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Water hyacinth conversion to biochar for soil nutrient enhancement in improving agricultural product

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The conversion of water hyacinth into biochar offers a sustainable solution to mitigate its proliferation and enhances its potential as a soil amendment for agriculture. This study examined the physicochemical properties of water hyacinth biochar (WHBC) and its impact on soil fertility. Water hyacinth (*Eichhornia crassipes*) was pyrolyzed at 300 °C for 40 minute with restricted airflow (2–3 m/s), producing biochar with desirable properties and a yield of 44.6%. WHBC exhibited a pH of 8.11 ± 0.91, electrical conductivity of 18.70 ± 1.15 mS/cm, and nutrient contents including TN (0.69 ± 0.10%), TP (8.80 ± 0.01%), OC (13.95 ± 0.65%), C/N ratio (20.22 ± 0.95), S (0.34 ± 0.03%), and metallic nutrients (Ca, Mg, K). Heavy metals (Fe, Mn, Cu, Ni, Cd, Pb, Cr, Zn) were within permissible limits for biochar. Soil amended with 2500 kg/ha WHBC (BC2) produced comparable Teff crop yields (fresh mass: 1191.67 ± 428.44 g, dry mass: 700.00 ± 248.34 g, grain yield: 95.00 ± 39.69 g) to those with mineral fertilizers and mixed amendments. Fourier Transform Infrared (FTIR) and Scanning Electron Microscopy (SEM) revealed significant structural changes in WHBC, enhancing its pore structure and surface morphology. These results demonstrate the potential of WHBC as an effective soil amendment to improve agricultural sustainability and soil fertility.

Keywords Water hyacinth, Biochar, Carbon stability, Nutrient, Teff

The manifestation of invasive water hyacinth (*Eichhornia crassipes*) presents considerable challenges and environmental consequences on a global scale. Water hyacinth (WH) outcompetes native aquatic plants by growing quickly and forming dense mats on water surfaces[1]. By decreasing dissolved oxygen levels, this invasive plant degrades water quality; it impacts fisheries by altering habitats and reducing plankton production[2]; and it blocks streams, making it more difficult for people to fish and navigate[3]. Effective control strategies, including physical, chemical, and biological treatments, are necessary because WH infestations cause environmental contamination, waterway closures, and aquatic organism death[4]. The environmental challenges posed by WH highlight the urgent need for sustainable management strategies to mitigate its detrimental effects on aquatic ecosystems and human livelihoods[5].

A sustainable approach to WH management is essential because of its negative effects on ecological, socioeconomic, and public health factors. According to Rajan et al.[6], WH can be efficiently employed for a number of advantageous applications, including the manufacture of bioenergy, animal feed, paper, and biofertilizer. While producing high-value products from collected biomass, the growth of WH can be efficiently managed by putting into practice sustainable control measures, such as biological and physical ways[7,8]. According to Akter et

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al.[9], sustainable management practices not only aid in halting the spread of this invasive weed but also support conservation, self-generation, ecosystem restoration, sustainable development, and the creation of new green job possibilities for nearby communities.

Lake Tana, with its abundant biodiversity, is Ethiopia's largest freshwater body. Since 2015, UNESCO has included the lake in its global network of biosphere reserves. Due to the invasion of water hyacinth, Lake Tana has been experiencing catastrophic environmental degradation and biodiversity loss despite its ecological and economic significance on a local and worldwide scale[10,11]. WH expansion causes several problems, especially raises the pace of evapotranspiration, attracts fish, and creates hygiene issues. It also functions as a barrier to shipping lanes and interferes with irrigation systems. The WH is a weed that is difficult to control because of its high rate of reproduction and dispersal, which can cause major environmental problems[12]. In high temperature and humidity environments, the number of plants can be more than double in just seven days. The biomass analysis of water hyacinth in Lake Tana reveals that approximately 1,990,787.8 tons of wet biomass and 554,523.8 tons of dry biomass can be harvested from the lake annually[13].

Since completely eliminating WH is challenging, there have been sustainable management methods to minimize its negative impacts on nearby ecological and socioeconomic systems[14]. For instance, to improve soil qualities a variety of soil amendment technologies are available, including lime, chemical, and organic fertilizers. The application of biochar increases agricultural yield by improving the soil ability to store water, exchange nutrients with other plants, and creating an environment that is favourable for soil microorganisms[15,16]. With its high hemicellulose (48%) and cellulose (20%) content and relatively low lignin content (3.5%), water hyacinth holds potential as a biomass for producing various valuable products[17]. Hence, the weed biomass a promising source for the production of biochar for soil amendment[12].

Although there is limited research on converting WH into biochar for soil enhancement, various studies have explored different applications of WH biomass, including soil improvement, nutrient extraction, and contaminant absorption. Masto et al.[12] investigated the impact of pyrolysis temperatures (ranging from 200 to 500 °C) and retention times (30 to 120 min) on water hyacinth biochar (WHBC) stability, as well as its effects on soil biochemical properties and corn seedling growth. Bottezini et al.[18] examined how pyrolysis temperature influenced the chemical and molecular composition of WHBC, as well as phosphorus forms and availability for potential soil enhancement at temperatures ranging from 400 to 600 °C. Bordoloi et al.[19] observed the positive effects of WHBC on water retention and reducing soil cracking. Jutakanoke et al.[20] demonstrated the enhanced impact of WHBC produced at 500 °C on convolvulus growth and soil acidity reduction. Zhang et al.[21] investigated the adsorption of cadmium by WHBC prepared at temperatures ranging from 250 to 550 °C. Gezahegn et al.[22] investigated the physicochemical characteristics of WHBC at three pyrolysis temperature (350, 550, 750 °C) for soil amendment.

Pyrolysis, which produces biochar, is a process in which biomass thermally decomposes at high temperatures without oxygen[23]. The type of biomass and pyrolysis conditions significantly influence the physicochemical properties of biochar[24]. Among these conditions, temperature plays a crucial role in determining various properties of biochar[25]. Research indicates that increasing pyrolysis temperatures lead to higher pore volume, specific surface area, ash content, carbon content, and concentrations of phosphorus (P) and calcium (Ca), while cation exchange capacity (CEC), volatile matter, and nitrogen (N) content decrease[24–26]. These changes are primarily attributed to the loss of volatile compounds at higher pyrolysis temperatures[27]. The highest biochar yield, 46.59%, has been observed at 300 °C[28,29]. Optimal pyrolysis conditions for achieving sufficient biochar yield are reported to be 300 °C for 30 min[29], although higher temperatures are associated with reduced biochar yield[22].

These studies mainly focused on physicochemical properties of WHBC relevant to soil use on laboratory scale. However, a more comprehensive characterization of biochar properties induced by pyrolysis temperature is needed for a better understanding of WHBC's potential on a large scale production and field application as a soil amendment. Additionally, there is a scarcity of literature on the production and characteristics of biochar at a large scale and field application derived from WH in Lake Tana, Ethiopia. Thus, this study investigates physicochemical properties of WH biochar for soil amendment and maximizing crop yield. These findings could offer valuable insights into managing and utilizing WH biomass for soil improvement through large scale production of WHBC.

Materials and methods

Water hyacinth sample collection area

Raw water hyacinth (RWH) biomass was collected from Sheha Gomengie Kebele near Gondar Town in Northwest Ethiopia, approximately 40 km away. The entire plant, including roots, leaves, and stem, was gathered and cleansed to remove debris. Manual detachment of the plant's stem was performed for biochar production. The area, chosen for its severe water hyacinth infestation, is situated along Lake Tana's North-eastern edge. Gondar Zuria experiences a predominantly 22% highland and 78% midland climate, with average rainfall between 950 and 1035 mm and temperatures ranging from 24 to 33 °C. The District is situated between 1800 and 2700 m above sea level[30] (Fig. 1).

