bahir Dar University, Ethiopia, under natural (open air) conditions from April to June 2022 (Supporting Information S1: Figure 1). Air temperature and relative humidity during the study period are presented in Figure 1. The experiment was laid out in a 3 × 2 factorial arrangement of three types of WHBs differed by the pyrolysis temperature, namely, WHB350, WHB550 and WHB750 and two biochar application rates (5 and 20 t ha^{-1}) along with a control without WHB in four replications. Biochar is often applied at a rate of 5–50 t ha^{-1}, according to Major (2010). Furthermore, the recommended biochar application rate for maize cultivation was 20 t ha^{-1} (Major et al., 2010). Consequently, it was decided that the two

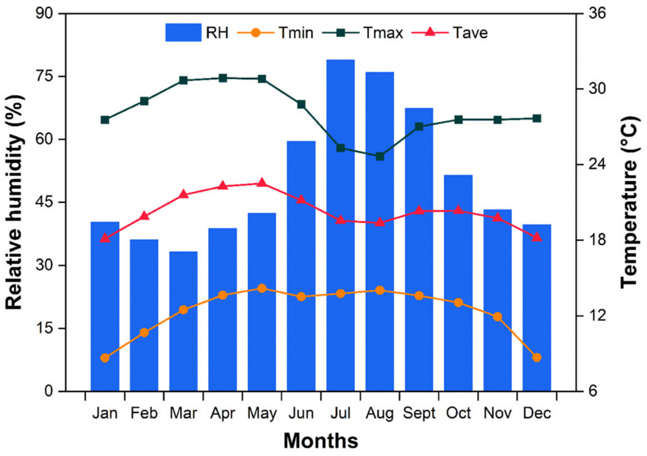


FIGURE 1 The relative humidity (RH), minimum temperature (T_{min}), maximum temperature (T_{max}) and average temperature (T_{ave}) of the study area during the study period in 2022.

application rates, 5 and 20 t ha^{-1}, would be the lowest and optimum rates, respectively. Each plastic pot (18.5 and 19 cm top diameter and height, respectively) was filled up with soil weighing 4 kg after thoroughly mixing with the biochar. The soil and biochar blend were incubated for 3 weeks before maize planting maintaining the moisture level at 70% of the soil's field capacity. The pots were set up in a randomized complete block design. After 3 weeks, four healthy seeds of maize (variety *Limu*) were sown in each pot. After germination, they were thinned down to two plants and cultivated for 62 days. Nitrogen and phosphorous fertilizers were uniformly applied to all pots at a rate of 138 kg N ha^{-1} (372.6 mg pot^{-1}) and 92 kg P_2O_5 ha^{-1} (248.4 mg pot^{-1}) as urea and triple super phosphate, respectively. The full dose of phosphorus fertilizer and the first half split of urea were applied during planting and the remaining urea fertilizer was applied 4 weeks after sowing as topdressing (Agegnehu et al., 2015). Maize plants were irrigated once a day to maintain the soil water content of not less than 70% of the soil's field capacity. All the necessary agronomic procedures were implemented during the crop growth stage.

2.4 | Data collection

2.4.1 | Maize growth parameters

Before harvesting, plant height was measured using a measuring tape from the soil level to the tip of the maize shoot. The chlorophyll concentration of the leaf was measured through the use of a chlorophyll concentration metre (MC-100; Apogee instruments) from three young fully developed leaves per plant with three replications. Leaf area was measured by taking the leaf length and width and multiplying by a factor of 0.75 (Elings, 2000). The shoot stem diameter was determined using a digital caliper. After 62 days of planting, the maize was cut above the soil level and the roots were cautiously separated from the soil. Shoot and root parts were cleaned using distilled water, allowed to air dry, then oven-dried at 70°C for 72 h in a paper bag and weighed to determine shoot and root biomass (Smider & Singh, 2014).

2.4.2 | Soil sampling and analysis

Soil samples taken before planting and after harvest were dried by air and passed through a 2 mm sieve for the analysis of selected physicochemical properties. The texture of the soil was examined using the hydrometer method (Bouyoucos, 1962). Soil pH and EC were determined in 1:2.5 soil (g) to water (mL) suspension (Rayment & Lyons, 2010) using a pH metre (9625, JF25; Horiba Scientific) and EC metre (Mettler-Toledo). The TN and TC were determined using an elemental analyzer (2400 Series II; Perkin Elmer). Following extraction with 1 mol L^{-1} KCl, the colorimetric determination of soil NH_4^+-N and NO_3^--N was made (Rayment & Lyons, 2010) using an autoanalyzer (FIAlyzer-1000, FIAlab Instruments, Inc.). Following the method of Mehlich (1984), P_{av} was determined using the Mehlich-3 extraction solution using an autoanalyzer (FIAlyzer-1000, FIAlab Instruments, Inc.). The CEC was determined using the 1 mol L^{-1} NH_4OAc method (Black, 1965).

2.5 | Data analysis

Lavene's test of homogeneity was conducted before the analysis of variance (ANOVA) test. ANOVA was conducted to determine the significant variations in maize growth and properties of soil among various treatments. The following model was used to quantify the overall variability for each treatment.

$$Y_{ij} = \mu + R_i + T_j + e_{ijk},$$

where Y_{ij} is total observation, μ is the grand mean, R_i is the effect of the *i*th replication, T_j is the effect of the *j*th treatment and e_{ijk} is the variation due to random error.

Significant variations between means of different treatments were separated by Tukey's multiple comparison test at $p < 0.05$. The significance level for all statistical analyses was set at $p < 0.05$ Correlations among soil chemical properties and maize dry biomass were computed with Pearson's two-tailed test at $p < 0.05$. The SPSS software (version 26) was used for data analysis and graphs were plotted with Origin software (OriginPro 2024).

3 | RESULTS

3.1 | Effect of pyrolysis temperature and application rate of WHB on maize growth

Except for maize root biomass, WHB pyrolysis temperature significantly ($p < 0.05$) impacted maize growth components (Table 1).

The application rate of WHB has significantly ($p < 0.05$) impacted all components of maize growth. However, an interaction effect of pyrolysis temperature and application rate of WHB was significant only for maize shoot dry biomass and plant height. The highest mean shoot dry biomass was recorded with the addition of low pyrolysis temperature biochar (WHB350) at 20 t ha^{-1} (Figure 2). Relative to the control, WHB350 at 20 t ha^{-1} increased the shoot dry biomass by 46.8%. At the same rate, WHB550 and WHB750 increased shoot dry biomass by 33.7% and 17.6%, respectively, compared to the control. Although higher than nonbiochar amended control, maize dry biomass decreased as the biochar pyrolysis temperature increased. Shoot dry biomass recorded between WHB350 and WHB550 was not significantly different, but the shoot dry weight recorded in WHB750 was significantly ($p < 0.05$) lower than WHB350 and WHB550. At the lower application rate of 5 t ha^{-1} WHB, only WHB350 showed a statistically significantly ($p < 0.05$) higher mean shoot dry biomass over the control. Significantly ($p < 0.05$) higher shoot biomass was found from the application of 20 t ha^{-1} WHB than the 5 t ha^{-1}, except for WHB750.

