Journal of Agriculture and Food Research 21 (2025) 101939

Contents lists available at ScienceDirect

Journal of Agriculture and Food Research

journal homepage: www.sciencedirect.com/journal/journal-of-agriculture-and-food-research

Synergistic effects of aquatic weed biochar and inorganic fertilizer on soil properties, maize yield, and nitrogen use efficiency on Nitisols of Northwestern Ethiopian Highlands

Ashenafei Gezahegn [a,b,*], Yihenew G. Selassie [a,c], Getachew Agegnehu [d], Solomon Addisu [a], Fekremariam Asargew Mihretie [e], Yudai Kohira [f], Mekuanint Lewoyehu [f,g], Shinjiro Sato [f]

[a] Department of Natural Resources Management, Bahir Dar University, Bahir Dar, P.O.Box 79, Ethiopia
[b] Department of Natural Resources Management, College of Agriculture and Environmental Sciences, Debark University, Debark, P.O.Box 90, Ethiopia
[c] Stichting Wageningen Research Ethiopia, Wageningen University and Research, Bahir Dar, Ethiopia
[d] International Crops Research Institute for the Semi-Arid Tropics, Addis Ababa, Ethiopia
[e] Agriculture and Food, CSIRO, Black Mountain, 2-40 Clunies Ross Street, Acton ACT 2601, Australia
[f] Graduate School of Science & Engineering, Soka University, 1-236 Tangi-Machi, Hachioji, Tokyo, 192-8577, Japan
[g] Department of Chemistry, Bahir Dar University, Bahir Dar, P.O.Box 79, Ethiopia

A R T I C L E I N F O

Keywords:
Agronomic efficiency
Artificial fertilizer
Biochar
Crop yield
Soil acidity
Water hyacinth

A B S T R A C T

Soil acidity and poor fertility limit crop production in Ethiopia. Biochar from organic wastes, such as water hyacinth (*Eichhornia crassipes*), offers a potential solution. This study investigated the effects of co-applying water hyacinth biochar (WHB) with inorganic fertilizers on soil characteristics, maize yield, and nitrogen (N) use efficiency under field conditions. Four rates of WHB (0, 5, 10, and 20 t ha^{-1}) were combined with two levels of recommended inorganic fertilizers (half and full rates of 180/138 kg N/P_2O_5 ha^{-1}), plus a control (no biochar/fertilizer), during the 2022 and 2023 growing seasons. Results indicated that WHB significantly improved soil physicochemical properties ($p < 0.05$), across fertilizer rates, demonstrating both additive and independent effects. Consequently, WHB application reduced bulk density, increased porosity, and soil pH, and decreased exchangeable acidity and exchangeable Al^{3+}, with the 20 t ha^{-1} WHB rate eliminating exchangeable Al^{3+}. Moreover, available phosphorus, organic carbon, total nitrogen, cation exchange capacity, and exchangeable potassium were significantly improved ($p < 0.05$). Co-applying WHB with half and full rates of chemical fertilizers enhanced maize grain yield by 33.6 % and 30.8 %, respectively, compared to sole half and full fertilizer rates (non-biochar), with yield increases of up to 10 % in the second year compared to the first. Maize total biomass and 1000-grain weight also showed significant improvements. Nitrogen use efficiency significantly improved, especially when WHB was used with half the fertilizer level. These findings demonstrate the potential of combining WHB with inorganic fertilizers to improve soil fertility and enhance crop production in acidic soils.

1. Introduction

In a region experiencing food insecurity, land degradation is occurring in Sub-Saharan Africa (SSA) amid a growing population and declining climate conditions [1]. Land degradation is a major obstacle to agricultural production, contributing to the ongoing cycle of poverty [2]. Agricultural productivity is severely limited by inadequate soil fertility in SSA [3]. Soil degradation has forced smallholder farmers to confront challenges related to low nutrient use efficiency and limited access to essential nutrients, particularly nitrogen (N) [4]. The reduced capacity of soil to sustain production and provide environmental services is driven by poor management practices that diminish the physicochemical and biological quality of soil in cropping systems [5]. Unsustainable soil management is a significant factor affecting the productive potential of agricultural land in SSA [1]. In SSA, soil acidification and the resulting insufficient availability of nutrients pose major obstacles to agricultural outputs [6].

The Ethiopian economy is primarily based on agriculture, with 85 % of the population relying on farming [7]. However, concerns about the agricultural sector's capacity to feed the expanding population have

* Corresponding author. Department of Natural Resources Management, Bahir Dar University, Bahir Dar, Ethiopia.
E-mail address: ashenafigezahegn@gmail.com (A. Gezahegn).

https://doi.org/10.1016/j.jafr.2025.101939
Received 10 March 2025; Received in revised form 14 April 2025; Accepted 21 April 2025
Available online 22 April 2025

grown due to soil fertility depletion, declining land holdings, and an increasingly variable environment [8]. One major issue affecting agricultural productivity is soil acidity, especially in highland areas with heavy rainfall [6]. Soil acidity affects more than 43 % of Ethiopian farmland, with approximately 28.1 % classified as strongly acidic (pH 4.1–5.5) [9]. This results in poor crop yields and production losses ranging from 20 % to 80 %, depending on the level of acidity, agronomic practices, and agroecological conditions [10]. Nevertheless, integrated soil and crop management techniques and liming can help reduce soil acidity [6]. However, lime is expensive and has a short-term impact, leading to infrequent applications [11]. Although research on biochar in Ethiopia is limited, its application with mineral fertilizers has positively affected soil acidity, enhanced fertility, and improved crop yields [12–14].

The carbon-rich material known as biochar is produced by thermally burning organic feedstock in a low-oxygen environment [15]. Due to its agricultural advantages, biochar has attracted increased attention [16]. Research on using biochar as a soil amendment is essential for ensuring the stability of the global food supply [17]. The application of biochar sequesters carbon (C) and enhances soil quality by neutralizing soil acidity, raising cation exchange capacity (CEC), and boosting microbial function [18]. Applying biochar to acidic soils increases nutrient availability, as most biochar types produced have an alkaline pH [19]. Furthermore, combining biochar with mineral fertilizer can enhance crop yield by up to 15 % [20]. Additionally, it increases crop yields by 14 % in acidic soils due to its liming effect and improved water-holding capacity [21].

Various organic wastes, including aquatic plants like water hyacinth (*Eichhornia crassipes*), can be used as feedstock to produce biochar. In Lake Tana, Ethiopia, water hyacinth has been abundant since its occurrence in 2011 [22]. Efforts to control water hyacinth have involved an investment of approximately USD 3.2 million and nearly 800,000 laborers. However, these measures have not effectively eradicated the weed [23]. The infestation has caused significant ecological, social, and economic repercussions [24]. Additionally, disposing of the harvested water hyacinth biomass has posed a major challenge in managing the weed infestation [25]. Thus, producing biochar from water hyacinths could positively impact the environment by aiding in weed control and serving as a soil amendment in agriculture [26].

The high pH, liming capacity, CEC, low C/N ratio, and high nutrient availability of water hyacinth biochar (WHB) make it a potential ameliorant for acidic soils [27,28]. Several pot and incubation studies have reported that WHB positively impacts plant growth and soil physicochemical properties. Masto, Kumar [29] noted that applying WHB promotes the development of maize seedlings. Jutakanoke, Intaravicha [30] also found that adding WHB increased the pH of acidic soil by 2.84 units compared to the control, thereby enhancing the growth of water convolvulus. Since WHB is highly hydrophilic, its application improves the soil's water retention capacity [31]. Accordingly, adding WHB at 5 % and 10 % to silty sand soil increased water retention while reducing infiltration and cracking potential [32]. Furthermore, combining WHB with organic fertilizers improved soil physical quality and barley growth [33]. A pot experiment by Gezahegn [34] demonstrated that applying WHB, developed at various pyrolysis temperatures, at rates of 5 and 20 t ha^{-1} significantly enhanced maize growth and soil characteristics.

Yet, a field-based WHB experiment has not been extensively studied [35]. A long-term field trial is crucial for understanding how the application of WHB with inorganic fertilizer impacts soil characteristics, crop productivity, and nutrient use efficiency in low-fertility and acid-affected regions, such as the Northwestern Highlands of Ethiopia. Therefore, this study aimed to examine the synergistic effects of WHB and inorganic fertilizers on maize yield, N use efficiency, and soil properties under field conditions over two consecutive cropping seasons.