Water hyacinth (WH) preparation

Identification and authentication of the water hyacinth plant was performed by a Botanist using taxonomic keys and floras, and voucher specimen (003/ATM/2022) was kept at Botanical Science and Herbarium, University of Gondar, for future references which was confirmed by Mr. Abiyu Enyew MSc in Botanical science. Currently, he is the head of the department of Biology, in college of natural and computational sciences, University of Gondar. The WH drying unit were built with wood sticks (Fig. 2a). The stem of the WH were separated from the whole part of the plant manually and placed over the plastic sheet. Then, WH stem sections were dried until their

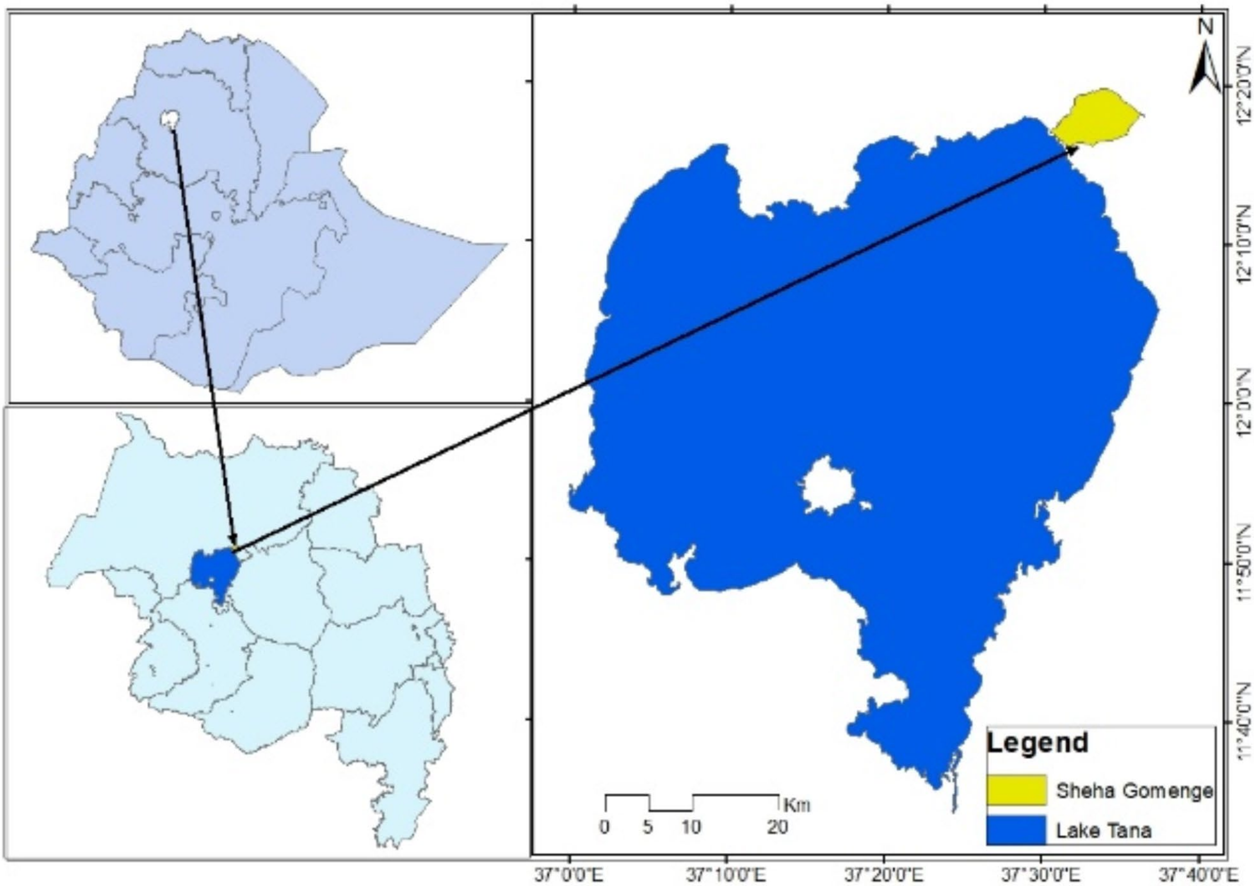


Fig. 1. Map showing the location of Lake Tana's WH sample collection region. The map of Ethiopia is displayed on the left above the figure, the map of the Amhara region is displayed on the left bottom, Lake Tana is depicted in blue, and the study location, Sheha Gomenge, is represented in yellow[30].

moisture content dropped below 5% by sun light for 25 days, monitored using an infrared thermometer. Drying extended beyond 30 days before further processing to biochar. The RWH moisture could be in the range of 5–10% to get the fine quality and quantity of biochar[31]. The wooden drying house used for water hyacinth (WH) accommodated approximately 100 kg of WH at a time, with a drying period of 30 days at room temperature. Decay was not observed in the drying unit, since it was kept well-ventilated to promote airflow, and through our observation decay indicators, such as strong odor or darkening (Fig. 2a). The dried WH was then cut into small pieces measuring 2–3 cm in length. Subsequently, the dried WH biomass was weighed and subjected to pyrolysis using steel barrels with surface areas of 0.212 and 0.237 m^2 (Fig. 2b).

The moisture content of WH dried by sunlight was determined using Eq. 1, the fresh weight of the plant material (W_i) was measured first. The sample was then left in sunlight until a constant weight is achieved, indicating that all moisture has evaporated. To ensure that a fresh WH sample was fully dried, the mass of sample was measured constantly. After this, the dried weight (W_f) was measured. The moisture content calculated using the formula[32]:

$$Moisture\ content\,(\%) = \frac{W_i - W_f}{W_i} \times\ 100. \tag{1}$$

Biochar production

Biochar production from WH involved utilizing a stainless steel cylindrical reactor (150 cm × 58 cm, height × diameter) under restricted air supply conditions, with a capacity of approximately 0.158 m^3. Control of the internal temperature during the pyrolysis process was achieved through air flow inlet perforations in the reactor. WH was introduced into the reactor through the upper section and subjected to slow pyrolysis at temperatures ranged from 200 to 500 °C and residence times of 20 to 40 min. During burning of WH, temperature was recorded by temperature sensor with the range of 200 to 500ºC and finally, the weight of biochar product was measured. After carbonization of WH, the biochar yield was recorded and milled it to prepare powdered for characterization experiment (Fig. 2b, and c).

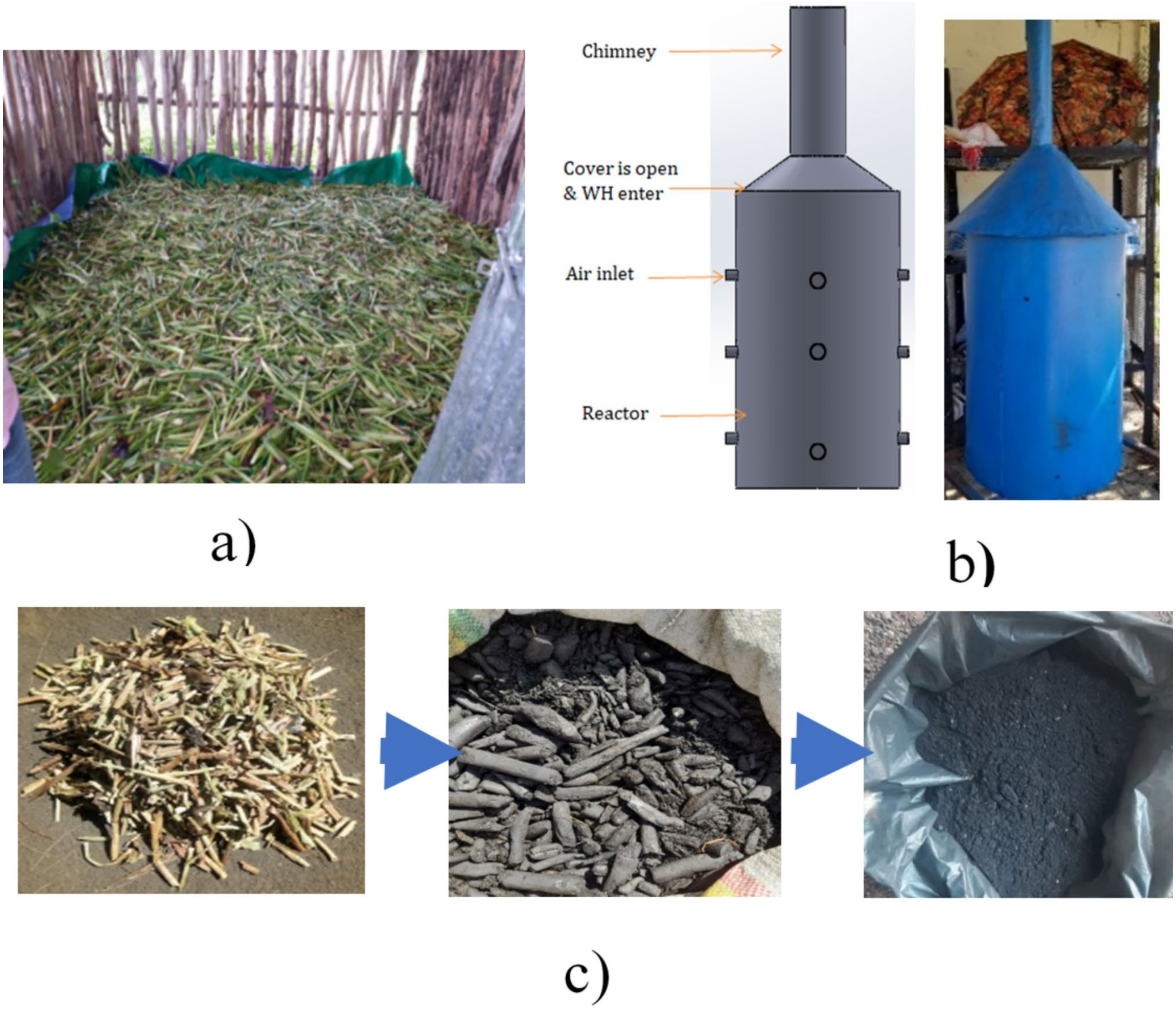


Fig. 2. Water hyacinth biochar pyrolyze process Steps: (**a**) WH drying processes, (**b**) Barrel type reactor, and (**c**) biochar milling process.