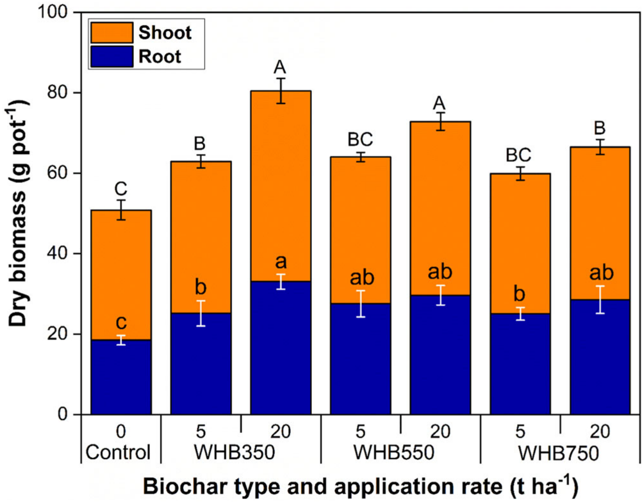


FIGURE 2 Maize shoot and root dry biomass by different pyrolysis temperatures and application rates of water hyacinth biochar. Values are presented as means ± standard deviations (*n* = 4). Distinct letters in lowercase and uppercase on the bars designated significant differences in the data points at $p < 0.05$. WHB350, WHB550 and WHB750, water hyacinth biochars prepared at 350°C, 550°C and 750°C.

Incorporation of WHB prepared under different pyrolysis temperatures and application rates significantly ($p < 0.05$) improved the root growth of maize compared to the nonbiochar amended control (Figure 2). The effect of the application of different rates of WHB on root growth was found significant ($p < 0.05$), but the effect of pyrolysis temperature was insignificant (Table 2). The root dry biomass of the maize plant varied from 18.5 ± 1.18 to 33.0 ± 1.86 g pot^{-1}. The addition of WHB350 at 20 t ha^{-1} showed the highest root development. Concerning the control, applying WHB350 at 20 t ha^{-1} improved root growth by 78.4%. Similarly, the application of WHB550 and WHB750 at the application rate of 20 t ha^{-1} increased root growth by 60.1% and 54.1%, respectively. Under the lower application rate of WHB (5 t ha^{-1}), a significant difference was not observed in root dry weight due to biochar pyrolysis temperature, but compared with the control a 35.7%, 48.6% and 35.1% increase was observed by applying WHB350, WHB550 and WHB750, respectively. Maize root dry biomass decreased as WHB pyrolysis temperature increased.

The highest (90.9 ± 3.1 cm) and lowest (78.9 ± 3.21 cm) plant heights were observed with the application of WHB350 at 20 t ha^{-1} and the control, respectively, where a 15.2% increase over the control was recorded (Figure 3a). Applying WHB produced at 350°C and 550°C exhibited statistically higher maize plant height. However, regardless of pyrolysis temperature, there was no statistically significant effect of the application of WHB at 5 t ha^{-1} on maize plant height.

The addition of WHB derived at varying pyrolysis temperatures and applied at different rates substantially ($p < 0.05$) impacted the

TABLE 2 The two-way ANOVA on the effect of biochar pyrolysis temperature, rate of application, and their interaction on maize biomass, growth parameters, and soil properties.

Source of variance	Shoot biomass	Root biomass	Plant height	Leaf area	Chlorophyll content	Shoot stem diameter	pH
T	<0.001	NS	0.038	0.006	0.034	NS	<0.001
R	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
T × *R*	0.016	NS	0.026	NS	NS	NS	0.003

Source of variance	EC	TC	CEC	TN	P_{av}	NH_4^+-N	NO_3^--N
T	<0.001	NS	0.001	<0.001	<0.001	0.008	<0.001
R	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001
T × *R*	0.02	NS	NS	0.001	<0.001	NS	0.003

Abbreviations: ANOVA, analysis of variance; CEC, cation exchange capacity; EC, electrical conductivity; NH_4^+-N: ammonium-nitrogen; NO_3^--N: nitrate-nitrogen; NS, nonsignificant; *R*, rate; P_{av}, available phosphorus; *T*, temperature; TC, total carbon; TN, total nitrogen;.