2. Materials and methods

2.1. Production of biochar

Biochar for this field trial was developed from water hyacinth. Dried biomass of water hyacinth was collected at the shore of Lake Tana, Ethiopia (12°07′12″ N, 37°36′54″ E), and a local method of biochar preparation was used (Fig. 1). A pile was formed and covered with Teff (*Eragrostis tef* [Zucc.] Trotter) straw. Soil was then applied over the straw to limit air exposure during charring. A small opening near the ground allowed the biomass stack to ignite and was left covered to pyrolyze until the smoke changed to blue, indicating complete carbonization. After removing the soil and straw cover, water was immediately sprinkled to stop further combustion. The duration of carbonization was approximately 30–40 min. The biochar was air-dried, and partially carbonized pieces were removed. Finally, the dried biochar was crushed and sifted through a 4-mm sieve for soil application.

2.2. Field experiment

2.2.1. Experimental site description

A two-year field experiment was undertaken in the Upper Blue Nile Basin at the Koga irrigation scheme in Merawi, specifically at Ambomesek (11°24′32″ N, 37°05′04″ E), Northwest Ethiopia, during the major cropping seasons of 2022 and 2023. This area falls within the Woina Dega agroecological zone at an elevation of 1800 to 2400 m above sea level (Fig. 2). The soil type is classified as Luvic Nitisols [36]. The region experiences unimodal rainfall, with the peak occurring from June to September based on long-term monthly rainfall patterns and air temperature at the research location (Fig. 3).

2.2.2. Experimental design

The experiment utilized a factorial design with four rates of WHB (0, 5, 10, and 20 t ha^{-1}) combined with two levels of inorganic fertilizer (half and full of the recommended rate). A control group (no biochar or fertilizer) was also included to calculate the N agronomic efficiency. In the study area, 180 kg of nitrogen (N) ha^{-1} as urea and 138 kg of phosphorus (P_2O_5) ha^{-1} as blended NPSB were the recommended rates for maize production (Amhara Agricultural Research Institute). The plots were set up in a randomized complete block design with triplicates, using plots measuring 9 m^2 (2.4 m wide and 3.75 m long). The spacing between blocks was 1.5 m, while the spacing within plots was 1 m. The trial land was plowed with oxen-driven plows three times before sowing. Biochar was manually applied in the first experimental season only, three weeks before maize planting, at a soil depth of approximately 15 cm. Fertilizers were applied each season, with all phosphorus fertilizer added at sowing and urea applied twice: the first half was applied at planting and the remaining half was applied after 45 days of maize emergence. The maize (*Zea mays* L.) variety used was BH546, planted with an inter-row spacing of 75 cm and intra-row spacing of 30 cm.

2.3. Biochar and soil analysis

2.3.1. Biochar

The electrical conductivity and pH of the biochar were determined using a 1:10 ratio of biochar (g) to distilled water (mL) suspension [37]. The biochar's total carbon (TC) and total nitrogen (TN) were determined with a CHN analyzer. The biochar's available phosphorus (P) was measured after a 2 % formic acid extraction using an autoanalyzer [38]. The ammonium acetate technique was employed to determine the CEC. The ASTM method D1762-84 was used to analyze the amount of ash in the biochar. The Brunauer, Emmett, and Teller (BET) method [39] was adopted to determine the specific surface area and porosity of the biochar. This was accomplished using nitrogen gas adsorption-desorption isotherms at 77 K, utilizing an Accelerated Surface Area and Porosimetry (ASAP) system (ASAP 2010, Micrometrics, USA). A scanning

Fig. 1. Water hyacinth biochar preparation (a) water hyacinth biomass collection, (b) covering up the weed biomass with teff straw and soil, (c) carbonization process of the biomass, and (d) sieved biochar prepared for field application.

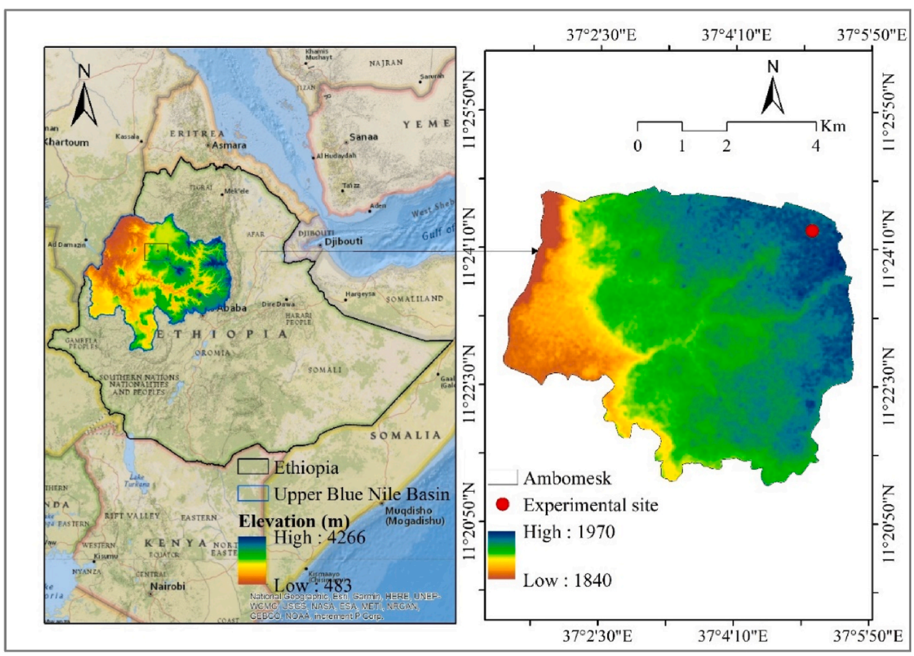

Fig. 2. Map of the research area (Ambomesk) in the Koga Irrigation scheme, Upper Blue Nile Basin, Ethiopia.

electron microscope (SEM) (JEOL, JSM-5600LV, USA) was used to examine surface morphology and structural imaging. The IRAffinity-1S Fourier Transform Infrared Spectroscopy (FTIR) equipment (Shimadzu, Japan) was utilized to obtain the spectrum readings. Using an average of 64 scans, infrared absorbance data were gathered for wavenumbers 400–4000 cm^{-1} at a spectral resolution of 2 cm^{-1} [40].

2.3.2. Soil

Before planting, composite soil samples (n = 3) were collected from a 15 cm depth at the experimental location. Following crop harvest, further samples were taken from every plot, dried in the air, crushed, and passed through a 2-mm mesh. Bulk density was calculated using the gravimetric method with oven-dried soil samples collected using core samplers [41]. Total porosity was determined using the soil's bulk density and standard particle density (2.65 g cm^3), following the equation (Eqn. (1)) described in Guo, Qian [42]:

$$\text{Porosity } (\%) = (1 - (\text{Soil bulk density} / \text{Soil particle density}))*100 \quad (1)$$

Soil pH was determined using a 1:2.5 soil (g) to distilled water (ml) suspension [43]. Soil organic carbon (SOC) was assessed via a wet digestion technique [44], TN was measured using the Kjeldahl method [45], and available P was measured using the Bray II method [46]. The CEC and exchangeable potassium (K) were measured with ammonium acetate at pH 7 [47]. Exchangeable acidity and exchangeable Al^{3+} were determined by soaking sample soils with 1 N KCl and titrating with 0.02 N NaOH and 0.002 N HCl, as per Rowell [48]. Key physicochemical characteristics of the WHB and experimental soil are described in Table 1.

2.4. Crop data collection

Maize was harvested at physiological maturity, and data were

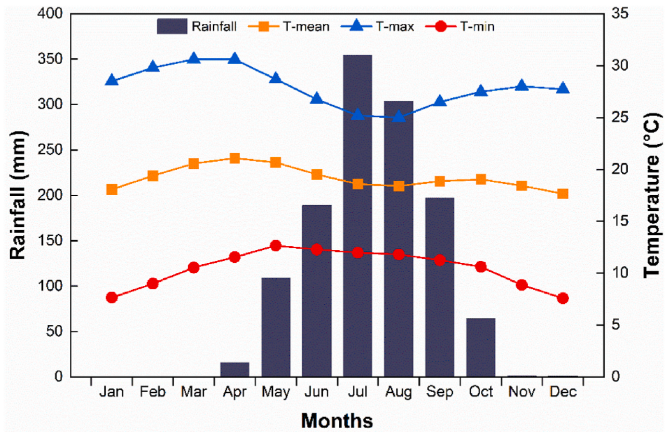

Fig. 3. The research area's long-term (2000–2023) average monthly rainfall, average temperature (T-mean), maximum temperature (T-max), and lowest temperature (T-min).

Table 1
Mean values of basic physicochemical properties of the experimental soil and water hyacinth biochar.

