Valorization of Invasive Water Hyacinth into Biochar for Sustainable Soil Amendment and Enhanced Okra Productivity

Muntaha Munir,[a] Aisha Nazir,[a,*] Muhammad Ishfaq Khan,[b,*] Samreen Aslam,[a] Faiza Irshad,[a] Imtiaz Khan,[b] Muhammad Nauman Ahmad,[c] Tariq Aziz,[d,e] *, Nawal Al-Hoshani,[f] Amal Mohamed AlGarawi,[g] Rania Ali El Hadi Mohamed,[f] and Rewaa S. Jalal [h]

This study demonstrated the conversion of a harmful weed into value-added product, biochar. Pyrolysis of water hyacinth biomass was carried out in a semi-automated charcolator at 500 ºC (yield 36.7% ± 1.2%) and applied into the soil at three different concentrations (low, medium, and high). The biochar presented alkaline pH (8.4±0.04), moderate cation exchange capacity (1.83±0.04 meq/100g) and moderate electrical conductivity (2709±44.73 μS/cm). Fourier-transform infrared spectra indicated diverse types of functional groups (phenols, alcohols, unsaturated carbon compounds, and aromatic compounds) in *Eichhornia crassipes* biochar (ECB). Scanning electron microscopy and element dispersive X-ray analysis confirmed the high porosity (2.5 μm to 7.8 μm) and abundance of micro and macronutrients on biochar surface. Thermogravimetric analysis of ECB showed high thermal stability. Ameliorated soil edaphic parameters improved plant growth conditions. ECB added at medium concentration, remarkably increased shoot length and germination, and those of ECB added at high concentration recorded the highest chlorophyll content (60.5 SPAD). The experimental results showed favorable prospects for sustainable waste biomass recycling to produce valuable biochar, enhance soil health, and increase productivity of okra (*Abelmoschus esculentus* L.).

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Contact information: a: Institute of Botany, University of the Punjab, Lahore 54590, Pakistan; b: Department of Weed Science & Botany, The University of Agriculture Peshawar-25130 Peshawar KPK Pakistan; c: Department of Agricultural Chemistry, The University of Agriculture Peshawar-25130 Peshawar KPK Pakistan; d: Laboratory of Animal Health, Hygiene and Food Quality, Department of Agriculture, University of Ioannina Arta 47132, Greece; e: Institute of Molecular Biology and Biotechnology, University of Lahore Punjab, Pakistan; f: Department of Biology, College of Science, Princess Nourah bint Abdulrahman University, P.O. Box 84428, Riyadh 11671, Saudi Arabia; g: Department of Botany and Microbiology, College of Science, King Saud University, Riyadh 11451, Saudi Arabia; h: Department of Biological Sciences, College of Science, University of Jeddah, 21493, Jeddah, Saudi Arabia;

** Corresponding authors: aisha.botany@pu.edu.pk; mishfaq@aup.edu.pk*

INTRODUCTION

Water hyacinth (*Eichhornia crassipes*) is a rapidly growing aquatic weed. It has been described as the world's worst aquatic plant (Ezzariai *et al*. 2021; Abba and Sankarannair 2024). It poses remarkable ecological and economic challenges in water bodies (Zheng *et al*.

2022; Lázaro-Lobo *et al*. 2023; Palai *et al*. 2024). Its rapid proliferation disrupts the water bodies, obstructs the drainage channels, destroys aesthetics of waterways and provides habitat to mosquitoes, flies and other parasites, thus demanding an effective and sustainable ecofriendly management approach (Fentie *et al*. 2024a; Lawa *et al*. 2024; Kassa *et al*. 2025).

However, instead of considering the water hyacinth entirely an annoyance, its biomass can serve as feedstock to produce biochar. Biochar is the carbon-rich material obtained by the pyrolysis of biomass in low oxygen conditions (Gezahegn *et al*. 2024a). This approach has gained special focus due to its potential to ameliorate soil deficiencies and provide long-term sequestration of carbon. The quality of the biochar produced depends on the amount of oxygen present during thermal degradation. Having too much oxygen results in the excessive combustion of the biomass, which decreases biochar yield and affects its properties. With too little oxygen, incomplete carbonization occurs. With controlled and limited oxygen conditions, effective pyrolysis can take place, resulting in the production of biochar with high fixed carbon content, desirable porosity, and stable functional groups with little biochar. These properties improve the biochar's effectiveness as a soil amendment (Bao *et al*. 2022). Solar drying presents an eco-friendly and cost-efficient alternative to reduce the high moisture content of water hyacinth biomass before pyrolysis. Because the plant has a very high water content (90 to 95%), direct pyrolysis of the biomass without prior drying would be inefficient and require exorbitantly high energy. Research is needed to determine whether solar drying can be a cost-effective and practical means to dry this kind of biomass (Sharma *et al*. 2025a).

Recently, two emerging global issues have grabbed more interest in this ecofriendly approach. Firstly, it is helpful in carbon sequestration. Secondly, it is being used as a soil amendment to enhance soil fertility (Hamidzadeh *et al*. 2023; Khan *et al*. 2023; Xu *et al*. 2024). Different types of materials, including leaf litter, weeds biomass, fruits/ vegetables peels, sewage sludge, and animal litter have been explored for biochar production (KC and Mahat 2024; Khan *et al.* 2024; Johnson Jeyaraj and Sankararajan 2025).

Biochar has been shown to improve soil quality while promoting sustainable crop production and decreasing the need for chemical fertilizers (Rahman *et al.* 2024). This soil amendment improves each of the following soil properties: physical, chemical, and biological. The application of biochar lessens bulk density and increases porosity and water-holding capacity. These attributes are especially advantageous to crops grown in arid, acidic, or sandy soils. Additionally, biochar's porous architecture and large surface area assist in nutrient retention, leaching reduction, and the gradual, prolonged delivery of critical nutrients, especially nitrogen, phosphorus, and potassium (Rostami *et al.* 2024).

Biochar also mitigates soil acidity and fosters root development and soil microbial activity. It augments nutrient cycling and soil fertility, rendering soil pest resistant. This decreases reliance on biochar and soil fertilizers. The aforementioned components are critical for the sustained productivity of agriculture and for the health of the soil (Zhu *et al.* 2025). In addition, using biochar decreases reliance on the commercial fertilizers, which lowers the production costs and the exposure to environmental risks such as groundwater pollution and GHG emissions (Zhang *et al.* 2025a).

Biochar has numerous benefits, including consistent availability of nutrients during the entire crop growth period, which enhances produce quality and increases crop yield. Biochar maintains soil and ecosystem equilibrium while also increasing agricultural productivity when used correctly. The capacity of biochar to bridge high productivity farming and ecosystem conservation makes it crucial to sustainable farming. This duality makes it invaluable to sustainable agriculture (Sangotoye *et al.* 2024).

Water hyacinth (*Eichhornia crassipes*) is an aggressive invasive water plant that grows quickly to cover the surfaces of bodies of standing water. The abundant biomass produces an increasingly viable sustainable feedstock for biochar production. Very few studies have investigated the viability of water hyacinth for pyrolysis of biomass to biochar. Most studies have focused on the pollutant adsorption potentials or the physicochemical properties of water hyacinth. Originality for the present study stems from moving from these preliminary investigations to a full evaluation of the plantation potential of biochar from water hyacinth to the quality of soil and the growth of the plants.

This study advances biochar literature by linking specific biochar features to benefits in soil fertility, soil nutrients, and crop yield. Additionally, it compares the performance of water hyacinth biochar with other biochar made from different biomasses to underscore the advantages of water hyacinth biochar as an economically viable, large-scale, and environmentally friendly soil amendment. This study also adds value to biochar production by demonstrating the utilization of an environmentally problematic weed. It tackles invasive weed species while restoring soil and boosting agricultural production. It employs circular bioresource utilization to provide an innovative and pragmatic answer to the growing agricultural and environmental problems.

This study was conducted to assess 1) the suitability of water hyacinth biomass to produce biochar, 2) its physico-chemical characterization, and 3) evaluation of *Eichhornia crassipes* biochar (ECB) for soil amelioration and its effect on the growth of okra.