WH Biochar yield

The yield of WHBC was determined by the quotient of the weight of the produced WHBC and the dried WH biomass used as a feedstock, and the result was expressed as a percentage, Eq. 2[33].

$$Yield\,(\%) = \frac{M_{WHBC}}{M_{RWH}} \times 100 \tag{2}$$

where M_{WHBC} is the mass of water hyacinth biochar (kg), and M_{RBC} is mass of dried raw water hyacinth biomass (kg).

Biochar characterization

Nutrient, pH, and electrical conductivity analysis of WH and biochar

In the nutrient analysis of biochar, the samples were oven-dried at 105 °C overnight and prepared by grinding and homogenizing them into a fine powder to ensure uniformity. Subsequently, the biochar samples were subjected to digestion using 5 mL HNO_3 and 3 mL $HClO_4$ concentrated acid solutions via hot plate digestion method to extract the nutrients present (optimized acid volumes). The extracted solutions were then analyzed using spectrophotometer (Abron, India) and Atomic Absorption Spectroscopy, AAS (Buck Scientific Model 210VGP, USA) for nutrient analysis. Calibration curve was made for each element and concentration of the element in each sample was determined from the respective calibration curve of the element. The curve was prepared by plotting absorbance of standard versus their concentration. Triplicate value of absorption was taken with each solution and an average value was taken. After the construction of such calibration curves of these elements, the absorbance of sample solutions of unknown concentrations was measured and the concentrations of these elements were determined from their constructed calibration curve. In addition, the N content was calculated from nutrient analysis result[34,35].

In 150 mL conical flask, 5 g biochar was mixed with 50 mL distilled water[36]. The biochar and deionized water blend were placed in a horizontal shaker at a speed of 160 rpm for 2 h and the suspension was then left for half an hour. The pH and EC were measured using a calibrated pH meter.

Nutrient, pH, and electrical conductivity analysis of soil and RWH

The pH of the soil samples was measured using a 1:2.5 soil-to-water suspension, where 105 °C air-dried and sieved soil was mixed with distilled water, placed in a horizontal shaker at a speed of 160 rpm for 2 h and the suspension was allowed to equilibrate for 1 h before measurement with a calibrated pH meter. Electrical conductivity (EC) was determined using the same suspension by analyzing the filtrate with an EC meter. For nutrient analysis, the Olsen method was used to determine available phosphorus in the soil. In this method, 1 g of air-dried soil was extracted with 20 mL of Olsen's extractant solution (0.5 M sodium bicarbonate at pH 8.5) and shaken for 30 min[37]. The suspension was filtered, and the phosphorus concentration in the filtrate was measured colorimetrically using the molybdenum blue method.

The pH of plant samples was measured using a 1:5 WH to water suspension prepared by homogenizing dried and ground WH material with distilled water. The mixture was placed in a horizontal shaker at a speed of 160 rpm for 2 h and the suspension was allowed to equilibrate for 1 h before measurement with a calibrated pH meter. Electrical conductivity (EC) was similarly determined by analyzing the filtrate of the WH-water suspension with an EC meter. For nutrient analysis, plant samples were first oven-dried, finely ground, and subjected to acid digestion using a mixture of concentrated perchloric acid ($HClO_4$) and nitric acid (HNO_3) to release macro and micronutrients. Other nutrients of both soil and WH plant were measured using the biochar analysis method[38].

Surface morphology and structure analysis

After drying a biochar sample for 24 h at 105 °C, its surface morphology and structure were examined. To analyze the surface functionality of the biochar, a 1 mg sample was finely ground and thoroughly mixed with 100 mg of KBr, then pressed into a 13 mm pellet under a pressure of 7845 kPa. Spectra readings were performed using Fourier Transform Infrared Spectroscopy (FTIR) (Thermo NICOLET-IS-50), with infrared absorbance data collected for wavenumbers ranging between 400 and 4000 cm^{-1} at a spectral resolution of 2 cm^{-1} with 64 scans[39]. For Scanning Electron Microscope (SEM) analysis, the biochar samples were coated with a thin layer of carbon, and a ZEISS EVO Series Scanning Electron Microscope EVO 50 was used.

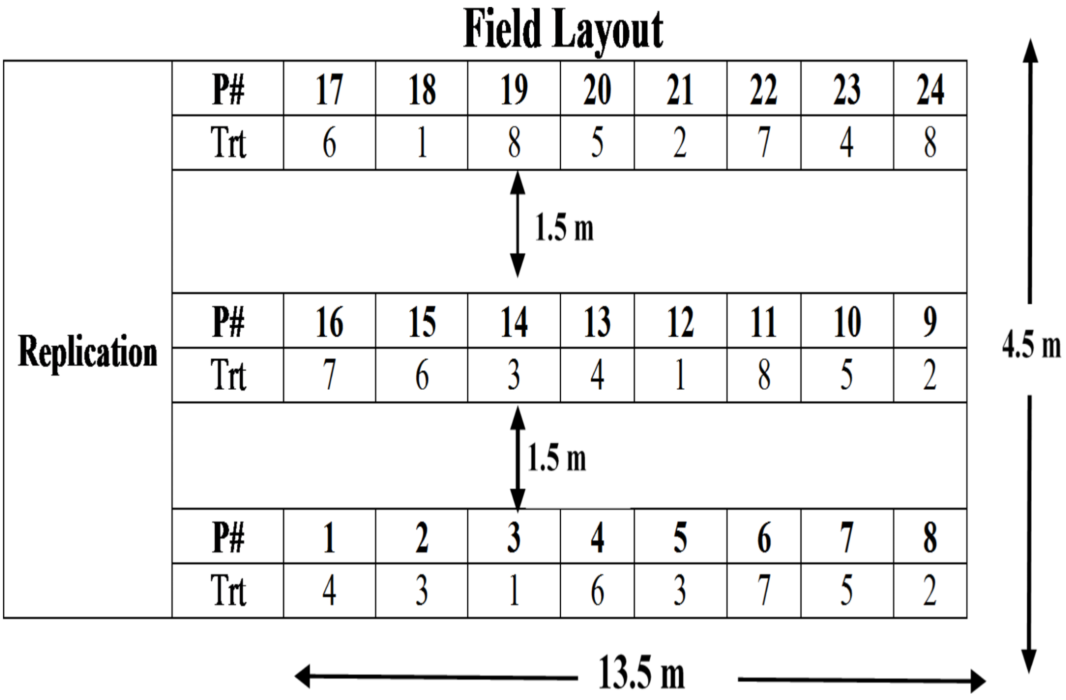
Field preparation (plotting)

The experiment was conducted at the University of Gondar farmland in the Amhara Region, Ethiopia. The experimental area underwent ploughing five times using oxen, and plots were established with dimensions of 1.6 m width and 2.4 m length. Employing a randomized block design, the experiment comprised three replications, resulting in a total of 24 experimental plots. Biochar was grounded into a powder; air dried, put through a 2 mm filter, and then treated with soil in varying amounts for nutrient analysis. The Effects of biochar was under evaluation using Teff as a test crop. The experiment was consists of 8 treatments with four levels of biochar, BC1, BC2, BC3, and BC4 of 1000, 2500, 5000 and 10,000 kg/ha respectively, one recommended mineral fertilizer, MF, (100 kg NPS and 100 kg Urea/ha), two combinations of biochar and mineral fertilizer, BC1M and BC3M and control treatments (C) (Table 1). Randomized complete block design (RCBD) with three replications was used for field layout (Fig. 3). A total area of 13.5 m × 4.5 m land was allotted for the experiment. Soil samples were taken separately in 24 plots and composite into 8 representative samples corresponding to each treatment.

Control (Teff plot without BC, MF, or mixed), BC1 (Teff plot 1000 kg/ha BC added), BC2 (Teff plot 2500 kg/ha BC added), BC3 (Teff plot 5000 kg/ha BC added), BC4 (Teff plot 10000 kg/ha BC added), MF (Teff plot mineral fertilizer 100 kg MF added), BC1MF (Teff plot mixed 1000 kg/ha BC1 + MF added), and BC3MF, (Teff plot mixed 5000 kg/ha BC3 + MF added).

Treatment code	Trt code	Plot number in triplicate		
Control	1	18	12	3
BC1	2	21	9	8
BC2	3	14	2	5
BC3	4	23	13	1
BC4	5	20	10	7
MF	6	17	15	4
BC1MF	7	22	16	6
BC3MF	8	19	24	11

Table 1. Treatments and their placement on each plot within the replications.



P#	17	18	19	20	21	22	23	24
Trt	6	1	8	5	2	7	4	8
P#	16	15	14	13	12	11	10	9
Trt	7	6	3	4	1	8	5	2
P#	1	2	3	4	5	6	7	8
Trt	4	3	1	6	3	7	5	2

Fig. 3. Farmland or field layout of Teff crop.

Statistical analysis

The results were presented as the average of three replicates along with their standard deviation. The homogeneity of variance was evaluated using Levene's test. Statistical analysis was conducted using Origin software (Originpro 16). An analysis of variance (ANOVA) was performed to determine the impact of water hyacinth BC in Teff yield. Significant differences between mean values were assessed using Tukey's (HSD) test at a significance level of $\alpha = 0.05$. Turning water hyacinth into biochar raises soil nutrient levels, which may increase agricultural output. In particular, it implies that water hyacinth-derived biochar will raise vital soil nutrients, which could improve crop output and growth.