Parameters	Units	Soil	Biochar
Texture class	–	Clay	–
Sand	%	13.7	–
Silt	%	32.1	–
Clay	%	54.2	–
Bulk density	g cm^{-3}	1.28	–
pH (H_2O)	–	4.83	10.3
Electrical conductivity	dS m^{-1}	–	11.5
Total carbon	%	–	34.7
Organic carbon	%	1.88	19.8
Total nitrogen	%	0.212	0.733
Available phosphorus	mg kg^{-1}	6.92	1.21×10^3
Cation exchange capacity	cmol$_{(+)}$ kg^{-1}	23.3	35.7
Exchangeable potassium	cmol$_{(+)}$ kg^{-1}	0.641	–
Ash content	%	–	40.1
Liming capacity	% CCE	–	20.3
Specific surface area	cm^2 g^{-1}	–	14.7
Total pore volume	cm^3 g^{-1}	–	0.0394

CCE: calcium carbonate equivalence.

gathered from the net plot area. Dry biomass was measured with a balance, followed by threshing and weighing the grain. The moisture level of the grain yield was adjusted to 12.5 % after measuring seed moisture with a sensor. The 1000-grain weight (TGW) was measured from randomly selected grains using a balance. The grain harvest index was calculated using Eqn. (2), detailed below.

$$\text{Harvest index (\%)} = (\text{Grain yield} / \text{Biomass yield}) * 100 \tag{2}$$

The N use efficiency was computed by using the agronomic efficiency (AE) formula (Fageria & Baligar, 2005) described below in Eqn. (3).

$$\text{Agronomic efficiency (AE)(kg/kg)} = (\text{GYf} - \text{GYu}) / \text{Na} \tag{3}$$

GYf, GYu, and Na are the grain yield (kg) of fertilized plots, non-fertilized plots, and the amount of N applied as a chemical fertilizer, respectively.

2.5. Data analysis

The data collected over two years were analyzed using analysis of variance (ANOVA) with the general linear model (GLM) of SAS version 9.4 (SAS Institute, Cary, NC). The Shapiro-Wilk normality test was used to assess the normal distribution of the data before analysis. A two-way ANOVA was performed at $p < 0.05$ to evaluate variance across treatments based on biochar and fertilizer rates. Fisher's Least Significant Difference (LSD) separated means at $p < 0.05$ after ANOVA for statistically significant results. Crop data from each growing season were analyzed independently before averaging. A paired sample *t*-test was used to evaluate differences in soil properties within treatments over the two years. Figures were produced using OriginPro 2024 (OriginLab, USA).

3. Results

3.1. Characteristics of water hyacinth biochar and soil before planting

3.1.1. Biochar characteristics

The WHB exhibited a high pH of 10.3, indicating a strongly alkaline nature, supported by its high electrical conductivity of 11.5 mS cm^{-1} (Table 1). Elemental analysis revealed a TC content of 34.7 %, with organic C comprising 19.8 % of the total and the remaining 14.9 % consisting of the inorganic C associated with carbonates and oxides. The TN content was 0.73 %, and the available P was 1.21 g kg^{-1}. The CEC of the biochar was 35.7 cmol$_c$ kg^{-1}, indicating a significant ability to retain essential nutrients. The specific surface area was 14.6 cm^2 g^{-1}, and the total porosity was 0.039 cm^3 g^{-1}, confirming the biochar's potential for enhancing soil properties. Additionally, the SEM analysis of the biochar displayed a highly porous structure (Fig. 4).

Based on the spectral bands and peaks of the biochar (Fig. 5), the wide band observed around 3784 cm^{-1} is likely due to the stretching of the hydroxyl (O—H) group [49]. A smaller band near 2349 cm^{-1} might be related to the stretching vibration of the C ≡ N groups in nitriles [28]. The peak intensity of the band at 1613 cm^{-1} is associated with vinyl ethers of both aromatic C=C and C=O bonds [50,51]. At the peak of 1432 cm^{-1}, the functional group was identified as the bending of in-plane C—O—H [50]. The peak at 1317 cm^{-1} links to the C—H group (Keiluweit et al., 2010). The peak at 1036 cm^{-1} also corresponds to the aromatic C—O group. Further aromatic C—H groups were detected at 874, 713, and 619 cm^{-1}, indicating their presence in the molecular structures [51].

3.1.2. Experimental soil properties

The experimental soil was characterized by heavy clay content, exceeding 50 % (Table 1), [52]. The bulk density was 1.28 g cm^{-3}, with the optimal limit of less than or equal to 1.4 g cm^{-3} necessary for healthy plant development [52]. With a pH of 4.83, the soil is categorized as extremely acidic, suggesting that the soil solution contains harmful aluminum (Al^{3+}) ions [52]. According to Landon [53], the TN level was medium, and the SOC level was low. Available P was also in the lower category [52]. The exchangeable K was classified as high, and the CEC as medium [54].

3.2. Impact of water hyacinth biochar and inorganic fertilizer on soil characteristics

3.2.1. Physical properties

The ANOVA result showed that applying WHB at varying rates significantly affected ($p < 0.01$) all tested soil properties in an additive manner. In contrast, the mineral fertilizer caused a significant ($p < 0.01$) impact only on soil available P in the second growing season. However, no significant interaction effects on soil properties were observed (Table 2).

Applying WHB at diverse rates significantly affected soil bulk density in both growing years ($p < 0.05$; Fig. 6a), with an overall decreasing trend as biochar rates increased. The lowest bulk density values of 1.06 ± 0.09 and 1.08 ± 0.07 g cm^{-3} were recorded with the application of 20 t ha^{-1} biochar in the 2022 and 2023 growing seasons, respectively. Compared to plots without biochar, applying 10 and 20 t ha^{-1} WHB reduced soil bulk density by 8.87 % and 14.5 % in 2022, and by 13.3 % and 15.6 % in 2023. However, applying 5 t ha^{-1} of WHB had no significant effect on soil bulk density compared to the zero-biochar

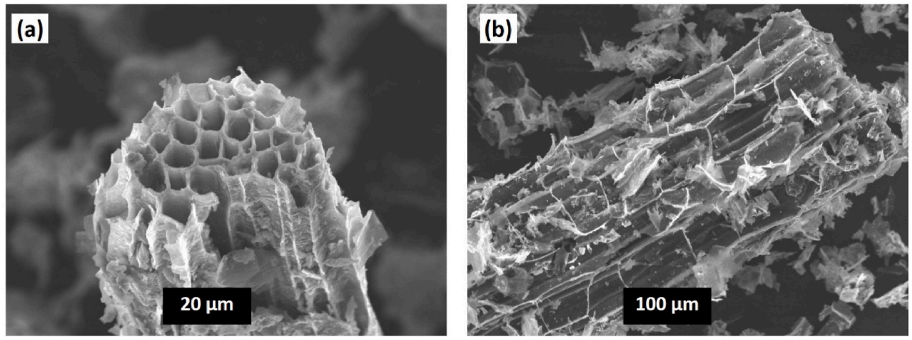

Fig. 4. Surface morphology and structure of water hyacinth biochar, generated at magnification levels of 20 µm (a) and 100 µm (b) using scanning electron microscopy.

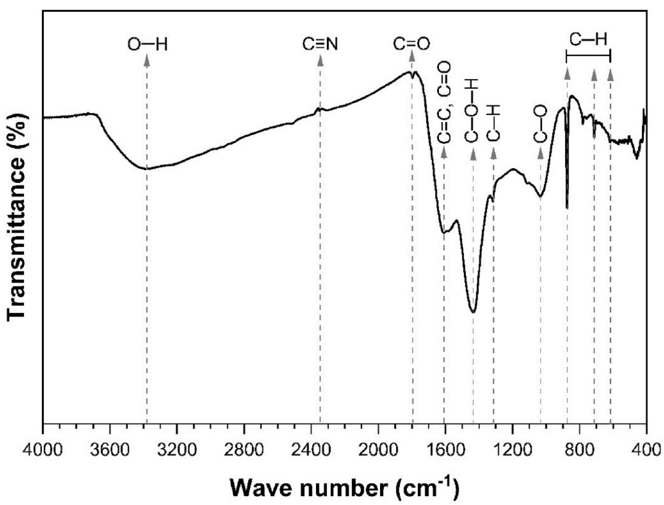

Fig. 5. The FTIR spectral band showcases the characteristic functional groups of water hyacinth biochar.

treatments. Pairwise comparisons revealed no statistically significant differences in bulk density between the two growing seasons for the same treatments.

On the other hand, applying WHB significantly enhanced soil total porosity in a linear manner with increasing biochar rates (Fig. 6b). At application levels of 10 and 20 t ha^{-1}, soil porosity was improved by 7.88 %–12.8 %, respectively, in the first growing period and 13.0 %–14.6 %, in the second year. Although the addition of 5 t ha^{-1} biochar increased soil porosity across all periods, the effect was non-significant. Additionally, the impact of WHB showed no variation in soil porosity across growing periods at the same application rates of biochar.