EXPERIMENTAL

Study Area

Water hyacinth was collected randomly from different ponds in Lahore (Punjab, Pakistan) and brought to Environmental biotechnology lab, Institute of Botany, University of the Punjab, Lahore.

Biochar Preparation

The weed biomass was washed and dried in sunlight for 15 days. The dried biomass was loaded in a semi-automated charcolator and pyrolyzed in a low supply of air according to the protocol used in our previous studies (Munir *et al*. 2025). Biochar was prepared under medium pyrolysis temperature at 500 °C for 3 h (This pyrolysis temperature is considered optimum, as shown by preliminary studies). The prepared biochar was collected the next day after cooling and stored carefully in polythene bags for further analysis and use.

Characterization of Biochar

The pH of biochar was measured using a calibrated pH meter (Model:WTW 82362 Wellheim Germany). A suspension of biochar was prepared by mixing 1:20 (w/v) ratio of biochar to deionized water, stirring for 20 min, and allowing the solids to settle for 1.0 h before measuring the pH. The electrical conductivity was measured with a precision EC meter (Model: HANNA HI 9835, Romania)). Samples were prepared similarly to the pH analysis. The total dissolved solids (TDS) and sodium chloride (NaCl) content were ascertained by using the same instrument, after a precision calibration with appropriate standard solutions (1:20 (w/v) - 0.5 g biochar in 10 mL DW). Yield (%) of biochar was computed using Eq. 1:

$$\text{Yield (\%)} = \frac{\text{mass of the biochar}}{\text{mass of feed stock}} \times 100 \qquad (1)$$

Proximate analyses including ash content (AC %), moisture content (MC %), and volatile matter content (VC %)) were determined according to ASTM D1762-84 and ASTM D3174-12 (ASTM D7582-15 (2013); Menon *et al*. 2018). Particularly, MC% was quantified by oven drying using 1.0 g of biochar sample at 105 °C for 24 h; VC% was calculated by heating the dried sample of biochar at 950 °C for 6 to 7 min in a covered crucible; and AC% was determined by combusting the residue at 750 °C for 4 h in a muffle furnace (Sairod *et al*. 2025). Fixed carbon content (FC %) was estimated by subtracting the pre-calculated values of proximate analyses from 100 as per Eq. 2.

$$\text{F.C (\%)} = 100 - [\text{V.C (\%)} + \text{M.C (\%)} + \text{A.C (\%)}] \qquad (2)$$

Elemental composition (C, H, N, S, and O) was determined by using an elemental analyzer (CHNS/O Analyzer, PerkinElmer 2400 Series II, USA). The oxygen content was estimated by subtraction of C, H, N, S, and ash from 100 (Chapman 2016). The cation exchange capacity (CEC) was measured using the ammonium acetate method (1 M NH_4OH at pH 7) in a strict accordance with (Chapman 2016), and bulk density (BD) was calculated by using a standard cylinder method (50 g of dried biochar was gently tapped into a graduated cylinder and mass/volume recorded).

Surface morphology and microstructure were observed by scanning electron microscopy (SEM Model: JEOL JSM-6479LV Japan). Conductivity was enhanced by coating biochar samples with gold (10 nm) using a Quorum Q150T ES coater. At magnifications of 500×, 1000×, and 5000× images were captured under the voltage of 15 kV. Energy-dispersive X-ray spectroscopy (EDX) attached to the SEM system was used to validate the elemental composition on the surface of biochar following the protocol given by (Eaton *et al*. 2005).

Fourier-transform infrared spectroscopic (FTIR) analysis was used to identify functional groups present on the biochar surface. The spectra were ascertained by using an IRPrestige-21 FTIR spectrometer (Shimadzu, Japan) operated at mid-infrared range (4000 to 500 cm^{-1}), 4 cm^{-1} resolution, averaging 32 scans/sample. The biochar sample was mixed with KBr (1:100 ratio) and pressed to form a pellet before scanning.

Soil Analyses and Pot Trials

Garden soil (sandy loam soil) was collected from the 20 cm depth of a field, air-dried at room temperature (25 ± 2 °C), and sieved by a 2 mm stainless steels sieve to remove pebbles and larger particles. The sieved soil was filled into fifteen polyethylene pots, with a 2 kg capacity. Certified seeds of okra (*Abelmoschus esculentus* L.) were obtained from a licensed supplier and soaked in distilled water for 24 h to enhance germination. The experiment was conducted in a completely randomized design (CRD) with five treatments, each with three replicates: (i) control (no amendment), (ii) low-dose biochar (ECBL: 1% w/w, equivalent to 20 g biochar per 2 kg soil), (iii) medium-dose biochar (ECBM: 3% w/w, 60 g biochar per 2 kg soil), (iv) high-dose biochar (ECBH: 5% w/w, 100 g biochar per 2 kg soil), and (v) commercial fertilizer (CF: diammonium phosphate at 0.22 g and urea at 0.13 g per 2 kg soil). Biochar and fertilizers were mixed into the top 10 cm of soil prior to sowing to ensure homogenous distribution.

Ten seeds were sown per pot at a depth of about 2 cm, and after germination, only three healthy seedlings were retained in each pot to maintain standardized plant density. All pots were kept under open-air conditions and irrigated every second or third day with approximately 300 mL of distilled water per pot in the early morning to maintain optimal moisture (60% to 70% field capacity). The plants were grown for 90 days, after which they were harvested. Morphological and growth parameters including germination index (%), chlorophyll content (SPAD meter value), number of leaves/plants, shoot length (cm), root length (cm), number of fruits/plants, dry plant weight (%), fresh plant weight (%) were recorded. Dry biomass was calculated by drying the plants in a hot air oven at 70 °C until complete dryness.

To study the effect of biochar on soil properties, physicochemical analyses were conducted on soil samples collected before sowing and after harvest. Soil samples were collected at a depth of 10 cm, air-dried, and sieved to 2 mm. Soil pH and electrical conductivity (EC) were estimated from saturation paste extracts, according to the USDA Handbook 60 method. The pH was calculated by using a calibrated pH meter (Model: WTW 82362), and EC was measured using a conductivity meter (Model: HANNA HI 9835). Soil organic carbon (SOC) was determined using the Walkley–Black dichromate oxidation method as reported by Murphy (2015), where 1.0 g of soil was digested with a mixture of potassium dichromate and sulfuric acid, and the remaining dichromate was titrated with ferrous sulfate. Bulk density (BD) was measured using the soil core method, consistent with the procedures described before, where oven-dried soil samples (100 cm^3) were weighed to calculate mass per unit volume. Water holding capacity (WHC) was determined following the protocol described by Munir *et al.* (2025); where 100 g of soil was saturated with water, drained under gravity for 24 h, and the retained water was measured gravimetrically.

All experiments were performed in triplicate to ensure reproducibility, and data were reported as mean ± standard deviation. Data were subjected to statistical analysis using one-way ANOVA followed by Tukey's HSD test at a 95% confidence level ($P < 0.05$). Origin Pro Learning Edition 2024 software (Origin Lab, Northampton, Massachusetts 01060, USA) was used to visualize the relationship between samples and variables at multivariate pattern by constructing Principal component analysis (PCA) and hierarchical clustering heat maps.

RESULTS

Physical, Chemical, and Nutritional Analyses of Biochar

A detailed analysis of the chemical and physical properties of water hyacinth biochar is represented in Table 1. The biochar was recorded as 36.7 ± 1.2. The ECB showed alkaline pH, *i.e.*, 8.4 ± 0.04. High electric conductivity was recorded as 2709 ± 44.73 µS/cm. NaCl had a minimal but noticeable value *i.e.*, 1.4 ± 0.04 µS/cm. Total dissolved solids (TDS) were recorded as 2492 ppm, evidencing a considerable amount of minerals and salts, a lower to moderate bulk density **(**g/cm^3) was calculated, *i.e.*, 0.56 ± 0.04, indicating porosity in the material. Cation exchange capacity (CEC) (meq/100 g) was recorded as 1.83 ± 0.04, which indicates the capacity of biochar to hold nutrients.