Method validation and performance

Linearity, determination coefficient, recovery, precision and accuracy, limit of detection (LOD), and limit of quantification (LOQ) were used to validate the method's performance along with certified reference materials (CRM). By calibrating the series of working standard solutions of each analyte and using the determination coefficient (R^2) of each analyte derived from their calibration curve, the linearity of the procedure was investigated. Analysis of the spiked soil and biochar sample revealed the method's recovery (Table 2). A triplicate analysis of the samples was used to determine it. For percent recovery, relative standard deviation, and bias were determined by Eqs. 3, 4, and 5[40–42].

$$Recovery\ (\%) = \frac{(Conc.\ spiked\ sample - Conc.\ in\ unspicked\ sample)}{Amount\ added\ conc.} \times 100 \tag{3}$$

A percentage recovery that falls between 80 and 120% is acceptable.

$$RSD\ (\%) = \frac{Standard\ deviation\ (SD)}{Mean} \times 100 \tag{4}$$

The percentage RSD in analytical sciences shouldn't be higher than 15%. Bias measures the difference between the mean measured value and the certified value. The acceptable range is ± 5%.

$$Bias\ (\%) = \frac{Mean\,measured\,value - cerified\,value}{certified\,value} \times 100 \tag{5}$$

The accuracy and precision of the procedure were assessed using RSD and percentage recovery. The standard deviation of the blank (obtained from 3 triplicate measurements for each analyte) was multiplied by 3 and 10 to calculate the LOD and LOQ, respectively. The final LOD and LOQ values were obtained by further dividing these values by the appropriate slopes of the calibration curve (Table 2).

Analyte	Unit	Certified value	Spiked conc.	Unspiked conc.	Added conc.	%*R*	%Bias	*R*^{2}	%RSD	LOD	LOQ
OC	%	13.63 ± 0.75	32.40	13.95 ± 0.65	20.00	92.25	+ 2.42	0.9997	4.45–4.89	0.002	0.047
TN	%	0.67 ± 0.10	20.85	0.69 ± 0.01	20.00	100.8	+ 2.99	0.9998	1.42–1.47	0.002	0.052
TP	%	8.79 ± 0.01	29.80	8.80 ± 0.01	20.00	105.0	+ 0.11	0.9997	0.113–0.114	0.002	0.059
S	%	0.35 ± 0.20	20.30	0.34 ± 0.03	20.00	99.8	− 2.86	0.9992	0.081–0.097	0.002	0.061
K	mg/kg	117.35 ± 1.82	135.28	117.50 ± 2.00	20.00	88.9	+ 0.13	0.9998	1.67–1.73	0.003	0.077
Ca	mg/kg	159.10 ± 0.30	177.50	159.00 ± 0.50	20.00	92.5	+ 0.25	0.9997	0.31–0.32	0.001	0.037
Mg	mg/kg	73.64 ± 0.53	92.12	73.50 ± 0.70	20.00	93.1	− 0.19	0.9992	0.94–0.96	0.002	0.073
Fe	mg/kg	228.92 ± 1.09	249.20	230.00 ± 2.80	20.00	96.0	+ 0.47	0.9995	1.20–1.23	0.002	0.063
Mn	mg/kg	13.82 ± 0.03	32.90	13.80 ± 0.07	20.00	95.5	− 0.14	0.9995	0.50–0.51	0.002	0.053
Cu	mg/kg	0.21 ± 0.001	19.18	0.20 ± 0.002	20.00	94.9	− 4.76	0.9997	0.99–1.01	0.002	0.067
Ni	mg/kg	0.52 ± 0.011	19.60	0.50 ± 0.016	20.00	95.5	− 3.85	0.9990	3.19–3.31	0.002	0.073
Cd	mg/kg	0.078 ± 0.001	20.01	0.08 ± 0.001	20.00	99.65	+ 2.56	0.9996	1.23–1.27	0.002	0.065
Pb	mg/kg	0.29 ± 0.009	19.90	0.30 ± 0.014	20.00	98.0	+ 3.57	0.9999	4.46–4.90	0.003	0.078
Cr	mg/kg	0.45 ± 0.01	19.99	BDL	20.00	99.95	–	0.9997	–	–	–
Zn	mg/kg	0.29 ± 0.02	19.20	0.30 ± 0.02	20.00	94.5	+ 3.45	0.9992	6.25–7.14	0.017	0.057

Table 2. CRM certified value (mg/kg), spiked (mg/kg), and unspiked (mg/kg), and added concentration (mg/kg), recovery, R^2, RSD (%), LOD, and LOQ of nutrients in soil samples.

Quality control (QC) and quality assurance (QA)

A thorough quality control method was applied to every analytical technique. Each biochar and soil sample was evaluated using a procedural blank (made only from the mixture of all chemicals and/or reagents used in sample digestion) and a spiked sample. To track and evaluate the amount of nutrients and trace metals added during the analytical process, these samples have gone through the full digestion and analysis process. Every reagent utilized in this investigation as standard were certified reference materials (CRM). All CRM were used Sigmaaldrich certified materials. Every piece of glassware was cleaned using soap and tap water, steeped for 24 h in diluted chromic acid, and then rinsed with distilled water and acetone before being used.

Results and discussion

Method validation

The method validation results are shown in Table 1. From the result, the percentage recovery (%R) of metals ranged from 88.9 to 99.65%, found within the acceptable analytical ranges of 80–120%, with reliable precision (%RSD < 10), which ranged from 0.31 to 7.14%, and the percent bias (%bias) of metals ranged from − 4.76 to + 3.57% also found acceptable range of ± 5.0% in which confirms the method was precise and accurate (equ.3, 4, and4). The determination coefficient R^2 ≥ 0.9990; showed a linear relationship between concentration and intensity. The LOD and LOQ were in the range of 0.001 to 0.017 and 0.037–0.078 mg/kg, respectively (Table 2), this result were less than the minimum concentration of metals in soil samples. This showed the method is accurate and precise for analyzing metal nutrients in soil samples.

Biochar yield

The harvested dried WH biomass (50 kg) was converted into biochar by the pyrolysis process at a temperature of 300 °C with a residence time of 40 min, an airflow rate of 2 m/s. Fresh WH biomass was dried in sunlight for 30 days in room temperature and ventilated drying unit. The result showed that dried WH with 5% moisture contents was obtained (Equ.1)[31].

Under these conditions, the pyrolysis process yielded 22.3 kg (44.6%) water hyacinth biochar (WHBC) (Equ.2). Previous studies also showed that the yield of biochar at the same temperature pyrolysis provided approximately the same yield[43,44]. The yield of WHBC was influenced by the composition of the plant's fresh materials, including leaves, stems, and roots. At higher pyrolysis temperatures, the roots and leaves were more challenging to convert to biochar, often being fully reduced to ash. In contrast, the stem produced more biochar than other plant parts. Leaves and roots contain more hemicellulose and cellulose, which are highly biodegradable and more readily turn to ash during pyrolysis[11,45]. The stem, however, has a higher lignin content, which is more resistant to decomposition[11]. Increasing the temperature accelerates the breakdown of lignocellulosic components, leading to a lower overall char yield[46]. The stable organic matter (SOM) in WHBC increased with higher temperatures and longer heating times, with the highest SOM observed at 300 °C. Moderate pyrolysis conditions specifically heating WH at 200, 250, or 300 °C for 30 to 40 min, with an airflow of 2 to 3 m/s created an optimal environment for WH biochar production[22]. As a result, this pyrolysis process was appropriate to get reasonable amount of WHBC yield that could be realistic to enhance the soil fertility and maximize plant production.

The fresh water hyacinth and biochar pH, EC, and nutrient concentration

As shows on the Table 3; Fig. 4, WHBC exhibited a significantly higher pH (8.11 ± 0.91) compared to RWH (6.1 ± 0.4). This increase in pH during biochar production was a common observation. The pH of the WHBC of this study was consistent with other studies which was in alkaline range at the same temperature[28]. According to Zhang et al.[21] and Liu et al.[47], this pH value is higher at temperatures between 250 and 550 °C and 300

Parameters	Unit	RWH	WHBC
pH	–	6.1 ± 0.4	8.11 ± 0.91
EC	mS/cm	13.2 ± 0.5	18.70 ± 1.15
C/N ratio	–	11.6 ± 1.0	20.22 ± 0.95
OC	%	11.6 ± 2.5	13.95 ± 0.65
TN	%	1.0 ± 0.4	0.69 ± 0.010
TP	%	11.0 ± 3.6	8.80 ± 0.01
S	%	0.3 ± 0.1	0.34 ± 0. 03
K	mg/kg	114.5 ± 0.9	117.50 ± 2.00
Ca	mg/kg	161.8 ± 2.6	159.00 ± 0.50
Mg	mg/kg	69.0 ± 1.8	73.50 ± 0.70
Fe	mg/kg	233.7 ± 1.6	230.0 ± 2.80
Mn	mg/kg	15.6 ± 1.6	13.80 ± 0.07
Cu	mg/kg	0.3 ± 0.03	0.20 ± 0.02
Ni	mg/kg	0.3 ± 0.04	0.50 ± 0.16
Cd	mg/kg	0.1 ± 0.03	0.08 ± 0.01
Pb	mg/kg	0.3 ± 0.05	0.30 ± 0.14
Cr	mg/kg	BDL	BDL
Zn	mg/kg	0.4 ± 0.10	0.30 ± 0.02

Table 3. Mean and standard deviation (std.) ($n = 3$ each measurement) of RWH and WHBC analyses. *RWH* raw water hyacinth, *WHBC* water hyacinth biochar.