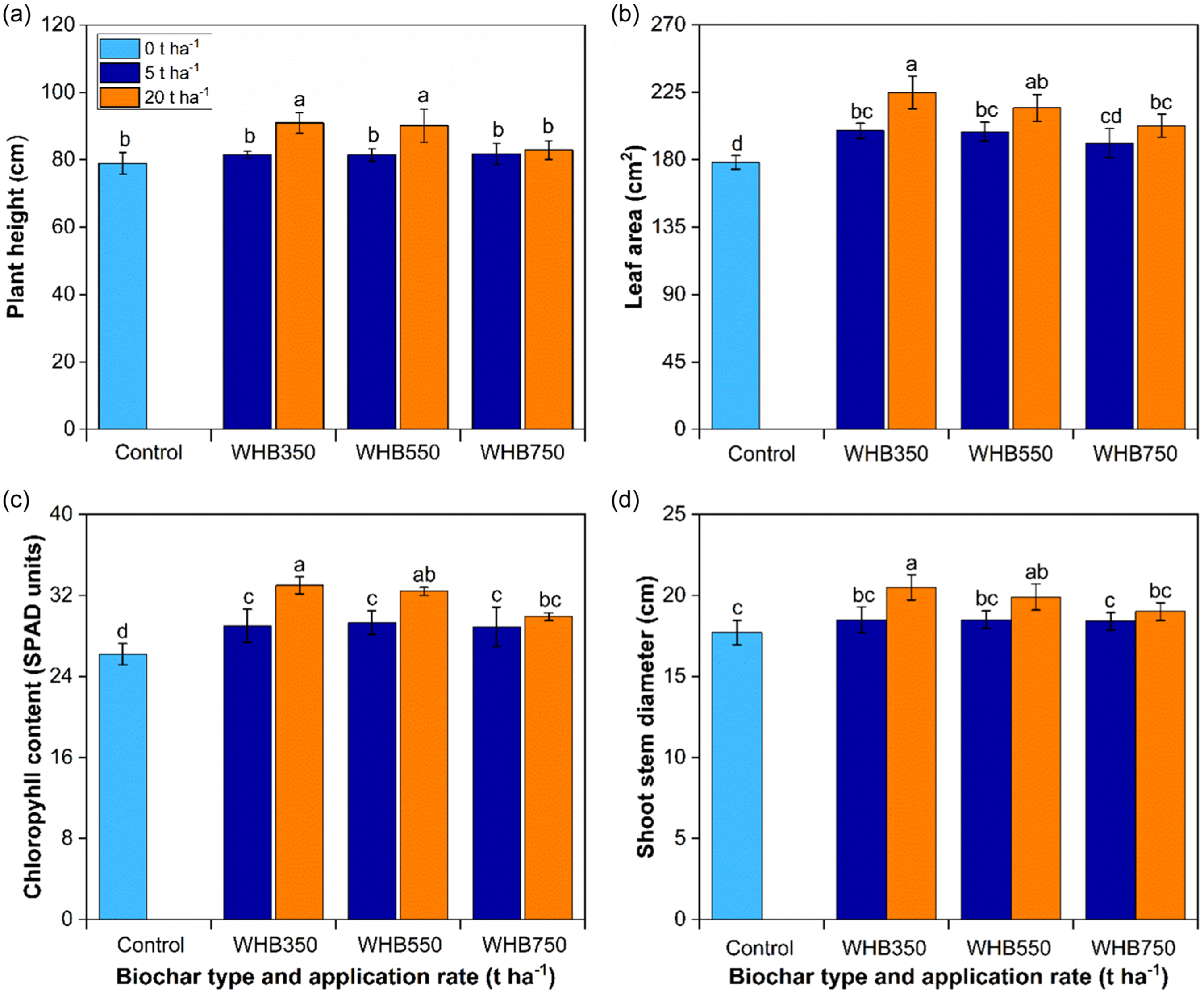


FIGURE 3 Plant height (a), leaf area (b), leaf chlorophyll content (c) and shoot stem diameter (d) of maize by different pyrolysis temperatures and rate of applications of water hyacinth biochar. Values are presented as means ± standard deviations ($n = 4$). Distinct letters on the bars in each figure designated significant differences in the data points at $p < 0.05$. WHB350, WHB550 and WHB750, water hyacinth biochars prepared at 350°C, 550°C and 750°C.

leaf area of maize compared to nonbiochar amended control (Figure 3b). The largest leaf area was found due to the application of WHB350 at 20 t ha^{-1}. With respect to the control, the addition of 20 t ha^{-1} of WHB enhanced the leaf area by 26.3%, 20.4% and 13.7% with the addition of WHB350, WHB550, and WHB750, respectively. Similarly, the application of WHB350 and WHB550 at a 5 t ha^{-1} rate increased the leaf area by 11.9% and 11.5%, respectively.

The chlorophyll content (SPAD units) of maize leaf was significantly impacted by the incorporation of WHB produced at varying pyrolysis temperatures and application rates (Figure 3c). The greatest leaf chlorophyll content was found with the addition of WHB350 and WHB550. In comparison to the control, the leaf chlorophyll content was greater by 26.0% and 23.7% with the addition of WHB350 and WHB550 at the 20 t ha^{-1} application rate, respectively. Despite being significantly higher than the control, the application of different pyrolysis temperatures at a 5 t ha^{-1} rate did not show a significant variation in leaf chlorophyll content. However, leaf chlorophyll content increased significantly at the given application rate of WHB compared to the control, and higher results were recorded at the 20 t ha^{-1} rate of application.

Maize shoot stem diameter was significantly impacted by the pyrolysis temperature and application rate of WHB (Figure 3d). Significantly ($p < 0.05$) the highest shoot stem diameter was recorded from the application of WHB350 followed by WHB550, with respective increases of 15.8% and 12.4% over the control at the rate of 20 t ha^{-1}. Yet, no significant variation was found between the control and the diverse pyrolysis temperature biochars at the 5 t ha^{-1} application rate.

3.2 | Effect of pyrolysis temperature and application rate of WHB on soil chemical properties after harvesting

The *p* values of the ANOVA test result owing to the application of diverse pyrolysis temperatures of WHB in different application rates and their interaction on soil properties were summarized (Table 2).

3.2.1 | Soil pH and EC

The two-way ANOVA results demonstrated that soil pH significantly varied ($p < 0.01$ and $p < 0.001$) among variances of biochar pyrolysis temperatures, application rates, and their interaction (Table 2). The lowest (5.58 ± 0.03) and highest mean pH values (6.3 ± 0.1) were recorded from the control and application of WHB750 at 20 t ha^{-1}, respectively (Figure 4a). Relative to the control, the addition of WHB350, WHB550 and WHB750 at the rate of 20 t ha^{-1} notably ($p < 0.05$) raised the mean pH value by 0.37, 0.61 and 0.72 units, respectively. Similarly, the application of WHB350, WHB550 and WHB750 at the rate of 5 t ha^{-1} raised the mean soil pH by 0.13, 0.17 and 0.21 units, respectively. However, a significantly higher pH value was found from the addition of WHB550 and WHB750 at the 5 t ha^{-1} rate compared to the biochar unamended soil.

Postharvest soil EC was significantly varied ($p < 0.05$, $p < 0.001$) due to the incorporation of WHB prepared at varying temperatures, rate of application, and their interaction (Table 2). The EC value increased with increasing biochar pyrolysis temperature and