Moisture content (MC%) was estimated as 3.76 ± 0.01%, suggesting a dry and stable nature of biochar. A high value of ash content (AC%) was estimated as 83.6 ± 0.2%, which indicates the presence of inorganic materials. A relatively low volatile content % was recorded as 9.35 ± 0.01%, which represents good carbonization and stability. Total organic matter (TOC% was relatively low, *i.e.*, 6.18±0.02%.

Elemental analyses of ECB *via* EDX analysis showed that carbon had the highest concentration, *i.e.*, 51.56 ± 0.48, indicating long term sequestration of carbon. Nitrogen was 1.746 ± 0.01, which can be regarded as good for soil fertility. Hydrogen was 2.08±0.01, which is typical for biochar. Sulphur was 0.42±0.005, which is expected to promote microbial activity. Oxygen was recorded as 42.96±0.32, indicating functional groups making biochar more reactive. Among functional groups, the H/C ratio was 0.036 ± 0.005, which indicated the carbonization of biochar and high level of stability, whereas the O+N/C ratio was 0.873 ± 0.01, which indicated reactivity with pollutants and microbes. Mineral content including micronutrients was recorded as zinc (Zn%) 0.53±0.008%, manganese (Mn%) 0.39±0.02%, and boron (B%) 0.44±0.02%, while key nutrients such as phosphorus (P%) 0.46±0.03% and potassium (K%) 1.19±0.17% indicated the suitability of biochar for soil nutrition and fertility.

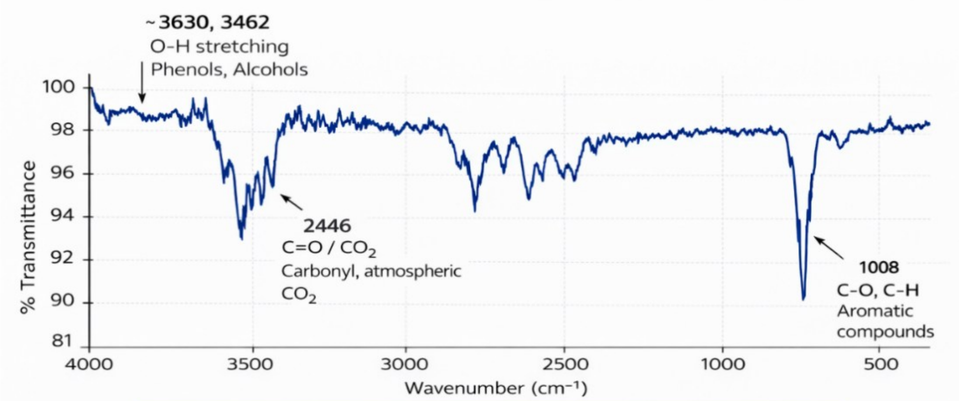
Table 1. Physico-chemical and Nutrient Analyses of Biochar

Parameters	Water Hyacinth Biochar
Yield (%)	36.7 ±1.2
pH	8.4 ±0.04
EC (μScm^{-1})	2709 ±44.73
NaCl	1.4 ±0.04
TDS(ppm)	2492 ±30.6
BD(gcm^{-3})	0.56 ±0.04
CEC (meq100g^{-1})	1.83 ±0.04
Moisture content (%)	3.76 ±0.01
Ash content (%)	83.6 ±0.24
Volatile content (%)	9.35 ±0.01
Total organic matter (%)	6.18 ±0.02
C (%)	51.56 ±0.48
H (%)	2.08 ±0.01
N (%)	1.746 ±0.01
S (%)	0.42 ±0.005
O (%)	42.96 ±0.32
H/C ratio	0.036 ±0.005
O+N/C ratio	0.873 ±0.01
Zn (%)	0.53 ±0.008
Mn (%)	0.39 ±0.02
B (%)	0.44 ±0.02
N (%)	3.96 ±0.12
P (%)	0.46 ±0.03
K (%)	1.19 ±0.17

Note: Given values are means of triplicates with standard deviations (±)

Functional Group, Surface/Structural, Elemental and Thermal Stability Analyses of Water Hyacinth Biochar

The FTIR spectrum of ECB, which elucidated the chemical structure and functional groups present in biochar, are shown in Fig. 1. Peaks observed at 3630 and 3462.1 cm^{-1} corresponded the O-H stretching vibrations (hydroxyl groups), which is consistent with the presence of phenols and alcohols. The possible presence of -C≡N groups was ruled out due to a lack of reason to expect such groups in the material. The peaks formed at 2163.2 and 1999.2 cm^{-1} were relevant to **-**C≡C stretching vibrations or -C=N stretching (nitrile bonds), indicating the presence of unsaturated compounds. A peak at 1008.2 cm^{-1} was linked to -C-H bending vibrations indicating aromatic carbon rings or compounds. All these traits are consistent with the biochar specimen ECB being suitable as a soil amendment and for carbon sequestration.



Wavenumber (cm⁻¹)	Functional Group	Assignment
~3630, 3462	O-H	Phenols, Alcohols
~2446	C=O / CO_2	Carbonyl, atmospheric CO_2
2163–1999	C=C, C=N	Unsaturated/aromatic structures
~1008	C-O, C-H	Aromatic compounds

Fig. 1. Fourier transform infrared spectrum of *Eichhornia crassipes* biochar

Scanning electron microscopic (SEM) images representing the surface morphology of ECB are presented in Fig. 2. At 1500× and 100 µm, SEM imaging showed a rough surface with many cracks and amorphous structure with grains indicating biochar had some particles suggesting biochar is porous and amorphous structure. At 3000× and 50 µm SEM showed more fibrous, defined, porous fractures and channels. At 6000× and 20 µm image reflected intricate texture having roughness and porosity**.**

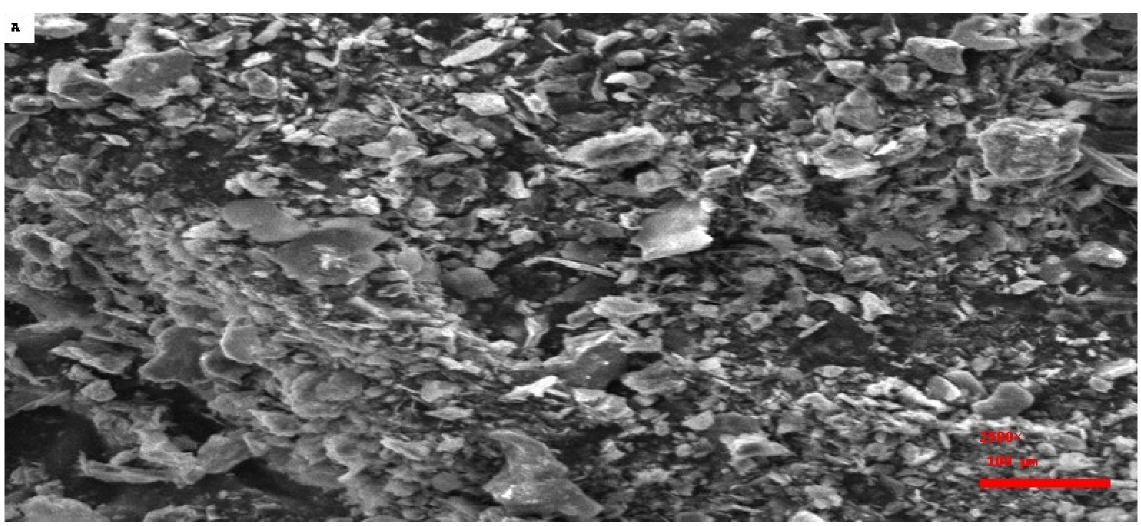
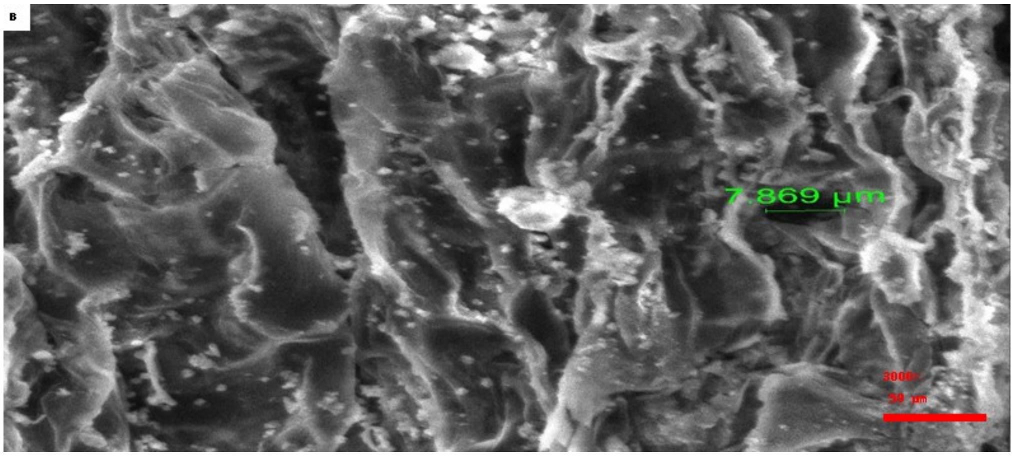