3.2.2. *Chemical properties*

Applying WHB significantly influenced soil pH, exchangeable acidity, aluminum levels, and available P (Fig. 7). When the WHB rate rose from 0 to 20 t ha^{-1}, soil pH showed a rising trend (Fig. 7a). In the first year, biochar applications at the rates of 5, 10, and 20 t ha^{-1} raised soil pH by 0.3 units (6.25 %), 0.85 units (17.6 %), and 1.16 units (24.0 %), respectively. In the second year, pH increases were 0.17 units (3.61 %), 0.79 units (16.8 %), and 1.1 units (23.4 %), respectively, with the application of the above rates. The effect of WHB on pH significantly varied over the years, with a significant decrease noted in the second year at the 20 t ha^{-1} application rate.

The addition of WHB significantly reduced exchangeable acidity over the two cropping years (Fig. 7b). The highest levels of exchangeable acidity were 3.45 ± 0.25 and 3.92 ± 0.43 cmol$_c$ kg^{-1} in biochar-untreated plots during the first and second years, respectively. Compared to plots treated with no biochar, applying WHB at 5, 10, and 20 t ha^{-1} decreased exchangeable acidity by 26.1 %, 79.4 %, and 92.2 % in the first year, and by 22.4 %, 63.0 %, and 84.2 % in the second year, respectively. The reduction in exchangeable acidity was more pronounced in the first year than in the second. Pairwise comparisons indicated a significant increase ($p < 0.05$) in exchangeable acidity across all biochar treatment rates in the second year over the first.

Applying WHB significantly reduced soil exchangeable Al^{3+} levels ($p < 0.05$; Fig. 7c). As the biochar application rate increased, exchangeable Al^{3+} levels decreased. In the first year, applying WHB at 5, 10, and 20 t ha^{-1} resulted in reductions of exchangeable Al^{3+} by 72.1 %, 100 %, and 100 %, respectively. In the second year, the reductions were 36.9 %, 89.6 %, and 100 %. Pairwise comparisons revealed that, except for the 20 t ha^{-1} application, the effects of other rates varied between years, with exchangeable Al^{3+} levels being higher in the second year than in the first, across treatments.

The use of WHB significantly increased the soil available P ($p < 0.05$; Fig. 7d). The highest P increase was recorded at 20 t ha^{-1} in both growing years. In the first year, applying WHB at 5, 10, and 20 t ha^{-1} resulted in increases of available P increases of 39.2 %, 63.1 %, and 78.0

Table 2
Analysis of variance results examining the effects of WH biochar, fertilizer, and their interaction on soil properties.

Source of variance	2022 Growing Season									
	BD		pH	SOC	TN	Pav	CEC	Ex. K	Ex. Ac	Ex. Al
Fertilizer (F)	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Biochar (B)	0.003	0.003	<0.0001	<0.0001	0.0256	0.0027	<0.0001	<0.0001	<0.0001	<0.0001
F × B	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	2023 Growing Season									
F	ns	ns	ns	ns	ns	0.0051	ns	ns	ns	ns
B	0.006	0.006	<0.0001	<0.0001	0.0046	<0.0001	0.001	<0.0001	<0.0001	<0.0001
F × B	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

BD, bulk density; TP, total porosity; SOC, soil organic carbon; TN, total nitrogen; Pav, available phosphorus; CEC, cation exchange capacity; Ex. K, exchangeable potassium; Ex. Ac, exchangeable acidity; Ex. Al, exchangeable aluminum.

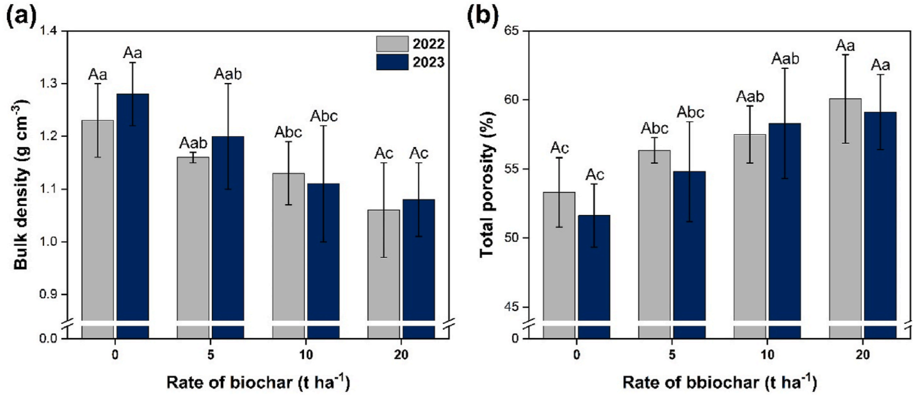

Fig. 6. Effect of water hyacinth biochar on soil bulk density (a) and total porosity (b) (2022–2023). Significant differences between various biochar application rates within the same year are marked with different lowercase letters, while significant differences in the same treatment across different years are designated by different uppercase letters at $p < 0.05$. Error bars represent ±1 standard deviation (SD) of the mean.

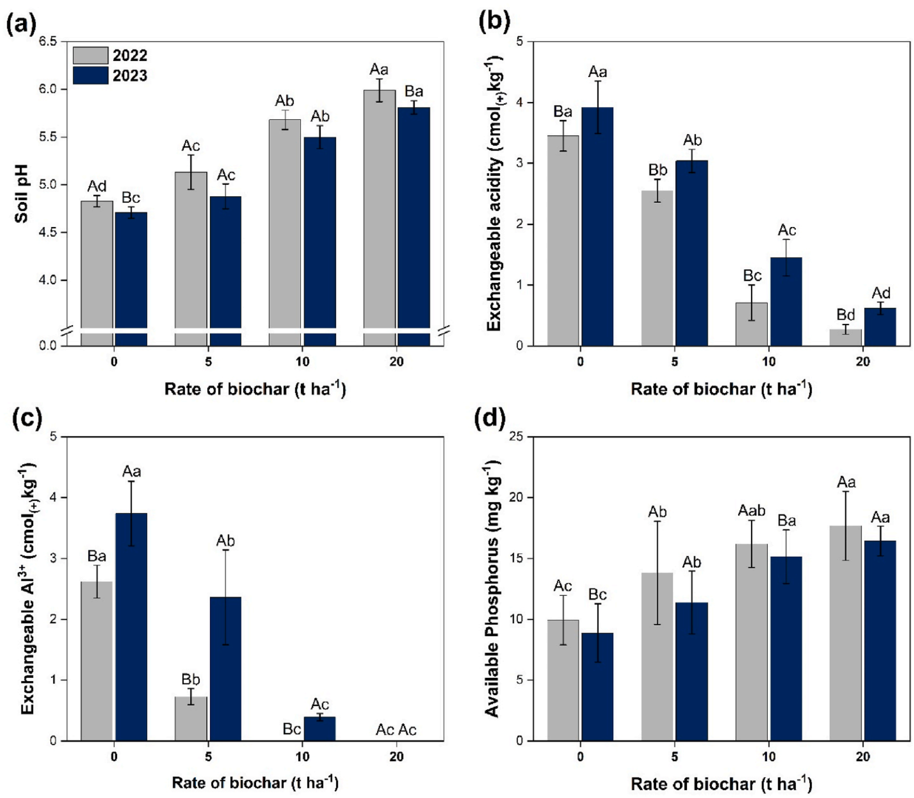

Fig. 7. Effect of WHB on soil pH (a), exchangeable acidity (b), exchangeable Al^{3+} (c), and available phosphorus (d) (2022–2023). Significant differences between various biochar application rates within the same year are marked with different lowercase letters, while significant differences in the same treatment across different years are designated by different uppercase letters at $p < 0.05$. Error bars present ±1 SD of the mean.

%, respectively. In the second year, the increments were 28.3 %, 70.6 %, and 85.1 %, respectively, compared to no biochar-treated plots. Although a decrease in available P was observed between years at the same biochar rates, the variations were not significant.

The application of WHB at different rates significantly increased the SOC levels across the growing years ($p < 0.05$; Fig. 8a). In 2022, compared to biochar-unamended plots, applying WHB at 5, 10, and 20 t ha^{-1} increased SOC by 16.6 %, 42.0 %, and 58.7 %, respectively. In 2023, SOC increases were 23.2 %, 43.5 %, and 59.3 % for the same rates, respectively. While SOC levels increased with higher biochar applications, the SOC content did not significantly differ between years for the same treatments.

The application of WHB significantly influenced soil TN levels ($p < 0.05$; Fig. 8b). Increasing biochar rates notably enhanced soil TN content. Compared to solely fertilized plots, applying WHB at 5, 10, and 20 t ha^{-1} increased soil TN by 8.33 %, 12.7 %, and 18.6 % in the first year, and by 12.3 %, 16.7 %, and 20.2 % in the second year, respectively. Except for the 5 t ha^{-1} application, no statistically significant variation in soil TN levels was observed across growing years for the same treatments.