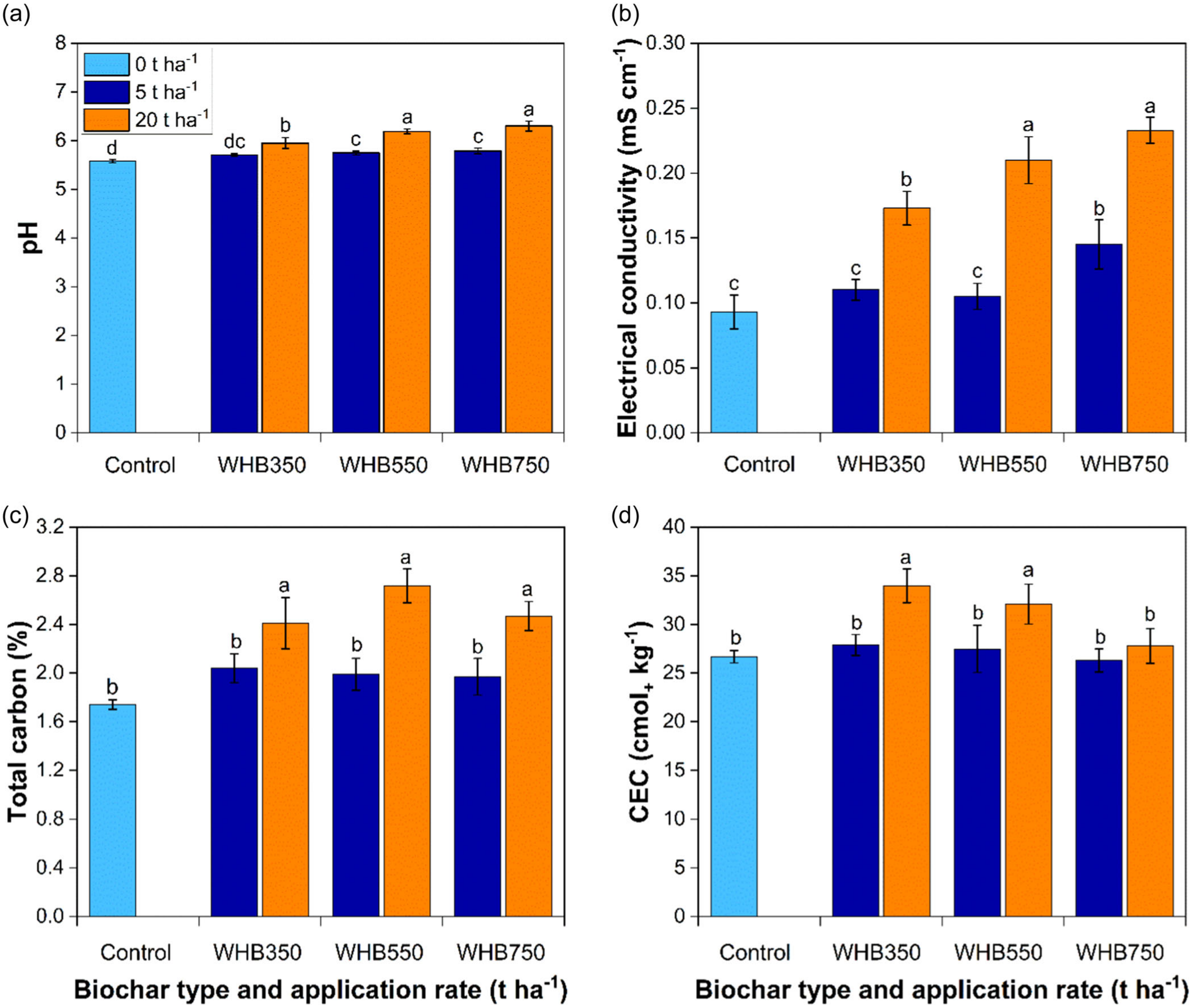


FIGURE 4 Soil pH (a), electrical conductivity (b), total carbon (c) and CEC (d) as influenced by water hyacinth biochar pyrolysis temperatures and rate of applications after maize harvest. Values are presented as means ± standard deviations ($n = 4$). Distinct letters on the bars in each figure designated significant differences in the data points at $p < 0.05$. CEC, cation exchange capacity; WHB350, WHB550, WHB750, water hyacinth biochars prepared at 350°C, 550°C and 750°C.

application rate. The highest mean EC value of $0.23 \pm 0.01\,\mathrm{dS\,m^{-1}}$ was found from the application of WHB750 at $20\,\mathrm{t\,ha^{-1}}$ and the lowest EC value of $0.093 \pm 0.013\,\mathrm{dS\,m^{-1}}$ was recorded from the control treatment (Figure 4b). The mean EC increased in the order of WHB750 > WHB550 > WHB350 at an application rate of $20\,\mathrm{t\,ha^{-1}}$, where the mean EC value increased by 151%, 126% and 86% relative to the control, respectively. However, with the addition of the lower rate of $5\,\mathrm{t\,ha^{-1}}$, only WHB750 showed a significant increase ($p < 0.05$) of mean EC by 55.9% over the control.

3.2.2 | TC and CEC

Only the application rate of WHB showed a significant main effect ($p < 0.001$) on postharvest soil TC content (Table 2). Applying WHB350, WHB550 and WHB750 at $20\,\mathrm{t\,ha^{-1}}$, led to soil TC increments of 38.5%, 56.3% and 42%, respectively, compared to the control (Figure 4c). However, the lower WHB application rate of $5\,\mathrm{t\,ha^{-1}}$ had no significant difference with the control and among the biochars.

The CEC of the soil significantly ($p < 0.01$, $p < 0.001$) differed due to the application of WHB pyrolyzed at different temperatures and different application rates (Table 2). Incorporation of low pyrolysis temperature biochars (WHB350 and WHB550) in $20\,\mathrm{t\,ha^{-1}}$ significantly raised the soil CEC by 27.3% and 20.2%, respectively, relative to the nonbiochar amended control (Figure 4d). High pyrolysis temperature (750°C) WHB resulted in the lowest CEC among biochar types and the difference with the control was insignificant. Besides, regardless of the pyrolysis temperature, there was no significant variation between the control and WHB incorporated at the lower rate.

3.2.3 | TN and P_{av}

After the pot experiment, the soil TN was significantly affected by the addition of WHB at different pyrolysis temperatures in different application rates (Table 2). The highest mean soil TN of $0.33 \pm 0.008\%$ was obtained from the addition of WHB550 at $20\,\mathrm{t\,ha^{-1}}$ (Figure 5a). The application of WHB550 and WHB350 at the higher rate of $20\,\mathrm{t\,ha^{-1}}$ increased soil mean TN by 25% and 17.9%, respectively, over the control. On the contrary, the addition of WHB at $5\,\mathrm{t\,ha^{-1}}$ had no significant impact on soil TN relative to the control and among different temperature biochars.

The addition of different pyrolysis temperature WHB at different application rates significantly ($p < 0.001$) affected the mean soil P_{av} (Table 2). Applying WHB350, WHB550 and WHB750 at $20\,\mathrm{t\,h^{-1}}$ significantly ($p < 0.001$) enhanced the soil P_{av} by 50.4%, 138% and 199%, respectively, compared to the control (Figure 5b). However, the application of WHB at the lower rate of $5\,\mathrm{t\,ha^{-1}}$ had a nonsignificant impact on soil mean P_{av} among the biochars and relative to the control.