Fig. 2(a). Scanning electron microscopic image of *Eichhornia crassipes* biochar observed under the resolving power of 1500× (a), 3000× (b), and 6000× (c) at 20, 50, and 100 µm



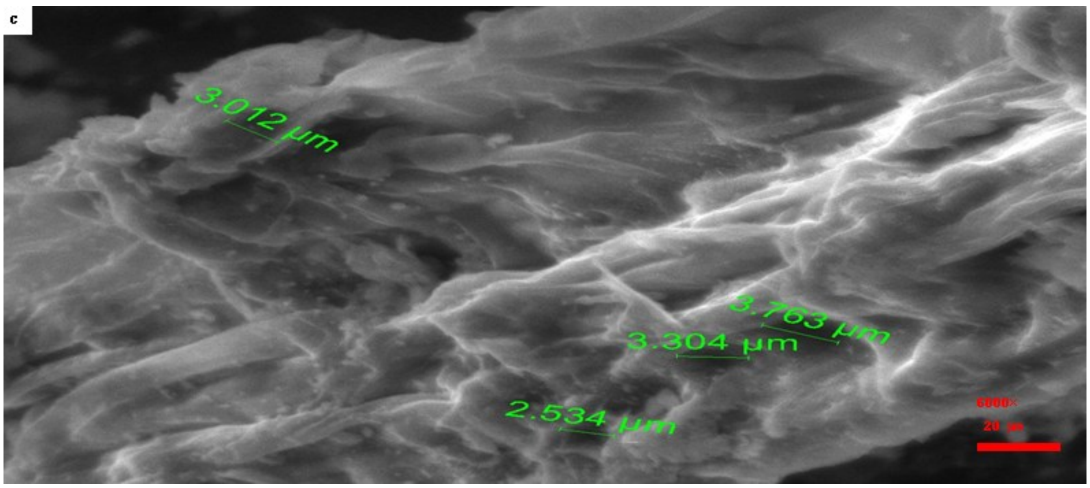


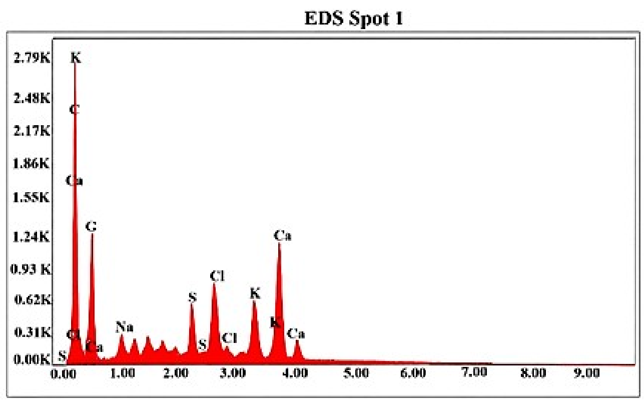
Fig. 2(b and c). Scanning electron microscopic image of *Eichhornia crassipes* biochar observed under the resolving power of 1500× (a), 3000× (b), and 6000× (c) at 20, 50, and 100 µm

The EDX analysis is shown in Fig. 3. The Spot 1 analysis shows that carbon was the dominant element (41.04 wt% and 58.01 atomic%), and oxygen was second most abundant element. Observed aspects included high calcium content, chlorine at lower level, sodium, sulfur, and potassium in minimal quantities.

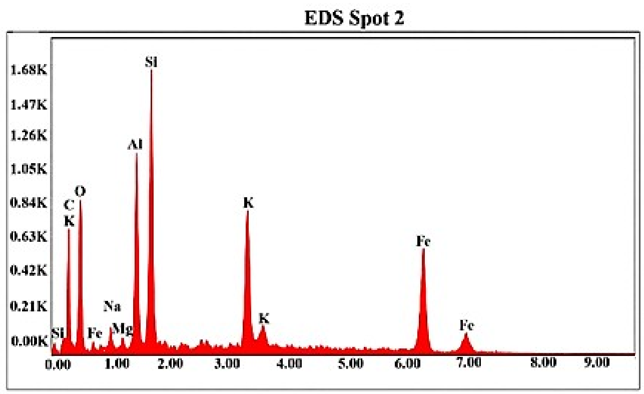
At Spot 2, carbon was still dominant, and oxygen was at the next level. Iron was found in significant quantity. Noticeable amounts of silicon and aluminium were detected, along with a small amount of sodium and potassium.

At Spot 3, carbon maintained its dominance, oxygen was detected in significant amounts, calcium was measured at 10.23 wt%, silicon was detected at 0.16 wt%, and phosphorus was at 2.85 wt%. Sulfur, chlorine, sodium, and potassium were present in small amounts.

Element	Weight %	Atomic %
C K	41.04	58.01
O K	24.82	26.34
NaK	1.21	0.90
S K	3.58	1.89
ClK	6.64	3.18
K K	5.78	2.51
CaK	16.92	7.17



Element	Weight %	Atomic %
C K	12.39	28.44
O K	10.50	18.48
NaK	0.95	0.59
Al$_5$K	14.01	10.19
SIK	14.00	8.31
K K	12.99	9.16
CaK	35.65	19.43



Element	Weight %	Atomic %
C K	28.83	45.50
O K	20.33	31.16
NaK	1.79	1.47
P K	2.85	1.74
S K	1.12	6.41
ClK	11.76	8.21

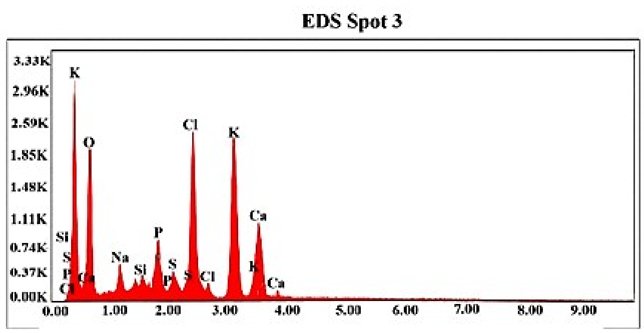


Fig. 3. Weight and atomic percentage of elements present in *Eichhornia crassipes* biochar at three different spots 1, 2, 3

Figure 4 shows the thermogravimetric analysis results on the biochar sample within the time frame of thermal decomposition of the sample. The figure depicts the percentage weight loss as a function of varying time. The biochar underwent weight loss and removal of components during the decomposition process. As the temperature rises, the biochar continues to undergo all three stages of the weight loss process-decomposition process. During the initial period, there was a slight reduction in weight, which was mainly attributed to the evaporation of physically adsorbed (free, bound, and interfacial) moisture in the biochar matrix. This evaporation happened in the initial or lower range of the temperature scale. During removal of free and bound water there were no striking alterations to the structure.