The addition of WHB significantly improved soil CEC over the two growing years ($p < 0.05$; Fig. 8c). The highest soil CEC values (30.8 ± 2.36 and 29.2 ± 2.35 $cmol_c$ kg^{-1}) were observed in plots receiving 20 t ha^{-1} of WHB in the first and second years, respectively. Applying WHB at 5, 10, and 20 t ha^{-1} in the first year increased soil CEC by 10.3 %, 18.1 %, and 33.2 %, respectively, compared to sole fertilizer application.

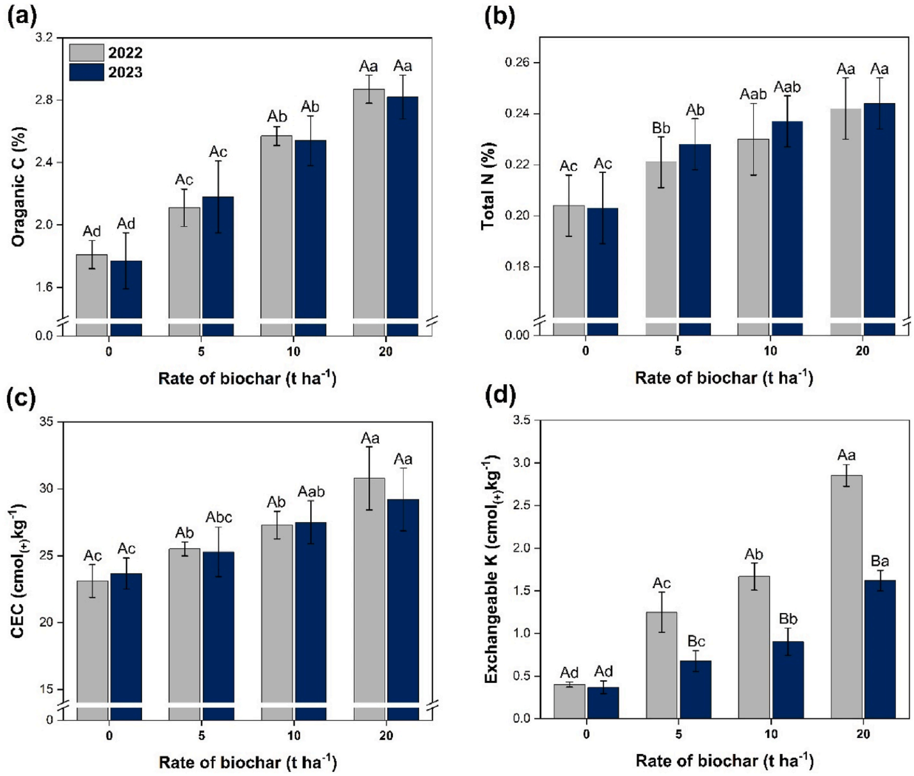

Fig. 8. Impact of water hyacinth biochar on soil organic carbon (a), total nitrogen (b), cation exchange capacity (c), and exchangeable potassium (d) (2022–2023). Significant differences between various biochar application rates within the same year are marked with different lowercase letters, while differences in the same treatment across different years are designated by different uppercase letters at $p < 0.05$. Error bars present ±1 SD of the mean.

In the second year, CEC increases were 6.84 %, 16.2 %, and 23.4 %, respectively, with the effect of 5 t ha^{-1} being non-significant. Although the same biochar treatments did not significantly alter CEC from year to year, their effects decreased in the second year.

The addition of WHB significantly affected exchangeable K levels over the growing periods ($p < 0.05$; Fig. 8d). Increasing the biochar rate to 20 t ha^{-1} significantly enhanced exchangeable K level. In the first year, compared to biochar-unamended plots, applying WHB at 5, 10,

Table 3
The main and interaction effects of water hyacinth biochar and inorganic fertilizer on maize grain yield and total biomass during the 2022 and 2023 growing seasons, and average results.

Treatment	Grain yield (t ha^{-1})			Total dry biomass (t ha^{-1})		
	2022	2023	Average	2022	2023	Average
Fertilizer (F; N/P_2O_5 kg ha^{-1})						
Half (H)	4.57b	4.6b	4.59b	11.24b	11.69b	11.46b
Full (F)	6.34a	6.73a	6.53a	17.56a	18.57a	18.06a
LSD $_{(0.05)}$	0.31	0.25	0.22	0.61	0.46	0.37
Rate of water hyacinth biochar (WHB; t ha^{-1})						
0	4.83c	4.86d	4.84d	12.81c	13.30d	13.06d
5	5.06c	5.43c	5.25c	13.53c	14.16c	13.84c
10	5.68b	5.85b	5.77b	14.97b	15.85b	15.41b
20	6.25a	6.52a	6.38a	16.28a	17.20a	16.74a
LSD $_{(0.05)}$	0.44	0.36	0.31	0.86	0.65	0.53
Interactions (F × WHB)						
90/69 × 0	3.73g	3.95f	3.84f	9.50	10.21f	9.85f
90/69 × 5	4.46f	4.61e	4.53e	10.70	10.96f	10.83e
90/69 × 10	5.00ef	4.68de	4.84de	12.16	12.49e	12.33d
90/69 × 20	5.10de	5.17d	5.13d	12.58	13.08e	12.83d
180/138 × 0	5.93bc	5.76c	5.84c	16.12	16.40d	16.26c
180/138 × 5	5.66cd	6.25c	5.96c	16.35	17.35c	16.85c
180/138 × 10	6.37b	7.03b	6.70b	17.79	19.21b	18.50b
180/138 × 20	7.41a	7.86a	7.64a	19.98	21.32a	20.65a
Significance level						
F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
WHB	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
F × WHB	0.0345	0.0242	0.0143	ns	0.0162	0.0088
CV (%)	6.57	5.17	4.48	4.86	3.48	2.93

LSD, least significance difference; ns, not significant; Means followed by the same letter across columns for growing years and average values are not statistically significant at $p < 0.05$.

and 20 t ha^{-1} increased exchangeable K by 210.4 %, 314.7 %, and 609.7 % respectively. In the second year, increases were 84.0 %, 145.1 %, and 340.2 % for respective rates. Overall, the increase in exchangeable K was more pronounced in the first year, with a significant decrease observed in the second year.

3.3. Effect of water hyacinth biochar and chemical fertilizers on maize yield

The main and interaction effects of WHB and inorganic fertilizers were significant ($p < 0.05$) for maize grain yield over the two growing years (Table 3). Grain yield increased with higher levels of both inorganic fertilizers and biochar. In 2022 and 2023, the maximum yields of 7.41 and 7.86 t ha^{-1}, respectively, were achieved with 20 t ha^{-1} of biochar combined with the full recommended synthetic fertilizer level. The lowest grain yields (1.01 and 0.98 t ha^{-1}) were recorded in the control group for 2022 and 2023, respectively. Applying WHB at 5, 10, and 20 t ha^{-1} rates improved yields on average by 18.0 %, 26.0 %, and 33.6 % with half of the recommended fertilizer rate, and by 2.05 %, 14.7 %, and 30.8 % with the full rate. Applying the full fertilizer level without biochar resulted in only a 13.8 % higher yield compared to applying half the mineral fertilizer with 20 t ha^{-1} of WHB. Notably, grain yield increased by up to 10 % in the second year compared to the first when using WHB with the full fertilizer rate. Regression analysis indicated that increasing biochar rates positively and significantly ($p < 0.05$) increased maize grain yield (Fig. 9). In both growing years (2022 and 2023) and the average grain yields, significant coefficients of determination ($p < 0.05$) were observed with the amount of biochar applied ($R^2 = 0.242$, 0.226, and 0.242, respectively).

The total maize biomass was significantly ($p < 0.05$) affected by the main and interaction effects of applying WHB and mineral fertilizers (Table 3). The main effects showed that higher levels of both inorganic fertilizers and WHB increased total biomass. The interaction effect was significant in 2023 and for average results, but not in 2022. On average, when combined with half of the required inorganic fertilizer, applying WHB at 5, 10, and 20 t ha^{-1} increased total biomass by 9.95 %, 25.2 %, and 30.3 %, respectively. With the full recommended rate of inorganic fertilizer, the increases were 3.63 %, 13.8 %, and 27.0 %, compared to the control without biochar-treated plots. Total biomass increases were greater when biochar was paired with half of the fertilizer rate rather than the full amount.