3.2.4 | Soil inorganic nitrogen

The concentration of NH_4^+-N showed a significant ($p < 0.01$) difference due to the pyrolysis temperature and application rate of WHB; however, their interaction did not have a significant effect (Table 2). The application of low pyrolysis temperature WHBs pyrolyzed at 350°C and 550°C significantly increased the NH_4^+-N content in the soil by 60.7% and 59.6%, respectively, relative to the control (Figure 5c). However, significant variation was not observed among the biochars and with the control due to the addition of WHB at $5\,\mathrm{t\,ha^{-1}}$. The result of the ANOVA test (Table 2) also indicated that the soil NO_3^--N level was significantly ($p < 0.01$; $p < 0.001$) altered owing to the varying pyrolysis temperatures, application rates of WHB, and their interaction. The maximum significant level of NO_3^--N was noted in the control compared to the other treatments (Figure 5d). The mean soil NO_3^--N significantly decreased by 72.4%, 62% and 26.5% due to the application of WHB350, WHB550 and WHB750 at the application rate of $20\,\mathrm{t\,ha^{-1}}$, respectively, from the control. Similarly, the application of WHB350 and WHB550 at $5\,\mathrm{t\,ha^{-1}}$ significantly reduced the level of mean soil NO_3^--N by 21.5% and 20.8%, respectively, compared with the control except for the highest pyrolysis temperature biochar. Overall, the soil NO_3^--N concentration was greater by 69% than the concentration of the mean soil NH_4^+-N.

3.3 | Relationships between maize dry biomass and soil properties

The Pearson correlation analysis showed that the dry shoot and root biomass of maize were notably ($p < 0.01$ and $p < 0.001$) correlated with postharvest soil parameters (Figure 6). Dry shoot and root biomass of maize showed a significant correlation ($p < 0.001$, $r = 0.71$). Shoot dry biomass was positively correlated with CEC, TN, NH_4^+-N and TC ($r = 0.83$, 0.75, 0.70 and 0.72, respectively). However, a significant correlation was not found between shoot biomass and soil P_{av}, and a negative correlation was found between shoot biomass and soil NO_3^--N. The root biomass had a positive correlation with shoot dry biomass and soil properties except for soil NO_3^--N. Soil pH was found to be positively correlated with EC, TC and P_{av} ($r = 0.93$, 0.76 and 0.91, respectively). Soil pH correlated with TN ($r = 0.45$), but not with soil NH_4^+-N. Total N correlated with TC and CEC ($r = 0.71$ and 0.75, respectively). Soil P_{av} did not correlate with CEC, TN, NH_4^+-N and NO_3^--N. Similarly, NO_3^--N did not correlate with P_{av} but negatively correlated with the rest of the soil properties. However, NH_4^+-N correlated with TN, TC and CEC ($r = 0.64$, 0.63 and 0.67, respectively).

4 | DISCUSSION

4.1 | Maize growth and growth components

The findings of the current study demonstrated that adding WHB to soil considerably increased maize dry biomass yield (Figure 2).

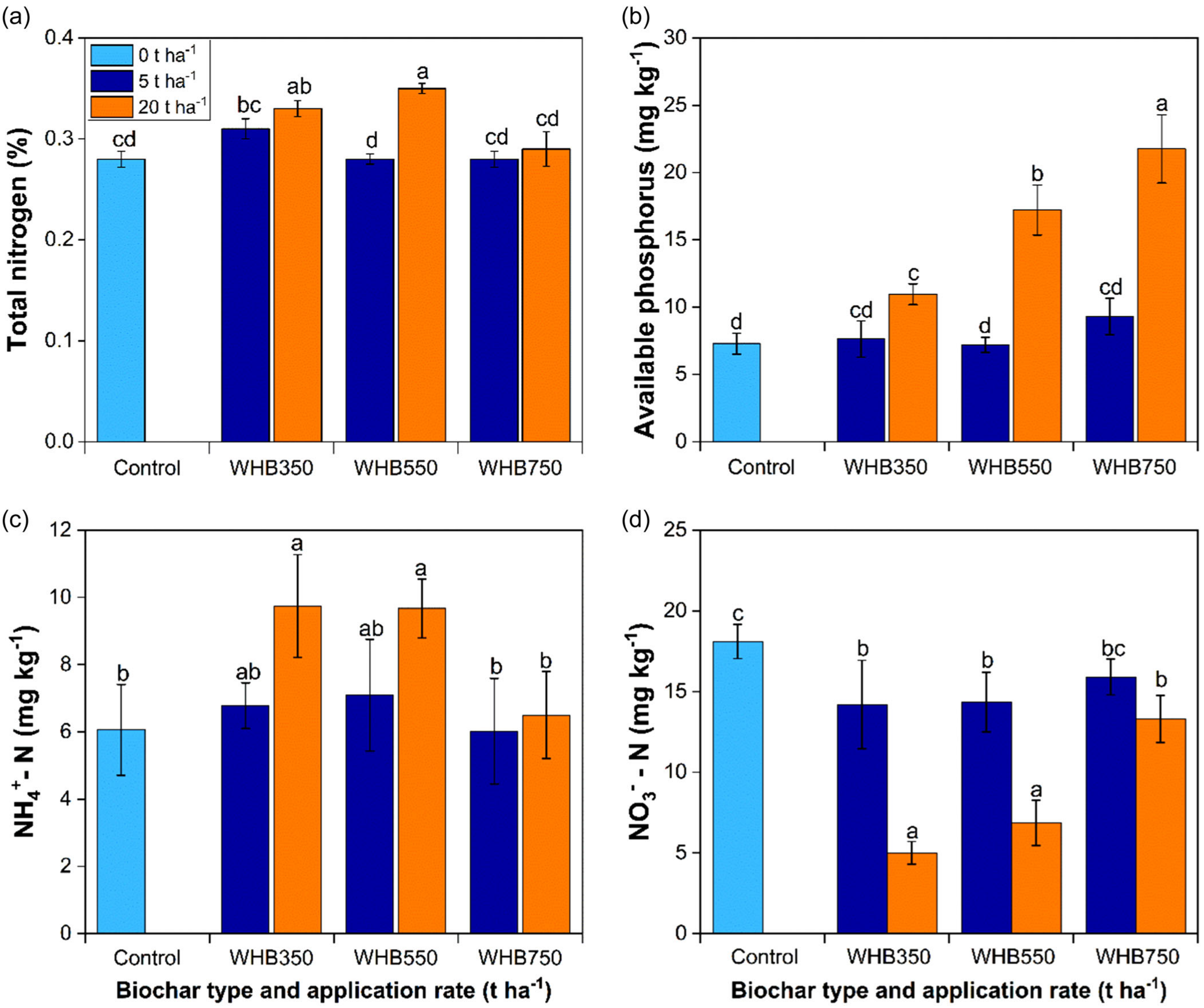
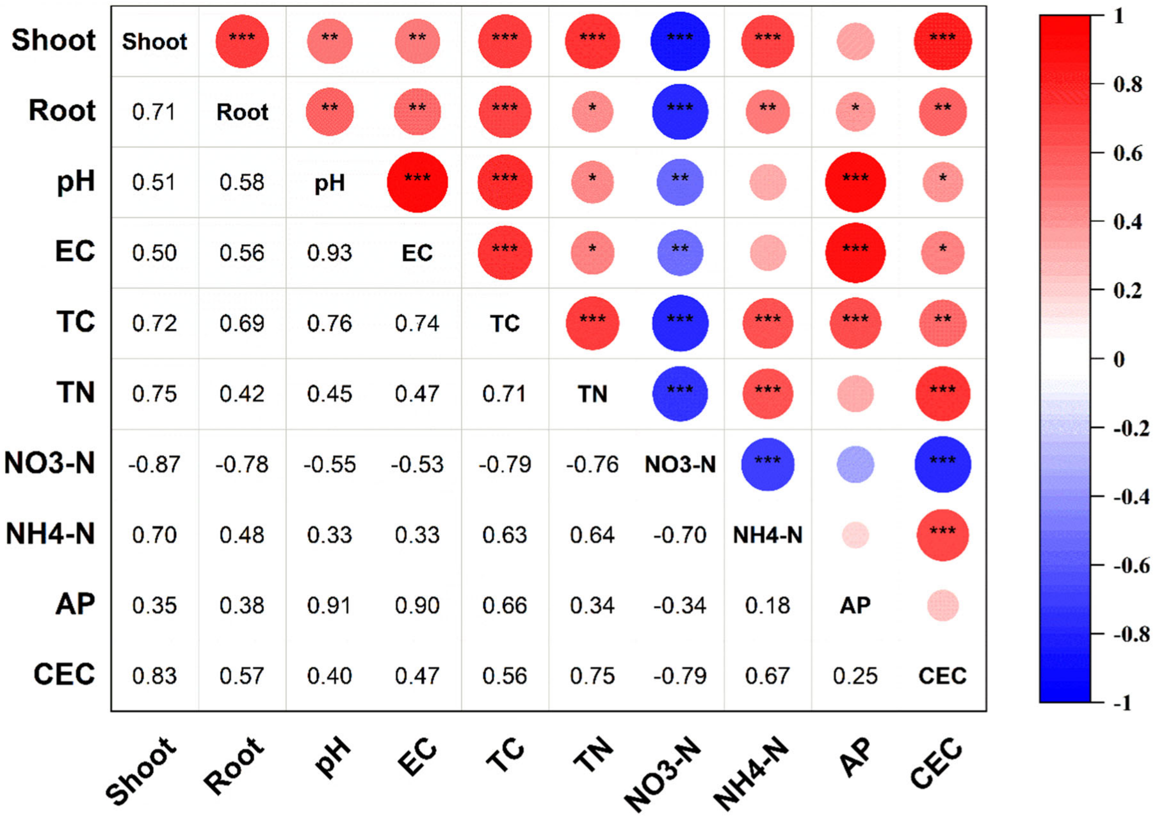