After this, as the temperature kept rising, the second period started, which involved a significant reduction in weight. This was attributed to the thermochemical decomposition of the biochar matrix, wherein the thermally labile fractions (mainly hemicellulose and some portions of cellulose) are broken down, and the light hydrocarbons and volatile organic compounds are released. The more steeply inclined portions of the weight-loss curve during this period are attributed to the active devolatilization processes that are occurring in the material.

At elevated temperature, the last phase of weight loss happened, which was related to the breakdown of more stable carbonaceous structures such as lignin and fixed carbon. The process of mass loss at this stage happened gradually and at a lower rate, as these refractory materials broke down into gaseous compounds and yielded residual ash. The lack of any sudden or dramatic loss of weight during the process indicates that the biochar had moderate to good thermal stability, with a constant carbon structure even at high temperatures. The general tendency of these three stages being gradual indicates the heterogeneous nature of the biochar and the resistance of the biochar against thermal degradation.

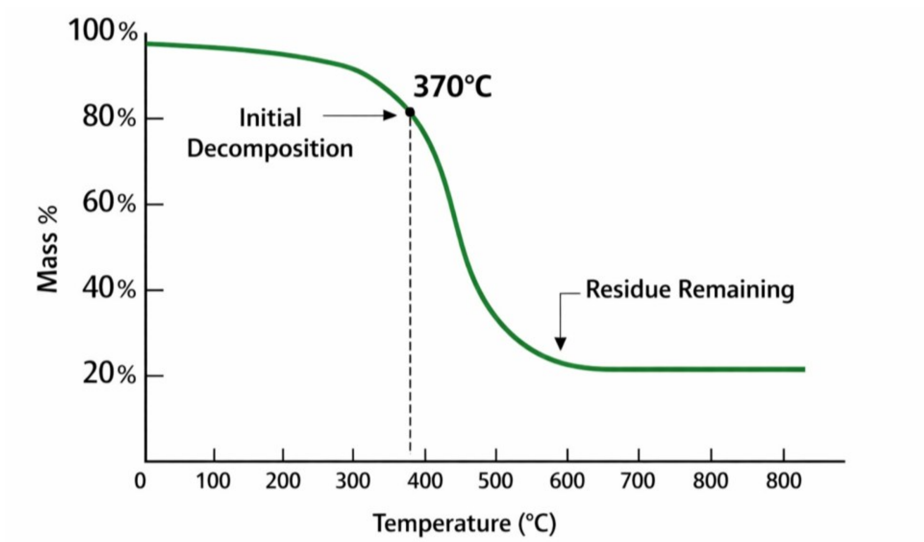


Fig. 4. Thermogram of water hyacinth biochar (thermogravimetric analysis, TGA) of water hyacinth biochar illustrating the weight loss-time relationship during the thermal decomposition process. While TGA data are typically graphed against temperature, in this case, the x-axis is temperature (°C) to indicate the actual real-time thermal degradation profile following a controlled linear heating program (This graph presents effective understanding of the thermal degradation kinetics).

Soil Analysis

The pre-sowing soil characteristics in various treatments (Control, ECBL, ECBM, ECBH, and CF) are tabulated in Table 2. The pH of the soil increased significantly ($p < 0.05$) upon the addition of biochar from 6.53 ± 0.16 in the control to a high of 7.10 ± 0.24 in ECBH. Yet, treatment differences were not statistically different (denoted by the identical superscript letter "a") indicating that biochar incorporation did not significantly change soil pH relative to the control. Electrical conductivity (EC) ranged between 1996 ± 2.16 µS/cm in the control and 2443 ± 1.69 µS/cm in the CF treatment, with EC significantly higher in CF than in control and ECBM treatments ($p < 0.05$).

Total dissolved solids (TDS) did not differ appreciably across treatments, although slightly greater values were observed for ECBM (227 ± 7.58 ppm) and ECBH (229 ± 4.96 ppm). Water holding capacity (WHC) was much increased in ECBL (52.16 ± 0.83 %) and CF (52.59 ± 0.72 %) treatments relative to the control (36.39 ± 0.84 %, $p < 0.05$), suggesting that biochar, especially at low concentrations, increases soil retention of water. Cation exchange capacity (CEC) was statistically equal across treatments (1.50 to 1.60 meq

/100 g), although slightly elevated values were registered in ECBM and ECBH. Bulk density (BD) was significantly greater with ECBH (0.70 ± 0.08 g/cm³) than in the control and CF treatments (0.27 ± 0.02 to 0.03 g/cm³, $p < 0.05$), demonstrating the more compact biochar-amended soils' structure.

Total organic matter (TOM) content was found to be significantly greater in ECBM (10.43 ± 0.24 %) and ECBH (10.33 ± 0.24 %) than in the control (9.79 ± 0.106 %), demonstrating increased carbon enrichment due to the addition of biochar. Ash content (AC) also increased significantly in ECBH (82.99 ± 2.40%) compared to control (76.80 ± 1.50%). The volatile content (VC) was highest in ECBH (7.34 ± 0.11%), significantly higher than for other treatments ($p < 0.05$). The large positive changes in WHC, TOM, AC, and VC indicate that biochar, particularly at increasing levels of application, significantly altered soil physicochemical properties and improves its organic matter content and nutrient retention.

Table 2. Pre-sowing Analysis of Soil Amendments

Treatments	pH	EC (µS/cm)	TDS (ppm)	WHC (%)	CEC (meq/100g)	BD (g/cm³)	TOM (%)	AC (%)	VC (%)
Control	6.53[a] ± 0.16	1996[a] ± 2.16	206[b] ± 3.08	36.39[b] ± 0.84	1.5[a] ± 0.07	0.27[a] ± 0.02	9.79[a] ± 0.106	76.8[a] ± 1.5	6.42[b] ± 0.29
ECBL	6.66[a] ± 0.12	2301[a] ± 1.34	212[a] ± 8.04	52.16[a] ± 0.83	1.54[a] ± 0.04	0.34[a] ± 0.004	9.62[a] ± 0.23	77.56[a] ± 1.56	6.76[b] ± 0.44
ECBM	6.86[a] ± 0.12	2007[a] ± 5.312	227[a] ± 7.58	44.09[ab] ± 1.18	1.6[a] ± 0.08	0.523[b] ± 0.12	10.43[b] ± 0.24	77.81[a] ± 1.96	6.9[b] ± 0.21
ECBH	7.1[a] ± 0.24	2332[ab] ± 1.88	229[a] ± 4.96	48.86[ab] ± 1.19	1.6[a] ± 0.08	0.7[a] ± 0.08	10.33b[a] ± 0.24	82.99[b] ± 2.40	7.34[a] ± 0.11
CF	6.9[a] ± 0.08	2443[b] ± 1.69	208[a] ± 9.53	52.59[a] ± 0.72	1.43[a] ± 0.16	0.27[a] ± 0.03	9.3[a] ± 0.21	77.3[a] ± 1.006	6.64[b] ± 0.49

Notes: EC: Electrical Conductivity, TDS: Total dissolved solids, WHC: Water holding capacity, CEC: Water Holding Capacity, BD: Bulk density, TOM: Total organic matter, AC: Ash content, VC: Volatile content, ECBL: *Eichhornia crassipes* biochar 1%, ECBM: *Eichhornia crassipes* biochar 3%, ECBH: *Eichhornia crassipes* biochar 5%, CF: Commercial fertilizer, The mean values ±S.E. are with common letters showing significantly different according to DMRT (p = 0.05).

Using biochar derived from *Eichhornia crassipes* (ECB) changed certain soil physico-chemical properties when compared to the untreated control (Table 3). There was an increase in soil pH in the biochar treatments due to the alkaline characteristic of biochar. The control had a pH of 6.53 ± 0.16, but the highest pH was recorded in the ECBH treatment (7.90 ± 0.08). This difference was statistically significant ($p < 0.05$). This increased pH shows that biochar can improve the neutralization of acidic soils, which can result in better nutrient availability and supporting plant growth.