Applying WHB at varying rates with mineral fertilizers significantly ($p < 0.05$) influenced the 1000-grain weight (TGW) of maize (Table 4). TGW increased with higher biochar and fertilizer rates, peaking at 370 g and 380 g with 20 t ha^{-1} of biochar and full fertilizer rate in the 2022 and 2023 growing seasons, respectively. When WHB was combined with half the fertilizer rate, TGW increased by 17.5 %, 22.9 %, and 25.3 % compared to plots without biochar. With the full fertilizer rate, WHB application increased TGW by 4.6 %, 13.2 %, and 20.7 % compared to plots without biochar.

The ANOVA showed that the harvest index (HI) was significantly influenced by inorganic fertilizer across all growing years ($p < 0.05$), while WHB had no significant main effect on maize HI (Table 4). The interaction between biochar and mineral fertilizer was significant only in 2023. The HI for applying half of the recommended inorganic fertilizer level was higher than that for the full rate, regardless of the biochar application rate. The highest HI (41.9 %) was observed with the addition of 5 t ha^{-1} of WHB and half the recommended mineral fertilizer, while the lowest HI (35.3 %) occurred with the same amount of WHB applied with the full fertilizer level.

3.4. Effect of water hyacinth biochar and chemical fertilizer on nitrogen agronomic use efficiency

Table 5 shows the main and interaction effects of WHB and inorganic fertilizers on maize nitrogen agronomic efficiency (AE) across two growing periods. Adding WHB and chemical fertilizers significantly ($p < 0.05$) influenced the AE. AE increased from 35.3 % to 48.9 % as WHB levels rose from 0 to 20 t ha^{-1}. Applying half the recommended rate of chemical fertilizer resulted in a higher AE (50.2 %) compared to the full recommended rate. The interaction effect of WHB and inorganic fertilizer on AE was significant in the 2022 cropping season and for average results. The highest AE values recorded were 56.6 % and 57.4 % in the first and second year, respectively, when 20 t ha^{-1} of WHB was applied with half of the recommended inorganic fertilizer rate. Based on average results, applying 5, 10, and 20 t ha^{-1} of WHB increased AE by 29.2 %, 37.7 %, and 46.2 %, respectively, compared to half the recommended mineral fertilizer level. When combined with the full recommended mineral fertilizer level, AE consistently increased with higher biochar rates. The highest AE values were 41.2 %, 43.7 %, and 42.4 % for 20 t ha^{-1} of WHB with the full fertilizer rate in 2022, 2023, and the average values, respectively. This combination increased maize AE by 14.5 % and 30.5 % on average in 2022 and 2023, respectively. Additionally, AE in the second year was higher than in the first year when WHB was paired with the full recommended inorganic fertilizer level.

4. Discussion

4.1. Effects of WHB soil physical characteristics

Applying WHB consistently reduced soil bulk density by up to 15.5 % and increased porosity by up to 14.6 % over the two experimental years. The results align with other studies showing the beneficial effects of biochar on soil physical characteristics, particularly bulk density and porosity [42,55]. Blanco-Canqui [55] noted that biochar reduces soil bulk density by 3–31 % and increases porosity by up 14–64 %, with effects becoming more pronounced as application rates increase from below 20 t ha^{-1} to above 80 t ha^{-1} [56,57]. According to Fentie,

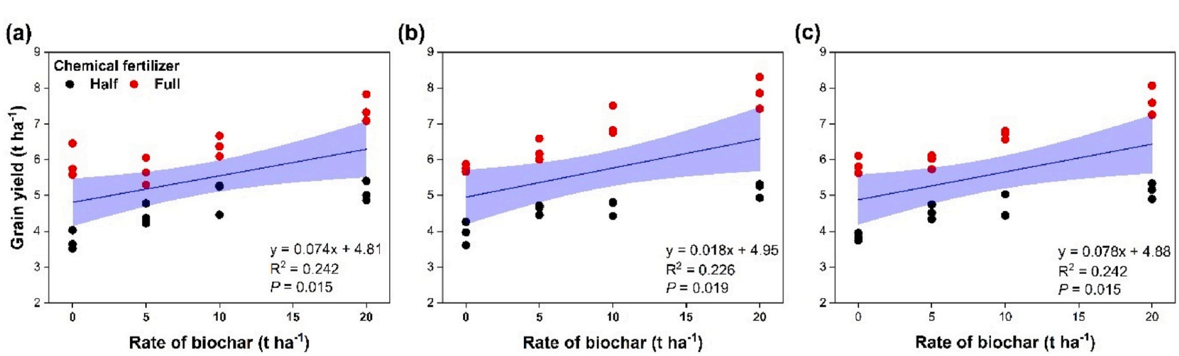

Fig. 9. Linear regression fitting of maize grain yield with the rate of water hyacinth biochar in different levels of mineral fertilizer during the growing years of 2022 (a), 2023 (b), and the average (c).

Table 4
Effect of water hyacinth biochar and inorganic fertilizer on maize thousand-grain yield and harvest index during the 2022 and 2023 growing seasons, including average results.

Treatment	Thousand-grain weight (g)			Harvest index (%)		
	2022	2023	Average	2022	2023	Average
Fertilizer (F; N/P_2O_5 kg ha^{-1})						
90/69	325.8b	321.7b	323.8b	40.64a	39.58a	40.11a
180/138	339.2a	342.1a	340.6a	36.11b	36.91b	36.51b
LSD $_{(0.05)}$	10.96	12.01	6.93	2.15	1.42	1.33
Rate of water hyacinth biochar (WHB; t ha^{-1})						
0	294.2c	295.0c	294.6d	38.06	38.07	38.07
5	330.8b	320.8b	325.8c	38.15	39.06	38.61
10	341.7b	351.7a	346.7b	38.47	37.62	38.04
20	363.3a	360.0a	361.7a	38.82	38.22	38.52
LSD $_{(0.05)}$	15.50	17.0	9.80	3.05	2.01	1.88
Interactions (F × WHB)						
90/69 × 0	283.3	273.3d	278.3e	39.28	39.14b	39.21
90/69 × 5	330.0	323.3c	326.7c	41.67	42.09a	41.88
90/69 × 10	333.3	350.0b	341.7b	41.07	37.50bc	39.29
90/69 × 20	356.7	340.0bc	348.3b	40.51	39.57 ab	40.04
180/138 × 0	305.0	316.7c	310.8d	36.83	37.00bc	36.92
180/138 × 5	331.7	318.3c	325.0c	34.64	36.03c	35.33
180/138 × 10	350.0	353.3b	351.7b	35.87	37.73bc	36.80
180/138 × 20	370.0	380.0a	375.0a	37.12	36.87bc	36.99
Significance level						
F	0.0202	<0.0001	<0.0001	0.0004	0.0011	<0.0001
WHB	<0.0001	0.0024	<0.0001	ns	ns	ns
F x WHB	ns	0.0144	0.0075	ns	0.0327	ns
CV (%)	3.81	4.18	2.41	6.49	4.29	4.02

LSD, least significance difference; ns, not significant; Means followed by the same letter across columns for growing years and average values are not statistically significant at $p < 0.05$.

Table 5
Effect of WHB and mineral fertilizer on maize nitrogen agronomic efficiency in 2022, 2023 growing years and average values.

Treatment	Nitrogen agronomic efficiency (kg kg^{-1})		
	2022	2023	Average
Fertilizer (F; N/P_2O_5 kg ha^{-1})			
90/69	49.8a	50.2a	50.0a
180/138	35.2b	37.4b	36.3b
LSD $_{(0.05)}$	3.64	2.70	2.87
Rate of water hyacinth biochar (WHB; t ha^{-1})			
0	35.3a	36.1c	35.7c
5	40.5 ab	43.0b	41.7b
10	45.4b	45.5b	45.5b
20	48.9c	50.6a	49.7a
LSD $_{(0.05)}$	5.15	3.82	4.06
Interactions (F × WHB)			
90/69 × 0	37.7bc	40.2	39.0c
90/69 × 5	49.5a	51.3	50.4b
90/69 × 10	55.5a	52.0	53.7 ab
90/69 × 20	56.6a	57.4	57.0a
180/138 × 0	32.9c	32.0	32.5d
180/138 × 5	31.5c	34.7	33.1d
180/138 × 10	35.4bc	39.0	37.2cd
180/138 × 20	41.2b	43.7	42.4c
Significance level			
F	<0.0001	<0.0001	<0.0001
WHB	<0.0001	<0.0001	<0.0001
F × WHB	0.0288	ns	0.0464
CV (%)	9.90	7.13	7.86

LSD, least significance difference; ns, not significant; Means followed by the same letter across columns for growing years and average values are not statistically significant at $p < 0.05$.