FIGURE 5 Soil total nitrogen (a), available phosphorus (b), ammonium-nitrogen (c), and nitrate-nitrogen (d) as influenced by water hyacinth biochar pyrolysis temperature and rate of applications after maize harvest. Values are presented as means ± standard deviations ($n = 4$). Distinct letters on the bars in each figure designated significant differences in the data points at $p < 0.05$. WHB350, WHB550 and WHB750 water hyacinth biochars prepared at 350°C, 550°C and 750°C.

Given that herbaceous feedstock increases crop production, using it to prepare biochar was advised (Singh et al., 2022). However, the biomass response of maize towards the addition of WHB varied due to the pyrolysis temperature and the application rate. In this study, higher shoot and root dry biomass was found at the application of lower pyrolysis temperature (350°C and 550°C) biochars which might be attributed to the N and P supply, improved CEC and the lower C/N ratio of the biochar, and enhanced root growth. The primary factor regulating plant growth is nitrogen, and low-temperature prepared biochar had more nitrogen content than high-temperature prepared biochar, its improvements in soil characteristics were greater (Xi et al., 2020). Besides, the rise in soil pH and CEC due to biochar addition may also led to improved crop growth (Peng et al., 2011). Furthermore, it was noted that adding WHB pyrolyzed at 300°C with an increasing rate of application significantly increased soil microbial activity, which in turn enhanced maize growth (Masto et al., 2013). Due to their high nutritional content, low surface area and available carbon biochar developed at a low pyrolysis temperature can boost soil's total microbial biomass and diversity. Furthermore, mesopores, which are important locations for microbial colonization, declined as pyrolysis temperature increased, which resulted in a reduction in the growth of soil microbial biomass (Trigo et al., 2016). In line with the current study, maize shoot dry weight was found to be higher with the addition of Eucalyptus biochar developed at a lower temperature (300°C) biochar compared to the higher temperature (800°C) biochar (Butnan et al., 2015). It was also reported that the application of WHB produced at 300°C at a rate of 20 g kg^{-1} improved the seed vigor index of maize by 62% over the



	Shoot	Root	pH	EC	TC	TN	NO3-N	NH4-N	AP	CEC
Shoot	Shoot	***	**	**	***	***	***	***		***
Root	0.71	Root	**	**	***	*	***	**	*	**
pH	0.51	0.58	pH	***	***	*	**		***	*
EC	0.50	0.56	0.93	EC	***	*	**		***	*
TC	0.72	0.69	0.76	0.74	TC	***	***	***	***	**
TN	0.75	0.42	0.45	0.47	0.71	TN	***	***		***
NO3-N	-0.87	-0.78	-0.55	-0.53	-0.79	-0.76	NO3-N	***		***
NH4-N	0.70	0.48	0.33	0.33	0.63	0.64	-0.70	NH4-N		***
AP	0.35	0.38	0.91	0.90	0.66	0.34	-0.34	0.18	AP	
CEC	0.83	0.57	0.40	0.47	0.56	0.75	-0.79	0.67	0.25	CEC

FIGURE 6 Pearson correlation heatmap of maize dry biomass with soil properties and among soil properties. correlation is significant at *$p < 0.05$, **$p < 0.01$ and ***$p < 0.001$. AP, available phosphorus; CEC, cation exchange capacity; EC, electrical conductivity; NH_4-N, ammonium-nitrogen; NO_3-N, nitrate-nitrogen; TC, total carbon; TN, total nitrogen.

biochar unamended treatment (Masto et al., 2013). Similarly, biochar derived from wheat straw at a temperature of 300°C improved maize shoot and root dry biomass by 36% and 38%, respectively, whereas rice straw biochar pyrolyzed at 500°C diminished maize shoot and root biomass yield by 18% over the control (Naeem et al., 2017). Moreover, biochar developed from poultry manure at low pyrolysis temperatures (300–350°C) was reported to be better for improving lettuce growth (Gunes et al., 2015). In consonant with the results of the current study, the dry matter of wheat was significantly improved due to the application of date palm biochar prepared at 300°C and 400°C, but the impact of high temperature (500°C and 600°C) biochar was insignificant compared to the control in alkaline soil (Alotaibi & Schoenau, 2019). According to Raj et al. (2021), it was suggested that 350°C be the ideal temperature for pyrolysis to produce biochar with balanced properties for plant growth.