The increased levels of electrical conductivity (EC) and total dissolved solids (TDS) was also a significant result of the addition of biochar ($p < 0.05$). The control treatment resulted in an EC of 1998 ± 1.24 µS/cm and a TDS value of 205 ± 2.05 ppm. In the ECBH treatment, the highest values were recorded (2452 ± 8.80 µS/cm for EC and 255 ± 10.27 ppm for TDS). The increased values can be attributed to the increased soluble ion concentration and from the nutrient release from the biochar matrix which improves soil fertility.

The effects of the addition of biochar on Water Holding Capacity (WHC) and Cation Exchange Capacity (CEC) were notable. WHC rose considerably from 37.00 ± 0.81 % in the control to 55.22 ± 0.86 % in the ECBH treatment ($p < 0.05$), while CEC climbed from 1.51 ± 0.008 meq/100g to 1.76 ± 0.04 meq/100g. Such enhancements are due to biochar's porosity, surface area, and the various functional groups, which increase retention of moisture and the nutrient holding capacity of the soil. Such improvements to soil structure and sustained crop production are highly helpful.

In regards to bulk density (BD), even though some changes were apparent, they were still statistically insignificant ($p > 0.05$). Nevertheless, a slight reduction of BD in biochar-amended soils indicated positive shifts in soil structure and aeration. All biochar treatments resulted in a notable increase of total organic matter (TOM), which moved from 0.31 ± 0.008 % in the control to as high as 0.46 ± 0.03 % in ECBH ($p < 0.05$). This demonstrated that the addition of biochar significantly improved soil organic carbon content, thereby improving soil fertility as well as enhancing activity of soil microbes. The variations observed in ash content (AC) and volatile content (VC) were minor and statistically insignificant ($p > 0.05$). The slight increase in ash content indicated the contribution of biochar minerals. The stable volatile content ratio suggested that the biochar incorporation into the soil did not significantly impact organic matter decomposition dynamics with the soil.

The ECB treatment enhanced soil agronomic parameters (pH, EC, TDS, WHC, and CEC). Tukey's post hoc test determined that the higher biochar dosages (ECBM and ECBH) were statistically different ($p < 0.05$) from the control, while the differences among the lower dose treatments (ECBL and CF) were more closely aligned. The biochar derived from water hyacinth certainly demonstrated potential as a soil amendment.

Table 3. Post-harvest Analysis of Soil Amendments

Treatments	pH	EC (µS/cm)	TDS (ppm)	WHC (%)	CEC (meq/100g)	BD (g/cm^3)	TOM (%)	AC (%)	VC (%)
Control	6.56^a ± 0.12	1998^b ± 1.24	205^a ± 2.05	37^b ± 0.81	1.51^a ± 0.008	0.31^a ±0.008	9.53^a ± 0.46	76.2^a ± 0.08	6.5^b ± 0.36
ECBL	7.53^{ab} ± 0.04	2320^a ± 3.55	214^a ± 3.39	52.26^a ± 0.80	1.62^a ± 0.008	0.45^a ± 0.008	10.06^b ± 0.18	76.84^a ± 0.45	7.4^a ± 0.08
ECBM	7.8^b ± 0.08	2345^a ± 1.69	214^a ± 1.63	54.55^a ± 0.77	1.71^a ± 0.03	0.46^a ± 0.01	10.3^b ± 0.09	78.86^a ± 0.52	7.76^a ± 0.12
ECBH	7.9^b ± 0.08	2452^a ± 8.80	255^b ± 10.3	55.22^a ± 0.86	1.76^a ± 0.04	0.46^a ± 0.03	10.2^{ab} ± 0.08	78.51^a ± 0.42	7.76^a ± 0.04
CF	7.5^{ab} ± 0.16	2308^a ± 0.94	240^{ab} ± 12.8	54.66^a ± 0.33	1.56^a ± 0.03	0.4^a ± 0.02	9.19^a ± 0.06	76.21^a ± 0.07	7.5^a ± 0.21

Notes: EC: Electrical Conductivity, TDS: Total dissolved solids, WHC: Water holding capacity, CEC: Water Holding Capacity, BD: Bulk density, TOM: Total organic matter, AC: Ash content, VC: Volatile content, ECBL: *Eichhornia crassipes* biochar 1%, ECBM: *Eichhornia crassipes* biochar 3%, ECBH: *Eichhornia crassipes* biochar 5%, CF: Commercial fertilizer, The mean values ±S.E. are with common letters showing significantly different according to DMRT ($p = 0.05$).

The Effect of Biochar Amended Soil on Plant Growth

Table 4 represents the influence of different treatments on plant growth and yield. Generally, ECBM affected the growth and yield parameters positively, and ECBL also revealed effective in contrast to control and commercial fertilizer (CF). The germination index also verified moderate responses to the treatments, but ECBM had a relatively higher influence indicating that moderate adjustment in biochar could enhance seedlings emergence and early vitality.

On the opposite end, high biochar (ECBH) seemed to have adverse effects on germination, probably because of oversalinity or other types of stressors. There was a general increase in chlorophyll contents, measured by SPAD values in ECBH, implying greater efficiency in photosynthesis in high biochar application, though the other treatments had the same trend with marginal changes. Leaves per plant was one of those parameters that did not change much with the treatments, meaning that this was a variable that is less sensitive to amendments in the stated conditions. There was a distinct positive effect on shoot length, with the ECBM bestowing positive effects toward shoot growth enhancing vegetative growth. The CF and the control had the minimum elongation, which indicated the ability of biochar to improve the structure of a plant.

The length of roots had a fairly unvarying trend among the treatments, just showing slight enhancement. Thus, there was a modest impact on the development of the roots. The efficiency of fruiting plant was relatively the same in most of the treatments but at slightly higher levels in ECBH and CF, despite the latter being not statistically different. Nonetheless, the weight of fresh pod (FPW) exhibited a spectacular enhancement towards ECBM, which represented a more favorable influence of moderate biochar on the biomass accumulation of fruits. Also, the dry pod weight (DPW) reached its highest value under ECBM, thus another propagation of the allegation that it is more effective in increasing yield components as compared to other treatments.

Table 4. Showing Response of *Abelmoschus esculentus* L. to 1%, 3%, and 5% Biochar Amendments, Control, and Commercial Fertilizer

Parameters	ECBL	ECBM	ECBH	C	CF
Germination Index (%)	66.6 ^{ab} ±11.7	75 ^{b} ±11.7	41^{a} ±11.7	58.5 ^{ab} ±11.7	66.6 ^{ab} ±11.7
Chlorophyll Content (SPAD value)	51.73 ^{ab} ±6.95	50.36 ^{ab} ±11.61	60.466 ^{b} ±13.00	49.9 ^{a} ±2.88	51.86 ^{ab} ±1.44
No. of Leaves/ Plant	4 ^{a} ±0.81	4 ^{a} ±0.47	5 ^{a} ±1.63	4 ^{a} ±0.81	5 ^{a} ±0.47
Shoot Length(cm)	16.33 ^{ab} ±1.24	20.66 ^{b} ±0.94	14.5 ^{a} ±1.08	13 ^{a} ±1.63	12.83 ^{a} ±1.92
Root Length(cm)	4.66 ^{a} ±0.94	4.66 ^{a} ±0.47	5.33 ^{a} ±0.47	4.33 ^{a} ±0.94	3.83 ^{a} ±0.235
No. of Fruits/Plant	1 ^{a} ±0	1 ^{a} ±0	2 ^{a} ±0.47	1 ^{a} ±0.47	2 ^{a} ±0.47
FPW(g)	5.75 ^{a} ±0.67	8.27 ^{a} ±0.33	5.74 ^{a} ±0.75	4.03 ^{a} ±0.33	3.72 ^{a} ±0.22
DPW(g)	0.37 ^{a} ±0.04	1.68 ^{a} ±0.12	0.48 ^{a} ±0.10	0.49 ^{a} ±0.12	0.63 ^{a} ±0.08

Notes: (ECBL: *Eichhornia crassipes* biochar (1%), ECBM: *Eichhornia crassipes* biochar (3%), ECBH: *Eichhornia crassipes* L. biochar (5%), C: Control, CF: commercial fertilizer, GI: Germination Index, C. content: Chlorophyll content, FPW: Fresh plant weight, DPW: Dry plant weight, LSD: Least significant difference. The mean values ±S.E. are with common letters showing significant difference according to DMRT (p = 0.05).