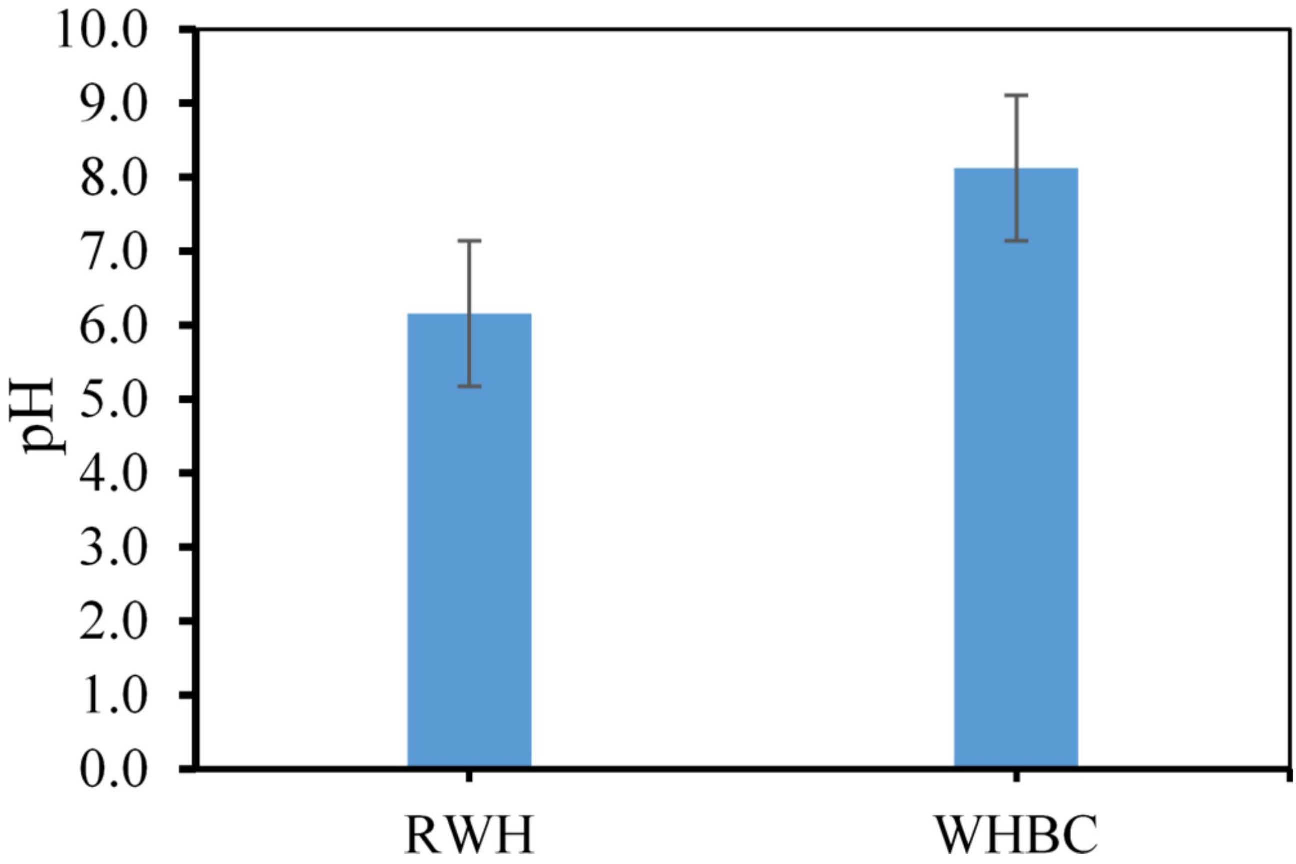


Fig. 4. The pH of raw water hyacinth and biochar (RWH is raw water hyacinth and WHBC is water hyacinth biochar).

and 700 °C, respectively. The pH values of biochar made from other plants, however, were consistent with this value[48,49]. The alkaline property of the biochar derived mainly from its composition, the formation of alkali salt, the rise in the amount of ash, and the replacement of acidic functional groups by alkaline during pyrolysis may be the cause as reported by[50–52]. In reducing the acidity of the soil, BC's alkalinity should be quite beneficial[53]. Consequently, WHBC ought to be applied as a regulating influence for soils with low pH.

WHBC showed a higher EC (18.70 ± 1.15 mS/cm) than RWH (13.2 ± 0.5 mS/cm) (Table 4). These occurrences were mostly caused by the increasing residue content, mineral ash content, and loss of volatile compounds at high temperatures during the pyrolysis process[54,55]. The amount of soluble salts present is confirmed by the biochar EC value, which is also a crucial indicator of the fertilizing potential of biochar[56]. Because of its mineral concentration, WHBC should be taken into consideration to increase soil fertility.

WHBC had a higher C/N ratio (20.22 ± 0.95) than RWH (11.6 ± 1.0) at optimized temperature, residence time, and air flow rate at 300 °C, 40 min, and 2 m/s respectively (Table 3)[43]. This indicates that a significant portion of the organic matter in RWH was retained during the biochar production process. This may be rises of the level of aromaticity as the charring temperature is rises[57]. The pyrolysis process at 300 °C temperature, 40 min residence time, and 2 m/s air flow rate revealed the aromaticity and stability of biochar carbon[12]. In comparison to biochar formed at high temperatures, those produced at lower temperatures (300 °C) may likely have more organic functional groups of COOH and C-OH, increasing sites for nutrient retention[58]. Approximately the same result reported by[43], higher C/N ratio 26.50 at 300 °C and 40 min residence time[59] and 15.5 at 350 °C[22] were recorded. Moreover, this difference may be due to the instrument, potentially utilized for the pyrolysis process in this study, facilitated large-scale biochar (BC) production, and featuring barrels with multiple perforations. In contrast, other studies conducted the pyrolysis process using an electric furnace. Moreover, a decreased C/N ratio causes ammonia volatilization, which results in the loss of surplus nitrogen[11]. The C/N ratio determines how well organic substrates in the BC may mineralize and release inorganic nitrogen when applied to soil. The C/N ratio of WHBC indicates that it has a higher nutritional profile; a larger ratio might be studied if it were applied to soil. A higher C/N ratio in biochar is generally desirable for soil amendment as it improves soil fertility and reduces nutrient leaching[60].

Both TN and TP showed a slight decrease in WHBC compared to RWH. This could be due to volatilization or leaching of these nutrients during the biochar production process[22]. As Bottezini et al.[18] reported the TP content for WHBC that was pyrolyzed at a temperature between 400 and 600 °C ranged from 7.23 to 7.56%. This might be due to WH ability to absorb large amounts of P[17]. Besides, pyrolysis temperature affects the volatilization properties and nutrient availability in biochar[61]. Therefore, WH biochar can be a viable option for soil fertility amendment.

Concentrations of metals like K, Ca, Mg, Fe, Mn, Cu, Ni, Cd, Pb, and Zn were generally similar or slightly lower in WHBC compared to RWH. This suggests that most metals were retained within the biochar during the pyrolysis process[46]. Moreover, the concentration of Fe in the WHBC was much higher than other available metals with the maximum value of 230 ± 2.80 mg/kg. The concentration of available metals Ca, K, and Mg were larger next to Fe. But, the concentration of heavy metals found in this report were Mn > Ni > Zn > Pb > Cu > Cd. Whereas, Cr was not found in the sample. Therefore, the WHBC was abundant in available and heavy metals (Table 3). Different scholars' agreed that the presence of Mg, Ca, and P in the biochar contribute to optimize cation-exchange processes between biochar and soil. According to feed regulations, the content of heavy metals including arsenic, lead, cadmium and mercury must be stated. Their limits differ from those for EBC-Agro organic quality. The use of biochar as feed is based on the following thresholds to be calculated on 88% DM (European Biochar Foundation (EBC)[62], : arsenic (2 mg/kg; lead (10 mg/kg); cadmium (0.8 mg/kg) and mercury (0.1 mg/kg). Results of all potential heavy metals are below these threshold values. Therefore, WHBC exhibited distinct chemical properties compared to raw water hyacinth. These changes have implications for its potential use as a soil amendment, including improved soil pH, enhanced nutrient retention, and potential for metal immobilization.