Among the pyrolysis temperatures applied, lower shoot and root dry biomass of maize was recorded in biochar produced at higher pyrolysis temperature (750°C), and the control, although the dry biomass of maize obtained due application of WHB750 at 20 t ha^{-1} was significantly higher than the control (Figure 2). As indicated in Table 1, the SSA and total porosity of WHB750 were higher than the other biochars that could adsorb much water making it difficult for plant roots to absorb water and nutrients. In addition, the higher EC and ash content of WHB750 could pose negative impacts on the plant development. This finding was corroborated by Olszyk et al. (2020), where a decrease in sweet corn dried shoot and root weights was reported due to the application of biochar generated at 700°C. The negative impacts of high temperature (>600°C) biochar on crop yields might have been due to the strong adsorption of water and dissolved minerals causing a shortage of available water and minerals to the plants (Li et al., 2019). Moreover, free radical-induced oxidative damage may be the primary cause of the phytotoxicity of rice straw biochar produced at 500°C and 800°C on maize seedlings (Bai et al., 2022). In addition, polycyclic aromatic hydrocarbons and high ash levels generated from high-temperature biochar impaired corn development (Butnan et al., 2015). Consequently, it may be concluded that using biochar derived from WH at a higher pyrolysis temperature (750°C) might not provide the expected positive impacts on maize growth.

Regardless of the pyrolysis temperature, the addition of WHB at a higher rate (20 t ha^{-1}) improved the dry biomass of maize (Figure 2). In consonant with this study, the addition of a higher rate (15 g kg^{-1} wt/wt; equivalent to 30 t ha^{-1}) of tomato waste biochar provided better shoot and root development of sweet corn (Smider & Singh, 2014). Furthermore, soil fertility and production were significantly improved by applying crop straw biochar, and these effects grew when application rates were raised (Zhao et al., 2014).

The impacts of biochar on crop growth and nutrition are dependent on the amounts supplied (Lehmann et al., 2003).

The addition of WHB, particularly produced at low temperatures, improved maize plant height, chlorophyll content, stem diameter and leaf area (Figure 3a–d). The improvement of maize growth parameters was in parallel with plant dry biomass. In line with our result, taller plant height, longer roots, vigorous leaves and stems and larger leaf area were found due to the incorporation of biochar prepared at 400°C than the application of 800°C biochar (Xi et al., 2020). Similarly, Calcan et al. (2022) reported that the addition of biochar developed from vine pruning residue that was slowly pyrolyzed at about 517°C improved tomato plant height, number of leaves and plant collar diameter. Moreover, the addition of willow biochar pyrolyzed at a temperature of 500°C and incorporated at a 10 g kg^{-1} (equivalent to 20 t ha^{-1}) rate significantly improved maize leaf chlorophyll content, but the effect on maize plant height was insignificant (Agegnehu et al., 2015). Furthermore, applying biochar (15.75–31.5 t ha^{-1}) increased the chlorophyll content in maize leaves, which subsequently increased maize yield (Cong et al., 2023). When biochar is used, plant growth and yield increases are ascribed to the optimization of plant nutrient availability (Amin, 2018; Lehmann et al., 2003). Therefore, for maize production, the application of WHB at a rate of 20 t ha^{-1} prepared at a pyrolysis temperature of ≤550°C could be suggested.

4.2 | Postharvest soil chemical properties

Both pyrolysis temperature and addition rate of WHB and their interaction significantly affected the soil pH and EC (Table 2). The rise in pH of the soil used in this study might be attributed to the liming effect of the biochar. An increase in pyrolysis temperature showed an increase in the liming capacity of the biochar as $CaCO_3$ equivalence (Table 1). It was reported that the ability of biochar to neutralize soil acidity was enhanced by higher pyrolysis temperature, regardless of the feedstock type (Pariyar et al., 2020). In line with the results of the current study, the pH of the soil was more affected by the biochars generated at 500°C than those produced at lower temperatures (Luo et al., 2014). Research by Deng et al. (2022) revealed that the application of wheel wingnut-based biochar increased soil pH in parallel with growing the pyrolysis temperature from 300°C to 700°C. In agreement with the results of the current study, Hass et al. (2012) also reported that the effect of biochar on soil pH increased with increasing biochar pyrolysis temperature from 350°C to 700°C and application rate of 10–40 g kg^{-1}. Similarly, the EC of the soil was improved as the temperature for pyrolysis and application rate of biochar increased (Figure 4b). Soil pH showed a positive significant correlation with EC (Figure 6). The increase in EC value with increasing pyrolysis temperature and application rate might be attributed to the enhanced level of ash content and EC of the biochar applied to the soil (Table 1). Khadem et al. (2021) reported that since biochar ash contains water-soluble basic cation, it is essential for raising soil EC. The increase in soil EC due to increasing pyrolysis temperature and application of biochar was in agreement with earlier studies (Khadem et al., 2021; Laghari et al., 2015). Therefore, the application of WHB (20 t ha^{-1}) derived in high pyrolysis temperatures (550–750°C) might be suitable for soil acidity amendment.

The application of WHB positively impacted the level of soil TC (Figure 4c). Applying biochar to the soil can boost the soil's organic C status by adding a substantial amount of organic C (Kätterer et al., 2019). However, only the rate of WHB addition induced a significant main effect on soil TC (Table 2). The improved level of TC in the soil might be ascribed to the addition of C from the biochar and the subsequent higher rate of application. Consistent with the findings of this study, soil organic C significantly increased when biochar application rates were raised (Bista et al., 2019; Laghari et al., 2015; Macdonald et al., 2014). Previous studies (Deng et al., 2022; Luo et al., 2014) also reported that adding biochar into the soil significantly improved soil C status. Thus, applying WHB could help improve soil C through carbon sequestration. Similarly, the addition of WHB significantly enhanced soil CEC (Figure 4d). Particularly, biochar generated at low temperatures (350–550°C) significantly improved soil CEC at 20 t ha^{-1} rate of application. An increase in soil CEC might be ascribed to the relatively high CEC of the added biochar pyrolyzed at 350°C and 550°C (Table 1). In consonant with the current study results, the application of date palm biochar pyrolyzed at 300°C resulted in a 43.7% and 27.7% increase in soil CEC over the control and the high temperature (600°C) biochar-treated soils (Alotaibi & Schoenau, 2019). It was also noted that the application of sewage sludge biochar pyrolyzed at 300°C enhanced the soil's CEC of maize fields compared to the higher-temperature biochar (Fachini et al., 2021). According to Pariyar et al. (2020), biochar produced at lower temperatures was favoured for retaining soil nutrients through enhanced CEC. In addition, the low-temperature biochar product, which has been pyrolyzed at temperatures between 400°C and 500°C, had its main advantage in increasing soil CEC (Tomczyk et al., 2020). In comparison to biochar formed at high temperatures, those produced at lower temperatures may likely have more organic functional groups of COOH and C-OH, increasing sites for nutrient retention (Ippolito et al., 2012). Therefore, in low CEC soils application of low-temperature WHB might be a sustainable management option.