Correlation of Biochar and Soil Amelioration with Plant Growth

The heatmaps (Figs. 5A and 5B) indicate that various concentrations of biochars affected soil properties pre- and post-sowing as compared with control and fertilizer group. Each color gradient in the heatmap corresponds to changes in soil attributes, including pH, EC, TDS, WHC, CEC, TOM, ash content, volatile matter, and BD. The effect of higher biochar concentration (5%) was clear in the improved soil properties shown as lighter yellow and red sections, but 1% biochar showed minimal impact, appearing as darker blue or medium shades.

Biochar application slightly raised ash content and decreased volatile matter, which may indicate enhanced stability of organic matter, but it did not affect BD much. The dendrogram clustering showed that the use of 5% biochar clearly deviated from both the control and fertilizer, representing notable effectiveness. Similarly, biochar treatments for plant growth parameters, such as germination percentage, shoot and root lengths, chlorophyll content, leaf and fruit number, fresh and dry plant weight, and fruit weight, are indicated in the heatmap (Fig. 5 C). 5% biochar concentration produced more significant advantages, rendering the heat map redder, in comparison to the 1% concentration effect, which showed as a deeper blue.

Biochar, at every concentration tested, advanced seed germination, chlorophyll amount, plant development, and fruit yield, showing the greatest gains at 5%. In addition, the significant increases in fresh and dry biomass revealed a general improvement in plant health. The results from hierarchical clustering once more indicate that 5% biochar stood apart from the control and fertilizer, reflecting its considerable potential to improve both soil and plant performance.

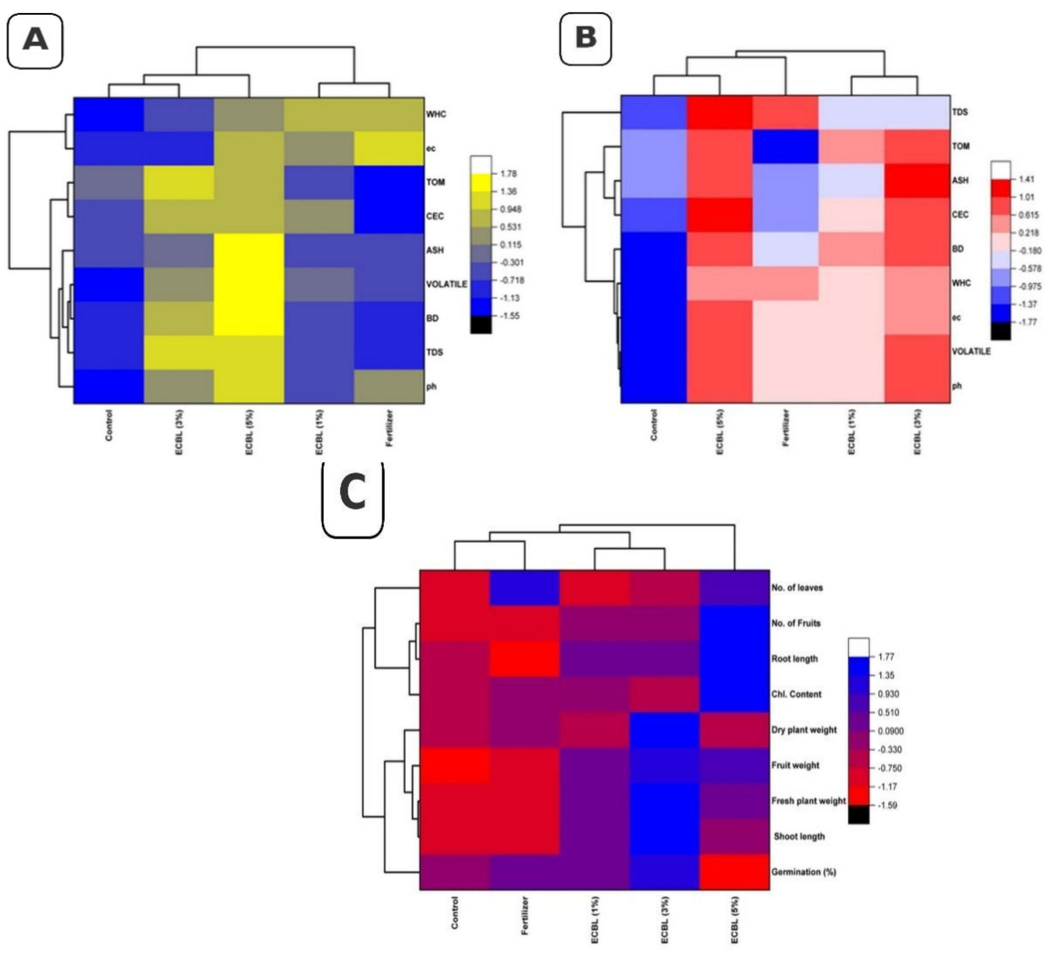


Fig. 5. Hierarchical cluster analyses heatmaps showing effect of biochar on (A) pre-sowing soil characters and plant's growth parameters, (B) post-harvesting soil characters and plant's growth parameters, and (C) plant growth in relation to treatments

DISCUSSION

Water hyacinth (*Eichhornia crassipes* L.) is an exotic aquatic plant that has remarkable adverse environmental effects due to its rapid proliferation and invasion in water bodies. Similar remarks have been made in previous literature (Hill *et al*. 2021; Prokopuk *et al*. 2021). Their biomass can be managed effectively by pyrolysis and conversion into biochar a carbon rich material to be used as a soil conditioner. This approach has grabbed the attention of scientists and the public.

Large-scale biochar production that relies solely on opportunistic removal campaigns may encounter logistical and supply chain issues because of unpredictable harvesting schedules or inconsistent management efforts. To tackle this problem, integrating biochar production into regularly funded aquatic weed management programs or forming partnerships between public and private sectors could help secure a steady biomass supply. Additionally, setting up localized collection and processing units near infested water bodies can lower transportation costs and make production more financially viable. Therefore, while water hyacinth offers an abundant and low-cost feedstock, its sustainable use at a commercial level will depend on careful planning, coordinated removal strategies, and long-term resource management.

Many studies (Gezahegn *et al*. 2024b; Jayathilake *et al*. 2024; Kassa *et al*. 2025) also converted water hyacinth into biochar after pyrolysis of the weed biomass. The current investigation has shown that water hyacinth biochar (ECB) has sustainable potential to serve as an amendment to soil because of its well-suited physicochemical properties. Findings of this research were in correspondence to the results of other studies in which the effect of biochar of different biomasses on fertility of soil were evaluated (Aslam and Nazir 2024; Fentie *et al*. 2024b; Lewoyehu *et al*. 2024).

The potential of ECB to ameliorate deficiencies in the soil and promote the growth and yield of okra is evidenced from the authors' previous research, in which similar experiments were conducted with *Typha angustifolia* biochar (Munir *et al*. 2025). The results revealed that ECB has a strongly positive effect on soil edaphic factors and okra growth, contributing to agricultural resilience. *Eichhornia crassipes* biochar (ECB) has a porous structure, large surface area, and remarkable carbon content, making it appropriate for soil amelioration.