Properties		Unit	Mean
pH		-	5.8
Bulk density		g cm^{-3}	1.14 ± 0.04
Texture	Sand	%	19 ± 3.00
	Silt	%	20 ± 2.65
	Clay	%	61 ± 3.61
TN		mg/kg	349
TP		mg/kg	194
TK		mg/kg	585
TS		mg/kg	133
OC		%	1.52

Table 4. Physicochemical the soil properties before cropping. *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *TS* total sulfur, *OC* organic carbon.

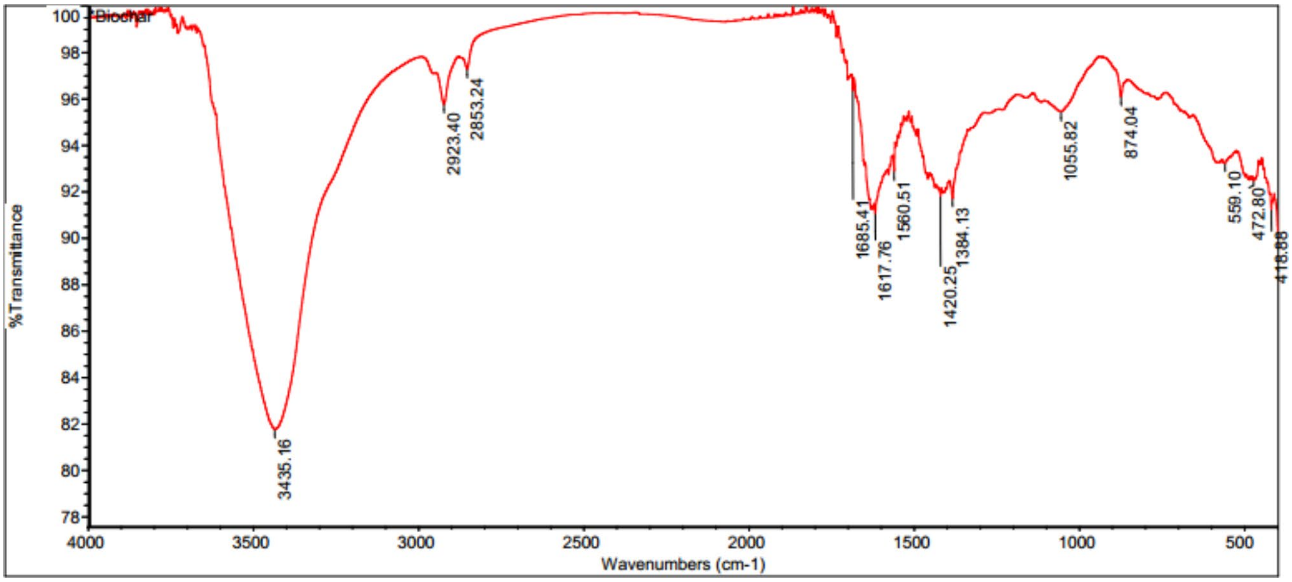


Fig. 5. Fourier transform infrared spectroscopy spectra of WHBC produced at 300 °C.

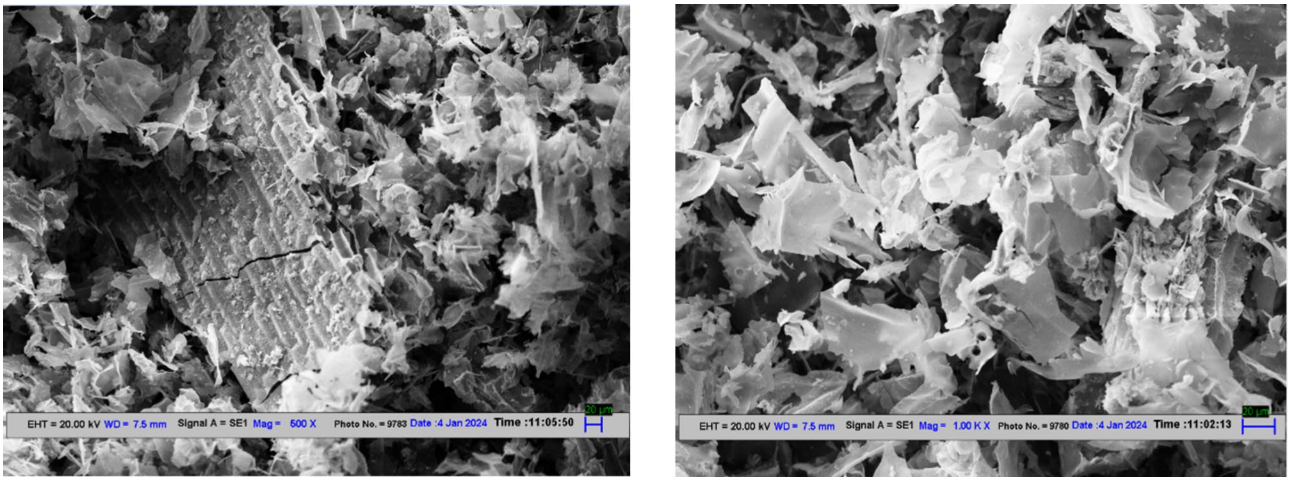


Fig. 6. Morphological structure of WH biochar using SEM.

Stractural and chemical characterization of WH Biochar

Figure 5 displays the FTIR spectra that representing the functional groups of WHBC prepared at 300 °C. The broad band around 3435 cm^{-1} likely corresponds to the hydroxyl (OH) group stretching to 2853 cm^{-1}. The spectra between 2923 and 2853 cm^{-1} are attributed to aliphatic CH stretching[63]. The spectral band around 1618 cm^{-1}, assigned to the stretching of aromatic C═C and C═O in vinyl ethers[50,51], was more prominent, likely due to the high-energy pyrolysis temperature breaking double bonds[23]. A band around 1420 cm^{-1} was associated with in-plane C–O–H bending[64]. The band around 1384 cm^{-1} was attributed to the stretching of the C–O group[65].

The smaller band around 1384 cm^{-1} could be related to the stretching of aliphatic ethers (C–O–C) and the bending of alcohol (C–H)[64]. A symmetric C–O stretching may explain the band around 1056 cm^{-1}[51,53]. The spectral bands around 874 cm^{-1} were likely due to poly-nuclear aromatics from the out-of-plane bending of C–H[65]. The bands below 665 cm^{-1} could be assigned to aromatic rings[66]. Regardless of the feedstock used, a 300 °C temperature biochar exhibited more surface polar functional groups[23]. Therefore, at 300 °C temperature biochar could be applied to improve soil nutrient adsorption capability due to its relatively high surface functionality.

Figure 6 shows the surface topography and morphology of biochar produced from water hyacinth at temperature condition of 300 °C and a burning time of 40 min using Scanning electronic microscope (SEM) at different magnifications (20 kV × 500 and 1000). WHBC produced under these conditions encompasses some vacuoles and honey-comb like pores structure which may be attributed to insufficient carbonization and probably catalyzed by biopolymers connected by biomolecular bonds in raw material cells. In addition, the SEM images for WHBC displays a heterogeneous rough surface, many pores in shape at 15 kV × 1000 as well as pores in different shapes, size and depth at different magnifications (Fig. 6).

Garg et al.[67] conducted SEM and FTIR analyses to understand the morphological structure of water hyacinth biochar. The SEM images revealed that WHBC has high porosity and specific surface area, while FTIR analysis identified three major surface functional groups (–OH, –COOH, and –CO) on the biochar particles. These functional groups suggest that the biochar produced from locally collected water hyacinth is porous and hydrophilic in nature.

Impact of WH Biochar on soil nutrients

The soil pH before planting was 5.8, classifying it as moderately acidic (Table 3). According to Osman[68], soils with pH ranges of 5.6–6.0, 6.1–6.5, 6.6–7.4, 7.4–7.8, and 7.8–8.4 are categorized as moderately acidic, slightly acidic, neutral, slightly alkaline, and moderately basic, respectively, while soils with a pH above 8.5 are considered strongly alkaline. Based on this classification, the soil sample's pH of 5.8 confirms it as moderately acidic. Therefore, this soil required amendment for improving soil fertility. The results of bulk density (BD) of the soil ranged from 1.1 to 1.2 with mean values of 1.14 ± 0.04. Soil texture values ranged from 16 to 22, 18 to 23 and 58 to 65 for sand, silt and clay, respectively. As expected, soil bulk density is related to the amount of organic matter present in the soil (Table 4) in this table there isn't any organic matter value. Organic matter content affects bulk density. The values are similar to most cultivated soils of Ethiopia, which is attributed to land use history such as complete removal of biomass from the field and rapid rate of mineralization[69].