Mihretie [35], applying WHB at 20 t ha^{-1} decreased soil bulk density by 15.1 % and increased porosity by 7.6 %, which is consistent with our findings. These improvements are likely due to WHB's lower density, higher porous structure (Fig. 4), and its organic carbon content, which enhances soil aggregation [58]. Additionally, the lower bulk density of biochars (0.3–0.6 g cm^{-3}) compared to typical agricultural soils further dilutes soil density [59]. The increased surface area and porosity promote microbial activity and root growth [60]. Accordingly, incorporating WHB could reduce soil bulk density, enhance porosity, and improve soil water-holding capacity, aeration, and root penetration.

4.2. Effects of WHB on soil chemical characteristics

This study found that applying WHB significantly ($p < 0.05$) reduced soil acidity by raising the pH and decreasing exchangeable acidity and Al^{3+} over two cropping periods (Fig. 7). Soil pH increased by 24.0 % in the first season and 23.4 % in the second, likely due to the substantial ash content and liming effect of high pH of WHB (Table 1). Research has shown a strong correlation between increased soil pH from biochar and its alkalinity with an R^2 value of 0.95 [61]. According to Camps-Arbestain, Amonette [62], the biochar used in this study was classified as Class 3 (CCE >20 %) based on its liming capacity. A characterization study identified WHB as a potential soil acidity ameliorant due to its high alkalinity and liming potential [27]. Consistent with our results, applying WHB produced at a temperature of 350–750 °C at 20 t ha^{-1} raised soil pH by 0.37–0.72 units relative to the control [34]. Furthermore, in a lab experiment, adding WHB at 10 % (w/w) raised soil pH from 5.08 to 6.82, a 34.3 % increase [30]. Similarly, under a field experiment, WHB raised the pH of acidic silty loam soil by 0.48 units compared to sole inorganic fertilizer addition [35]. Additionally, a study using 1 % and 2 % (w/w) WHB application showed that the biochar outperformed lime in resisting soil acidification due to its enhanced pH buffering capacity [28]. The increased buffering capacity was linked to improved soil CEC following biochar incorporation [63].

Biochar reduces Al^{3+} bioavailability in acidic soils, alleviating its toxicity to plants [63]. In this study, the addition of WHB significantly decreased exchangeable acidity; applying biochar at 10 and 20 t ha^{-1} substantially reduced exchangeable acidity levels and adsorbed exchangeable Al^{3+} to undetectable limits (Fig. 7c). The carryover effect of biochar persisted in the second year, particularly with the addition of WHB at 20 t ha^{-1}. These findings agree with research conducted in Ethiopia by Abewa, Yitaferu [12] and Berihun, Tadele [14] who reported reduced exchangeable acidity due to biochar use. The reduction in exchangeable acidity may be attributed to the substitution of acidic cations with base cations from the biochar [64]. Additionally, the high CEC (Table 1) and the presence of several functional groups in the WHB (Fig. 5) enable it to adsorb acidic cations, particularly by binding exchangeable Al^{3+}, thereby reducing its availability in the soil solution. Furthermore, alkaline anions in the biochar, such as carbonates and oxides, interact with H^+ and Al^{3+} species precipitating as $Al(OH)_3$ and $Al(OH)_4^-$ in acidic soils. This process raises pH and decreases exchangeable acidity [65,66]. Moreover, the carboxylic functional groups in biochar provide additional binding sites for Al^{3+}, along with the inorganic components and functional oxygen groups present in oxidized biochar [67]. Additionally, biochar's large surface area and porosity provide more adsorption sites for Al^{3+} and other metals [68]. Therefore, WHB can serve as an effective alternative amendment for managing acidic soils and improving crop yields.

This study found that applying WHB at 5–20 t ha^{-1} significantly increased P availability over two growing seasons, with improvements ranging from 33.8 % to 81.6 %. The increase in available P could be attributed to the substantial P content in the biochar (Table 1). Additionally, enhanced soil pH and reduced exchangeable acidity likely lowered P fixation by Al^{3+}. Available P showed a significant negative correlation with exchangeable acidity ($p < 0.001$, $r = -0.68, -0.72$) and exchangeable Al^{3+} ($p < 0.001$, $r = -0.82, -0.76$), while it was positively associated with pH ($p < 0.001$, $r = 0.71, 0.82$) across both growing years. Consistent with our findings, applying WHB at 20 t ha^{-1} improved available P by 85.6 % compared to sole fertilization, while the effects of 5 and 10 t ha^{-1} were not significant [35]. Several studies have demonstrated that applying biochar positively affects P availability in acidic soils [69,70]. A meta-analysis by Gao, DeLuca [71] found a 45 % increase in soil available P due to biochar application. This increase may result from the immediate supply of soluble P from the P-rich biochar [27,72]. Additionally, biochar enhances soil CEC, alters pH, and releases organic ligands that promote cation adsorption, such as calcium, iron, and aluminum. This process reduces P adsorption and precipitation, ultimately increasing available P [73]. Thus, using biochar like WHB may enhance P availability and uptake by plants by reducing P precipitation and fixation.

In this study, incorporating WHB significantly enhanced the soil's nutrient status and retention capacity (Fig. 8). To maintain soil fertility, it is crucial to use stable, nutrient-retaining compounds like biochar [74]. The use of WHB consistently increased SOC over the two growing seasons, with a nearly 60 % rise observed at a 20 t ha^{-1} application rate. This increase is likely due to the high carbon content of biochar, a product of the pyrolysis process [75]. Consistent with our findings, acacia biochar applied at 10 t ha^{-1} in Ethiopian soils boosted SOC by 23 %–34 % compared to sole fertilizer treatments [13]. Several studies have reported similar results, showing that SOC improves with biochar addition, with effects increasing as application rates increase [56,76,77]. Thus, incorporating biochar into the soil can enhance soil fertility while increasing carbon sequestration [78].

Likewise, applying WHB alongside chemical fertilizer increased soil TN by about 20 % over two consecutive growing periods (Fig. 8b). Nitrogen is the primary nutrient for healthy plant growth and yield outcomes, and its deficiency limits crop yields [79]. However, nitrogen loss from the soil occurs through NH_3 volatilization, N_2O emission, and NO_3^- leaching, with leaching accounting for 56 %–71 % of total nitrogen loss [80]. A meta-analysis by found that applying biochar reduces NH_3 volatilization by 19 %, N_2O emissions by 32 %, and leaching of NH_4^+ and NO_3^- by 22 % and 29 %, respectively. Moreover, biochar helps mitigate nitrogen leaching losses by increasing soil water-holding capacity, enhancing NH_4^+ adsorption, and improving nitrogen immobilization [81]. Additionally, biochar retains NO_3^- within its pores [82]. Li, Wang [83] noted that adding 20 t ha^{-1} of biochar made from apple branches, combined with N fertilizer, improved nitrogen availability, and reduced NO_3^- leaching. A field experiment also showed that applying 20 t ha^{-1} of biochar with mineral fertilizer reduced NO_3^- leaching by 8 % [84]. Güereña, Lehmann [85] demonstrated that biochar adoption enhanced nitrogen concentration in the soil microbial community, where microorganisms converted NO_3^--N into organic N, which was then readily adsorbed by soil minerals and biochar. Thus, integrating inorganic N fertilizers with biochar may be the most effective strategy for improving N retention and availability.

Biochar is widely recognized for its positive effects on soil CEC. In this study, applying WHB at rates of 10 and 20 t ha^{-1} significantly enhanced soil CEC by 17.2 % and 28.3 %, respectively, while a lower application rate of 5 t ha^{-1} had no significant impact (Fig. 8c). These improvements in soil CEC can be attributed to the high CEC and surface area of the applied biochar (Table 1). As shown in Fig. 5, WHB contains various carbon and oxygen-containing functional groups that can contribute to enhancing soil CEC. Furthermore, the soil's capacity to adsorb cations is increased when acidic aromatic carbon on the surface of the biochar oxidizes, generating functional groups such as -OH and -COOH [86]. Additionally, biochar's natural oxidation may further enhance soil CEC over time [87]. In line with our results, applying WHB at 20 t ha^{-1} improved soil CEC by up to 27.3 % [34]. Previous studies have shown that biochar application increases the total soil charge and CEC increased by about 20 %–40 % [60]. A meta-analysis also suggests that biochar use in field studies enhances soil CEC by 31 % compared to untreated controls [88]. Consistent with our findings, several studies have demonstrated that adding biochar at increasing rates significantly boosts the CEC of acidic soils [12,70,89]. Accordingly, applying biochar can effectively enhance the exchange capacity of acidic soils.