Biochar from WH obtained at 350°C and 550°C of pyrolysis temperatures were found better in improving soil TN when applied at a higher application rate (Figure 5a). The higher TN in soils treated with low temperature (350°C and 550°C) WHBs might be associated with the relatively higher TN in the biochars (Table 1). There were also reports of close correlations between the soil's TN and the TN of the biochar applied (Luo et al., 2014). In agreement with this result, among the range of pyrolysis temperatures (400–800°C) of pine sawdust biochar, the addition of the biochar pyrolyzed at 400°C raised the soil TN by 20% compared to the other biochar developed at 800°C and the control (Laghari et al., 2016). Thus, the use of biochar prepared at low temperatures could be a useful method to reduce nitrogen losses (Gao et al., 2019).

With increasing the pyrolysis temperature and application rate of WHB the availability of phosphorus in the soil was improved (Figure 5b). The increased availability of phosphorus might be attributed to the increased level of phosphorus in the biochar (Table 1); and the improvement of soil pH when biochar pyrolysis temperature and application rate increased. Soil pH and P_{av} were significantly positively correlated ($r = 0.91$, $p < 0.001$). It has been reported that soluble PO_4^{-3} can be supplied directly from the biochar (Gundale & DeLuca, 2006). Consistent with this result greater increases in soil available P were observed with biochars prepared at higher temperatures (Luo et al., 2014). In agreement with this study, increasing the pyrolysis temperature of biochar produced from poultry manure exhibited an increasing trend of P_{av} in the soil (Gunes et al., 2015). Likewise, the addition of wheel wingnut-based biochar pyrolyzed within a range of temperatures of 300–700°C enhanced the availability of phosphorus in the soil by 20.2%–79.4%, respectively, compared to the nonbiochar amended soil. Thus, it can be suggested that WHB could be used as a source of plant-available P in maize production.

The incorporation of WHB significantly enhanced the retention of NH_4^+-N in the soil (Figure 5c). Low-temperature (350°C and 550°C) WHB-treated soils showed an enhanced effect of ammonium retention in the soil at a higher application rate of 20 t ha^{-1}. Consistent with this finding, the addition of wheat straw biochar improved the retention of NH_4^+-N, although NH_4^+-N retention declined with increasing pyrolysis temperature of the biochar (Cheng et al., 2017). At pyrolysis temperatures below 400°C, biochars adsorbed more NH_4^+ than biochar derived at higher temperatures (Zheng et al., 2013). However, NO_3^--N level in the soil was significantly lower in the biochar-amended soils and was found to be higher in the control soil (Figure 5d). The NO_3^--N level and plant biomass were found significantly negatively correlated ($r = -0.87$ and -0.78, $p < 0.001$; Figure 6), which might indicate higher NO_3^--N uptake by the plant in WHB amended soils. The addition of lower temperature (350°C and 550°C) WHBs at 20 t ha^{-1} might enhance the uptake of NO_3^--N by the plant. Moreover, under natural field circumstances, the comparatively higher NO_3^--N present in the control and the lower rate of biochar treated soils, the NO_3^--N might be lost through leaching or denitrification. Consistent with the results of the current study, because of improved crop growth and increased NO_3^--N uptake, soil NO_3^--N levels fell as biochar application rates increased (Bista et al., 2019). Calcan et al. (2022) also showed that the level of NO_3^--N in nonbiochar amended soils was greater by two to six times than biochar amended soils. This could be associated with plant uptake of more NO_3^--N in biochar-treated soils. Maize shoot biomass has shown a significant correlation with maize plant NO_3^--N concentrations (Agegnehu et al., 2015). Thus, the addition of WHB, particularly produced at lower temperatures could help in increasing plant uptake of soil nitrate.

5 | CONCLUSION

The findings of this study revealed that the pyrolysis temperature at which the water hyacinth biochar was produced as well as the application rates added to Nitisol had a substantial impact on maize growth and the soil properties. The application of water hyacinth biochar resulted in greater maize shoot and root growth than the nonbiochar treated control. It was discovered that water hyacinth biochar pyrolyzed at 350°C and 550°C were superior for enhancing maize growth due to improved soil conditions and enhanced nutrient uptake. Similarly, adding WHB pyrolyzed at 350°C and 550°C improved the characteristics of the soil, such as TN, TC, NH_4^+-N and CEC. The addition of WHB prepared at 550°C and 750°C also relatively improved the soil's pH and EC. Moreover, the availability of soil P was enhanced due to the application of WHB, particularly, with the addition of the biochar prepared at 750°C. Despite being limited to a short-term pot experiment, the findings of the study provide valuable insights into the management of WH by converting this highly proliferating aquatic weed into biochar under different pyrolysis temperatures, which may then be applied as soil management for improving soil fertility, plant growth and yield. Therefore, to fully evaluate the agronomic and soil effects of using water hyacinth biochar, further research involving field conditions over the years under different pyrolysis temperatures, rates of application and soil types should be conducted.

AUTHOR CONTRIBUTIONS

Ashenafei Gezahegn: Conceptualization; methodology; data acquisition; data analysis; data interpretation; writing—original draft; writing—review and editing. **Yihenew G. Selassie**: Conceptualization; methodology; supervision; writing—review and editing; final approval. **Getachew Agegnehu:** Conceptualization; methodology; supervision; writing—review and editing; final approval. **Solomon Addisu**: Conceptualization; methodology; supervision; funding acquisition; writing—review and editing; final approval. **Fekremariam Asargew Mihretie**: Conceptualization; methodology; writing—review and editing. **Yudai Kohira**: Methodology; data analysis; writing—review and editing. **Mekuanint Lewoyehu:** Methodology; data analysis; writing—review and editing. **Shinjiro Sato**: Conceptualization; methodology; funding acquisition; writing—review and editing; final approval.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data of this work can be obtained from the corresponding author upon reasonable request.

ETHICS STATEMENT

The authors attest to their adherence to the journal's ethical policy.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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