The results on Table 5 revealed that biochar application significantly improves soil fertility by enhancing total nitrogen (TN), total phosphorus (TP), total potassium (TK), total sulfur (TS), and total organic carbon (TOC) levels compared to the control and untreated soil. All the treatments, BC exhibited the nutrient enrichment, with a range of TN from 461 to 805 mg/kg, TP from 1009 to 1092 mg/kg, TK from 1029 to 1255 mg/kg, and TOC from 11.43 to 12.62%, indicating the impact of application conditions biochar. In contrast, the untreated soil showed the lowest nutrient levels, highlighting the transformative impact of biochar amendments. WHBC is therefore a useful tool for adjusting the adsorption of nutrients and carbon storage capacities of soil[70]. Phosphorus and potassium exhibited the most pronounced increases, while sulfur showed minimal variation, suggesting that biochar's influence on sulfur dynamics may be limited or require complementary inputs. The dramatic rise in TOC underscores biochar's role in contributing organic matter, improving soil structure, and enhancing microbial activity. Incorporating biochar into soil can substantially enhance soil quality by increasing its water retention capacity, enriching nutrient availability, improving soil structure through reduced bulk density, elevating pH levels in acidic soils, and promoting microbial activity. These improvements collectively contribute to enhanced plant growth and increased crop yields[71]. Particularly at optimized levels like BC2, BC4 and BC3M, were a promising tool for sustainable soil management, with potential to boost soil fertility, support agricultural productivity, and enhance resilience to soil degradation. Mixing biochar with mineral fertilizer (BC3M) plays a synergistic role in enhancing soil fertility (Table 5). Biochar, rich in stable organic carbon, improves soil structure, water retention, and microbial activity, while mineral fertilizers provide readily available nutrients to plants. Together, they address both short- and long-term soil nutrient needs[72,73]. Biochar can reduce nutrient leaching and volatilization losses from mineral fertilizers, enhancing nutrient use efficiency and ensuring a steady nutrient supply to plants over time[60]. Additionally, biochar's porous structure adsorbs and retains nutrients from fertilizers, preventing their rapid depletion and increasing their availability in the root zone[74]. Thus, integrating biochar with mineral fertilizer is an effective strategy for sustainable soil management, promoting agricultural productivity while reducing environmental impacts. Further studies are recommended to explore long-term effects, nutrient cycling dynamics, and the integration of biochar with other soil management strategies.

The BC4 sample's surplus nitrogen may have low N usage efficiency (NUE), which would result in a large financial loss for the farmer[75]. Suitable nitrogen (N) in the soil can play a significant role in sustaining crop production on nutrient deficient soil. However, excessive application of nitrogen fertilizer may pollute the soil[76].

As Fig. 7 shows, the BC4 sample showed the highest levels of TN, TK, TP, and TOC compared to the treated samples, indicating the nutrient richness of the treated soil[77,78]. The BC2 treatment showed relatively moderate TN, TK, TP, and TOC levels but significantly different from other treatments ($p < 0.05$), reflecting that application of BC to the soil improves nutrient availability and can positively impact crop yield[79,80].

Sample	TN (mg/kg)	TP (mg/kg)	TK (mg/kg)	TS (mg/kg)	TOC (%)
Control	468	243	668	237	2.43
BC1	471	1009	1029	239	11.59
BC2	689	1056	1119	245	12.26
BC4	805	1092	1255	254	12.62
BC3MF	420	1021	1035	242	11.43
Before (B)	349	194	585	133	1.52

Table 5. WH biochar–soil incorporating nutrient analysis. Control (Teff plot without BC, MF, or mixed), BC1 (Teff plot 1000 kg/ha BC added), BC2 (Teff plot 2500 kg/ha BC added), BC3 (Teff plot 5000 kg/ha BC added), BC4 (Teff plot 10000 kg/ha BC added), MF (Teff plot mineral fertilizer 100 kg MF added), BC1MF (Teff plot mixed 1000 kg/ha BC1 + MF added), and BC3MF, (Teff plot mixed 5000 kg/ha BC3 + MF added)

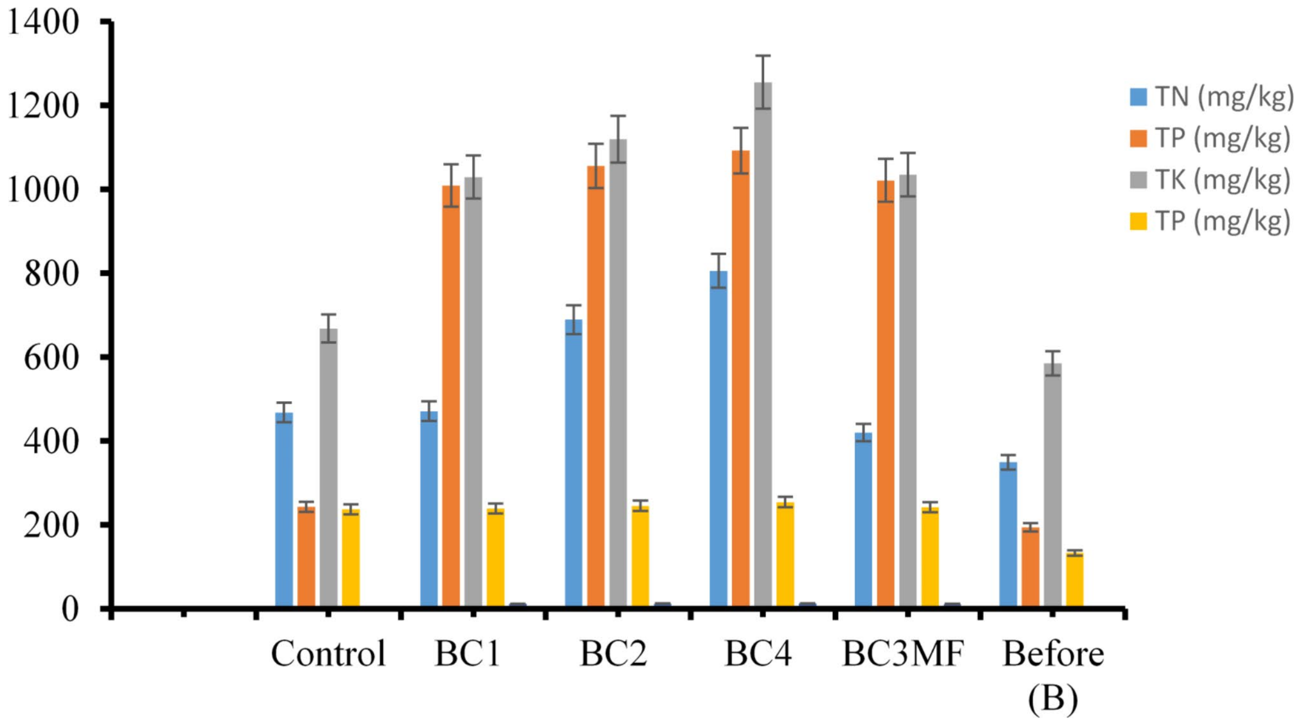


Fig. 7. The impact of WH biochar on soil nutrients and organic carbon levels across different biochar treatments. The concentrations of total nitrogen (TN), total phosphorus (TP), total potassium (TK), total organic carbon (TOC) and in soil samples across different treatments: Control, BC1, BC2, BC4, BC3MF, and the "Before" plantation, (B). The "Before" sample represents the initial soil properties prior to any treatments, while the others correspond to various amount of biochar treatments.

Addition of BC on farmland and its yields

Figure 8 presents the effects of different biochar (BC) treatments on the fresh mass, dry mass, and grain yields of Teff crops, analyzed at a 95% confidence interval. The analysis of variance (ANOVA) for the Teff fresh mass data revealed significant differences among the soil treatment groups ($p < 0.05$), confirming that the treatments had distinct effects on Teff growth. Specifically, the treatments BC1, BC2, MF, BC1MF, and BC3MF showed significantly higher fresh mass compared to the control, with mean values ranging between 1050 g and 1250 ± 50 g. The control group exhibited a lower mean fresh mass of 1000 ± 206.64 g, indicating the limited productivity of untreated soil. Meanwhile, BC3 and BC4 treatments demonstrated significantly lower fresh mass, with mean values below 800 ± 250.14 g (Fig. 8a), the reduced yield could be caused by nutrients having an adverse impact on plant growth by perhaps generating waterlogging from excessive water retention, decreasing nutrient availability, and impeding root development by making the soil less porous, which would ultimately result in lower crop yields[77,78].

The analysis of variance (ANOVA) for the Teff dry mass data indicated statistically significant differences among the soil treatments ($p < 0.05$). Treatments BC1, BC2, MF, BC1MF, and BC3MF displayed significantly higher dry mass compared to the control, with mean values ranging from 600 g to 750 ± 95.2 g. The control group showed a lower mean dry mass of approximately 543.33 ± 82.82 g, highlighting the limited productivity of untreated soil. In contrast, BC3 and BC4 treatments recorded the lowest dry mass values, averaging below 400 ± 44.5 g (Fig. 8b)[77]. BC2 had the highest mean dry mass, shows an effective treatment. The MF treatment produced also a substantial dry mass, highlighting its efficacy[81]. Moreover, treatments BC1 and BC2 showed relatively smaller standard errors (SE ≈ ± 30 g), signifying consistent performance across replicates, while BC3 and BC4 treatments displayed higher variability (SE ≈ ± 50 g) (Fig. 8b). Combinations of biochar with mineral fertilizers (BC1MF and BC3MF) produced the highest dry mass values (700–750 g) and exhibited statistically significant differences compared to the control and single-component treatments ($p < 0.05$).