This study found that applying WHB significantly increased soil exchangeable K by over 300 %, with more pronounced effects observed at higher biochar application rates (Fig. 8d). The increase in K is likely due to the direct supply of K from the biochar, which has a high ash content (Table 1). Additionally, improvements in K availability may be associated with increases in soil pH, CEC, and reduced leaching. Water hyacinth biochar has been recognized as a significant source of available K [27]. By adding K through the biochar's ash fraction, exchangeable K levels in the soil rise, while leaching losses are reduced [90]. Major, Rondon [84] also observed that applying biochar at 20 t ha^{-1} reduced soil K leaching by 36 % compared to the control. Increased carbon oxidation and decreased soil acidity with higher biochar rates may enhance K availability [56]. A field study in Zambia demonstrated that applying biochar made from maize cobs improved soil pH and directly increased K levels [91]. However, in this study, the impact of biochar on soil exchangeable K was substantially lower in the second year compared to the first (Fig. 8d). This could be attributed to increased plant uptake of K, leading to a gradual decline in its availability. Qayyum, Haider [90] noted that improved soil conditions from biochar addition supported greater uptake and utilization by plants.

4.3. Effects of WHB and chemical fertilizer on maize yield

Maize is a major global cereal crop, but its production is often limited by poor soil fertility, low organic matter, and high acidity [92]. Using biochar with inorganic fertilizers has been proposed as a strategy to enhance soil fertility and maize yields. This study found that applying different rates of WHB up to 20 t ha^{-1} combined with inorganic fertilizers increased maize grain yield on average by 32.2 % and total biomass by 28.7 % (Table 3). Research has shown that biochar can enhance crop yields in tropical soils by 25 % [93] and improve yields by 10–38 % within 1–5 years of application [94]. Field studies have documented yield increases of 30 % [88], and Ye, Camps-Arbestain [20] reported a 15 % improvement when $\leq$20 t ha^{-1} of biochar was applied alongside fertilizers. The co-application of inorganic fertilizers with biochar significantly increased maize grain and biomass yields, especially at higher biochar rates [70,89,95–97]. In agreement with our findings, applying willow wood biochar at 10 t ha^{-1} increased maize grain yield by 29 % and biomass by 17.7 % in Ferralosols [98]. A long-term trial of a one-time biochar application demonstrated sustained yield improvements in maize and soybeans over ten years [99]. Consistent with our findings, applying 20 t ha^{-1} of WHB with inorganic fertilizer resulted in 173 % more grain yield and a 260 % increase in biomass yield of wheat compared to inorganic fertilizer alone [35]. However, several factors related to biomass availability, labor costs, and logistics must be considered to enhance the agronomic and economic feasibility of biochar application [100]. Improved crop production due to biochar application is mainly attributed to increased soil pH and better nutrient retention from biochar application [97]. Additionally, applying biochar significantly reduced harmful aluminum levels and increased crop yield in Ultisols (pH_{KCl} = 3.6) in the humid tropics by neutralizing acidity [95]. Moreover, biochar enhances agricultural productivity and soil fertility by improving SOC, increasing nutrient availability, and enhancing water retention [101]. Biochar addition also enhances nutrient retention and availability by increasing exchange capacity, surface area, and directly contributing nutrients [78]. Biochar's long-term yield benefits primarily result from the improvement in SOC levels [94]. Furthermore, studies indicate that combining biochar with nitrogen fertilizer provides more nutrients than using either amendment alone, leading to increased crop productivity [102]. In this study, although a significant positive relationship was observed between maize grain yield and biochar application rate (Fig. 9), the low R^2 values (0.22–0.24) suggest that biochar alone explained only a small proportion of the yield variability. This limited explanatory power likely stems from confounding factors such as interannual climate variability (precipitation and temperature fluctuations), which strongly influence yield and may overshadow biochar's effects [103].

The joint application of WHB and chemical fertilizer markedly improved the 1000-grain weight (TGW) of maize, especially at higher biochar and fertilizer rates (Table 4). This increase in maize TGW is likely linked to improved nutrient use efficiency and soil fertility resulting from biochar addition. For instance, applying straw-derived biochar at 8 and 16 t ha^{-1} notably boosted maize TGW [96]. However, applying willow wood biochar at 10 t ha^{-1} did not show a significant difference in the hundred-grain weight of maize compared to the control [98]. Overall, combining WHB with chemical fertilizers appears to be more effective for enhancing crop production in nutrient-poor, acidic soils than using fertilizers alone.

4.4. Effects of WHB and inorganic fertilizers on maize nitrogen use efficiency

Our results show that applying WHB in combination with chemical fertilizers significantly improved nitrogen agronomic efficiency (AE). Nitrogen AE was higher when WHB was applied with a lower fertilizer level compared to a higher level (Table 5). Applying the full fertilizer rate alone achieved a 13.8 % greater yield compared to the combined application of half fertilizer with 20 t ha^{-1} WHB. However, the half fertilizer plus 20 t ha^{-1} WHB treatment demonstrated a 75.4 % improvement in nitrogen AE relative to the sole full fertilizer treatment. These findings suggest that integrating WHB with reduced fertilizer rates can significantly enhance nutrient use efficiency, offering a dual benefit of mitigating environmental pollution from regular fertilizer application while concurrently reducing input costs [104,105]. In line with our result, biochar application improved nitrogen AE by up to 16.6 %, with AE decreasing as fertilizer levels increased [42]. Furthermore, applying acacia-based biochar at 10 t ha^{-1} improved nitrogen AE at two sites when combined with reduced nitrogen fertilizer [106]. In another study, applying biochar at 30 t ha^{-1} a reduced nitrogen fertilizer increased nitrogen AE of maize by 52.6 % and 84.1 % under full and reduced irrigation, respectively [107]. Employing pinewood biochar in combination with nitrogen fertilizer increased maize nitrogen AE by up to 46 % compared to using inorganic fertilizer alone [108]. According to Shi, Li [109], higher nitrogen rates resulted in lower utilization efficiency, reduced grain yield, and increased nitrate leaching. However, biochar application significantly reduced ammonium and nitrate leaching, leading to improved nitrogen use efficiency [110]. Combining biochar with nitrogen fertilizer reduces nitrogen loss while promoting root growth and uptake. This combination enhances nitrogen use efficiency by improving soil characteristics such as pH, organic matter content, electrical conductivity, and adjusting the C/N ratio [111]. Therefore, using biochar alongside inorganic fertilizers improves nutrient use efficiency, reduces loss, and mitigates environmental pollution.

5. Conclusion

Our findings demonstrated that water hyacinth biochar significantly improved soil properties, with more pronounced effects at higher application rates (up to 20 t ha^{-1}). Specifically, bulk density, exchangeable acidity, and exchangeable Al^{3+} levels decreased, while porosity, soil pH, available phosphorus, total nitrogen, organic carbon, cation exchange capacity, and exchangeable potassium increased. These results confirm its effectiveness as both a soil conditioner and acidity ameliorant. Following the improvements in soil physicochemical properties, combining water hyacinth biochar with chemical fertilizers significantly enhanced maize grain yield and total biomass over two growing periods. The highest yields were observed when the highest biochar rates were paired with elevated fertilizer levels, although even lower fertilizer applications still showed benefits in improving soil properties and yield. Additionally, the co-application of water hyacinth biochar and nitrogen fertilizer notably improved nitrogen agronomic efficiency, especially when biochar was applied alongside reduced nitrogen fertilizer. However, since biochar may not require annual application, long-term field studies are crucial to evaluate its lasting residual effects on crop yield and soil characteristics such as soil pH, nutrient availability and retention capacity, carbon sequestration, and microbial diversity and activity. Additionally, since this study tested only two levels of mineral fertilizers, which is a limitation, further optimization of biochar-mineral fertilizer combinations could identify ideal application levels to balance productivity, sustainability, and economic feasibility across diverse agroecological zones and soil types. In conclusion, biochar produced from unwanted aquatic weed biomass can be effectively integrated with inorganic fertilizers to enhance soil fertility and improve crop production, particularly in the acidic soils of northwestern Ethiopian Highlands.

CRediT authorship contribution statement

Ashenafei Gezahegn: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yihenew G. Selassie:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Getachew Agegnehu:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Solomon Addisu:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Fekremariam Asargew Mihretie:** Writing – review & editing, Methodology, Conceptualization. **Yudai Kohira:** Writing – review & editing, Methodology, Formal analysis. **Mekuanint Lewoyehu:** Writing – review & editing, Methodology, Formal analysis. **Shinjiro Sato:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research received financial support from the MEXT-funded

Plankton Ecoengineering for Environmental and Economic Transformations project, as well as from the Japan Science and Technology Agency and the Japan International Cooperation Agency (JICA) through the Project titled EARTH: Eco-engineering for Agricultural Revitalization Toward Human Nutrition, was conducted under the Japan Science and Technology Research Partnership for Sustainable Development (SATREPS) with grant number JPMPSA2005.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2025.101939.

Data availability

Data will be made available on request.

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