In addition, grain yield is a critical parameter, and the results showed significant variability across treatments. The analysis of variance (ANOVA) for Teff grain mass revealed significant differences among the soil treatments ($p < 0.05$). The control plot yielded a mean of 50.00 ± 13.23 g. The BC2 treatment produced the highest grain yield (95.00 ± 39.69 g), demonstrating its superiority in enhancing grain production. This indicates that BC2 provided optimal soil conditions for grain yield, likely due to improved nutrient retention and availability[78]. The BC1, BC1MF, and MF treatments also demonstrated moderately increased grain mass (~ 70–80 g) compared to the control but were significantly lower than BC2 ($p < 0.05$). The MF treatment yielded 75.00 ± 36.06 g, which was also relatively high, supporting the positive influence of mineral fertilization. In contrast, BC4 had the lowest grain yield (41.67 ± 16.19 g), suggesting it might be the least effective or potentially even detrimental under the

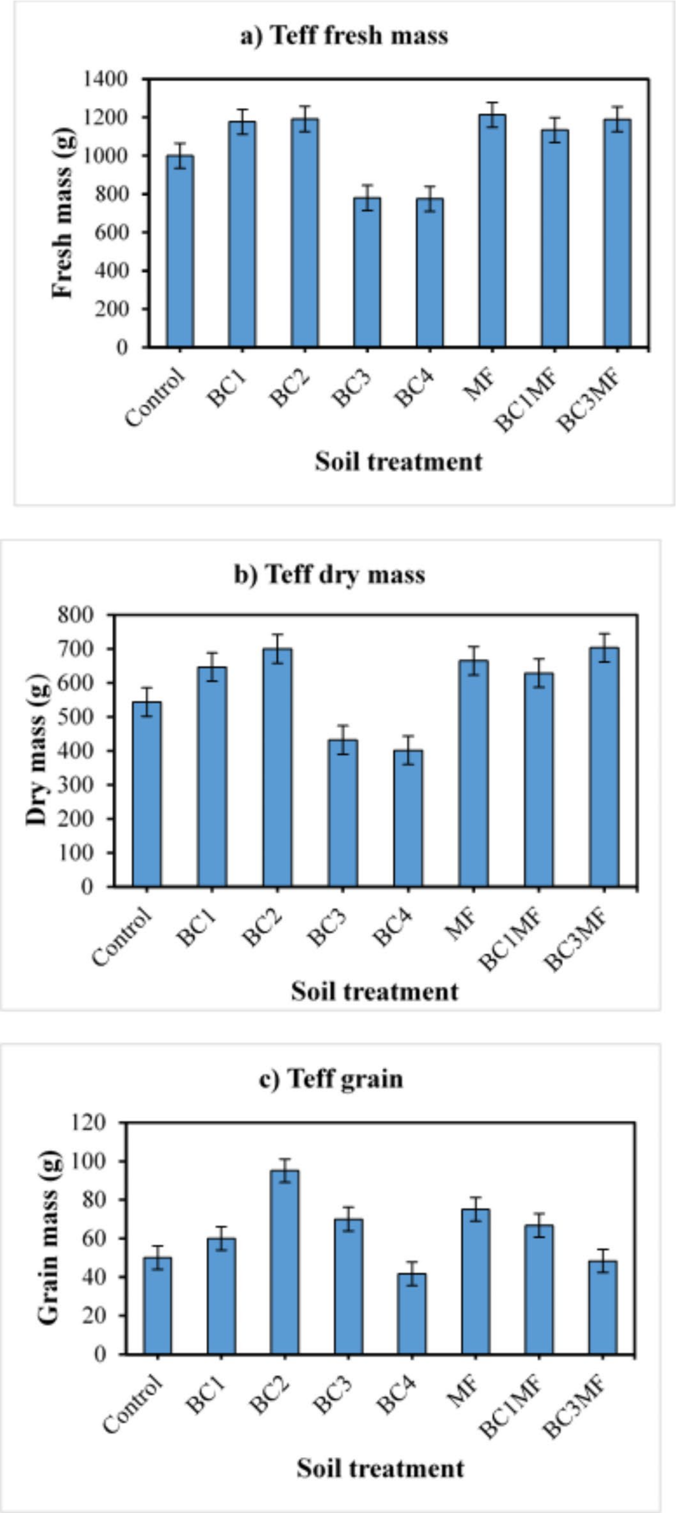


Fig. 8. Teff yield ((**a**) fresh, (**b**) dry, and (**c**) grain) with different soil treatment with biochar (BC). Control (Teff plot without BC, MF, or mixed), BC1 (Teff plot 1000 kg/ha BC added), BC2 (Teff plot 2500 kg/ha BC added), BC3 (Teff plot 5000 kg/ha BC added), BC4 (Teff plot 10000 kg/ha BC added), MF (Teff plot mineral fertilizer 100 kg MF added), BC1MF (Teff plot mixed 1000 kg/ha BC1 + MF added), and BC3MF, (Teff plot mixed 5000 kg/ha BC3 + MF added).

given conditions (Fig. 8c). The combination treatment BC3MF showed a slight improvement over BC4 but still underperformed compared to BC1MF and MF treatments.

Other studies on biochar from water hyacinth disclosed that enhanced maize seedling vigour index and soil biological activity, indicating potential for increased crop yield, fresh mass, and dry mass in treated soil[12,60,61]. Fentie et al.[82], reported WHBC application increasing wheat dry biomass by 260% and grain yield by 173%, showcasing its potential to improve crop productivity. The increment of Teff crop productivity may be due to the enhancement of nutrient availability, soil porosity and aeration, soil pH, and carbon sequestration. The combined treatments suggest that when biochar used with mineral fertilizers, can still be effective but may not always outperform individual treatments depending on the type and combination used[83]. The results demonstrated that different types of biochar had varying effects on Teff crop yields. BC2 consistently showed the best performance across all parameters, indicating its potential as a beneficial soil amendment. In contrast, BC4 was the least effective. The use of mineral fertilizer also resulted in high yields, comparable to the best-performing biochar treatments, BC2. Combining biochar with mineral fertilizer did not always yield better results, indicating the need for careful selection and application of biochar types in combination with other fertilizers.

Remarkably, despite the overall lack of significant differences, the yields from the BC2 treatment are comparable to those of the mineral fertilizer (MF) and the combined treatments. This finding suggests that BC2 may have a beneficial effect on Teff yield, similar to that of mineral fertilizers. The comparability of BC2 yields to MF and combined treatments highlights BC2 as a potentially effective biochar type for enhancing Teff productivity. These findings highlighted the importance of selecting the appropriate biochar type to maximize crop productivity. These findings underscore the potential of biochar as a sustainable soil amendment strategy to optimize crop yields in nutrient-deficient soils. Further studies could focus on the long-term impacts and the specific mechanisms driving the observed interactions.

Conclusion

According to the result WH biochar production involved using raw dry WH with a 5% moisture content and producing the necessary amount of WHBC over 40 min at 300 °C with a 2 m/s air supply. The characterization result of WHBC such as pH, EC, and nutrient concentration showed WHBC has significant agricultural benefits. The alkalinity properties of the BC could make valuable for improving soil acidity challenges. Besides, EC of WHBC could make use of increasing the amount of soluble salts present is confirmed by the biochar EC value, which is also a crucial indicator of the fertilizing potential of biochar. WHBC's acceptable C/N ratio may also make it a good organic substrate for mineralization and the release of inorganic nitrogen when added to soil. The presence of Mg, Ca, and P in the biochar contribute to optimize cation-exchange processes between biochar and soil. FTIR and SEM results showed that WHBC exhibited more surface polar functional groups, it could be applied to improve soil nutrient adsorption capability due to its relatively high surface functionality. The optimized BC (2500 kg/ha) added to the Teff plot considerably enhanced the fresh mass, dry mass, and grain yield of the Teff crop. These findings have implications for WHBC's sustainable agricultural practices aimed at enhancing both soil health and crop productivity in Teff crop cultivation systems. Future studies should explore the long-term effects of biochar on soil properties and crop yields to provide comprehensive recommendations for farmers.

Data availability

Data is provided within the manuscript.

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Author contributions

Conceptualization: D.T, Y.K., A.A.; Methodology: T.N., M.G.,B.C; Formal analysis: B.F., T.M., B.W., M.A.; Investigation: A.A.,D.T., T.M., M.G., T.N., G.A.; Writing original draft preparation: D.T., M.A., A.A.; Writing review and editing: D.T., A.A., T.N., G.A. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Ethical approval and guidelines

All methods are carried out according to the institution's guidelines and regulations.

Statement on permission for Water Hyacinth Collection

We confirm that all necessary permissions and licenses for the collection and utilization of water hyacinth were obtained from college of natural and computational science ethical committee in University of Gondar. These permissions ensure compliance with local and national regulations regarding the sustainable management of invasive species in the ecosystem surrounding Lake Tana.

Identification and authentication of the water hyacinth plant

The water hyacinth plant was identified and authenticated by Botanist Mr. Abiyu Enyew, MSc in Botanical Sciences, who currently serves as the Head of the Department of Biology at the College of Natural and Computational Sciences, University of Gondar.

Additional information

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