The traits of ECB depend on pyrolysis temperature, duration, and conditions. ECB has high carbon content, which enhances soil carbon sequestration and boosts its CEC. These features facilitate nutrient retention and exchange. The alkaline pH can counteracts the acidic nature of some soil and refine nutrient availability. The porous structure enhances water retention and aeration, as well as the presence of macro and micronutrients such as potassium, phosphorus, and calcium, which are vital for plant growth and yield. Biochar can significantly affect the cation exchange capacity (CEC) of soil. CEC is a major factor in soil fertility, nutrient retention, and crop productivity. The porous structure and large specific surface area of biochar, along with the many oxygen-containing functional groups (such as –COOH, –OH), improve the soil's ability to hold onto important cations such as K^+, Ca^{2+}, Mg^{2+}, and NH_4^+. Over time, biochar experiences surface oxidation, which increases its functional groups and further boosts CEC. This improved CEC not only decreases nutrient leaching but also enhances nutrient availability to plants, supporting sustainable soil fertility and greater crop yields. Additionally, biochar's role in increasing soil CEC is especially useful in sandy or nutrient-poor soils, where nutrient retention is often a challenge. These benefits make biochar a valuable addition for maintaining long-term soil health and productivity (Lehmann and Joseph 2015). Pyrolysis temperatures affect the extent of thermolysis and aromatization of the lingo-cellulosic biomass, resulting in the formation of aromatic compounds. These lead to the high carbon content in biochar. Lignin in ligno-cellulosic material plays a pivotal role in producing stable carbon compounds, as shown in previous studies (Viswanathan *et al*. 2020; Dhinesh *et al*. 2024; Narayanan and Aloufi 2024).

The detailed analysis of water hyacinth-derived biochar (ECB) has demonstrated that the biochar has significant potential to overcome deficiencies in soil fertility, which is demonstrated by a moderate-high yield (36.7 ± 1.2%) after complete pyrolysis of biomass into biochar. The biochar showed an alkaline pH (8.4 ± 0.04) and high electrical conductivity (2709 ± 44.73 µS/cm), which indicate a substantial presence of minerals and salts. A low bulk density (0.56 ± 0.04 g/cm³) indicated highly porous structure, which magnify its capacity to capture nutrients, as proved by the CEC value (1.83 ± 0.04 meq/100g). Low moisture content (3.76 ± 0.01%) and high ash content (83.6 ± 0.2%) of biochar shows that it is dry, stable, and rich in inorganic minerals.

Elemental analysis unveiled a high carbon content (51.56 ± 0.48%), favoring long-term carbon sequestration, while nitrogen, sulfur, and phosphorus participated in its soil amelioration potential. The functional group ratios (H/C = 0.036 ± 0.005, O+N/C = 0.873 ± 0.01) represented good carbonization, high stability, and reactivity with pollutants and microbes. Additionally, the presence of essential micronutrients such as zinc, manganese, and boron, alongside organic components like humic acid and amino acids, emphasizes its value for soil health and fertility. These findings were supported by previous studies on characteristics of water hyacinth biochar (Kumari *et al*. 2021; Masto *et al*. 2013).

The FTIR spectral study of ECB has given important insights into the chemical composition and functional groups, which perform a crucial role in its application to ameliorate soil and sequester carbon. The O-H stretching vibrations represents hydroxyl functional groups, suggesting alcohol and phenols, which contributing nutrient retention hydrophilic nature of biochar. The C=O (carbonyl) stretching vibrations (2445.7 cm^{-1}) indicated the presence of carbonyl-compounds, which may increase reactivity of biochar. C=N (nitrile) stretching vibrations showed the occurrence of unsaturated compounds in accordance with reactivity of biochar. C-H bending vibrations at 1008.2 cm^{-1} are attributing the presence of aromatic carbon structures, making biochar resistant to decay and long-lasting carbon sequestration potential. These findings support the potential of biochar to improve soil health as noticed by others (Allam *et al*. 2020; Mulyatun 2020).

The SEM of ECB revealed a highly porous and amorphous structure with cracks and granules that represented intricate pores and fibrous channels. At 6000× (20 µm) magnification, the biochar exhibited significant porosity which confirms the potential of ECB to ameliorate soil. EDS analyses show variable concentration of elements at different spots; however, the amount of carbon is dominant in comparison to other elements. Similar SEM images of water hyacinth biochar were also observed (Johnson Jeyaraj and Sankararajan 2025; Wang *et al*. 2025).

The TGA plot revealed that biochar had weight loss in response to temperature expansion, suggesting the presence of thermo-degradable compounds. The passive decline in the weight loss curve indicates good thermal stability of the water hyacinth biochar. Various previous studies have also revealed the same thermal stability of biochar derived from different biomasses, including invasive weeds (Sahu *et al*. 2020; Gurav et al. 2021; Viswanathan *et al*. 2024).

ECB improved soil aggregation, lowered soil compaction, and enhanced aeration. Soil's water-holding capacity increased due to the porous nature of biochar, which is beneficial for dried or arid regions which are in agricultural practice. Biochar behaves as a nutrient reservoir and soil conditioner. In addition, it hampers leaching of key nutrients such as N, P, and K. This phenomenon is specifically advantageous in perished, sandy or degraded soils with weak nutrient retention capacity.

Many agricultural soils suffer from nutrition deficit or acidity issues, hindering plant growth. ECB has alkaline pH, which can effectively counterbalance acidic soils, correspondingly optimize microbial activity and nutrient uptake. Biochar acts as a habitat for beneficial microbial communities. These microbes enhance nutrient recycling, improve soil fertility and plant health. Soil amelioration potential of biochar was also confirmed from previous experiments to treat perished soil in which they proved biochar amendment in soil is a favorable treatment with respect to soil fertility (Batool *et al*. 2023; Ghosh and Maiti 2023; Jutakanoke *et al*. 2023).

The pot experiment revealed that amending ECB into soil can boost seed germination by creating a more commendatory soil environment. The enhanced water retention, porosity, and aeration promote seedling emergence and root establishment. Vegetable crops such as lettuce, tomatoes, and spinach can increase biomass and yield when grown in biochar-amended soils. The improved nutrient availability and soil structure promotes the plant growth and higher yield (Jia *et al*. 2012; Yilangai *et al*. 2014; Boersma *et al*. 2017). ECB improves the nutrient absorption by plants while acting as a slow-release fertilizer, ensuring that nutrients remain available for prolong period (Shen *et al*. 2020; Bi *et al*. 2022; Hussain *et al*. 2025). This is particularly advantageous for fast-growing vegetables that demand a steady supply of nutrients. Biochar-amended soils manifest substantial resilience against drought and soil-borne afflictions (Xu *et al*. 2025).

The growth of *Abelmoschus esculentus* was positively influenced by the ECBM treatment, which showed the highest germination index (75), shoot length (20.66 cm), fresh plant weight (8.27 g), and dry plant weight (1.68 g). ECBH recorded the highest chlorophyll content (60.47) and root length (5.33 cm). The CF and control treatments exhibited lower growth parameters, with CF showed the lowest root weight as well as less fresh weight. Statistical analysis would provide insight into the significance of these differences, especially with LSD values at 0.05. These findings of plant growth and yield were according to previous results of similar experimentations (Frimpong *et al*. 2025; Sharma *et al*. 2025b).

Regardless to the benefits of ECB, the application must be optimized to prevent its worst effects. Excessive biochar can raise the soil pH beyond its optimum range, thereby adversely affecting nutrient solubility. The efficacy of ECB depends on pyrolysis conditions, such that a standardized state is required to obtain constant results. The novelty of this research is that a biochar is produced by means of using the most typical invasive aquatic weed, water hyacinth (*Eichhornia crassipes*) to promote biochar manufacture *via* pyrolysis. It is not only a sustainable way of dealing with this noxious weed, but it is also a good soil amendment to alleviate the land and to improve the productivity of okra (*Abelmoschus esculentus* L.), which will solve both environmental and agricultural problems.

CONCLUSIONS

1. This research achieved the successful valorization of invasive water hyacinth into biochar, converting an environmental weed into a useful product for sustainable agriculture.
2. The use of water hyacinth biochar greatly enhanced important soil characteristics, such as pH buffering, water retention, cation exchange capability, and organic content, thus improving soil fertility and microbial activity.
3. Amongst all treatments, medium-dose biochar (ECBM) had the most significant positive impact on okra growth and yield, ascertaining its efficacy as a good soil amendment.
4. Fourier transform infrared (FTIR) analysis indicated the presence of stable functional groups including nitrile, carbonyl, and hydroxyl, thereby showing the structural stability and nutrient-retention capacity of resultant biochar.
5. Incorporation of water hyacinth biochar into agricultural systems provides a two-pronged advantage — lowering the environmental impact of invasive species and aiding in soil health, crop yields, and long-term sustainability.
6. Future studies should aim to maximize application rates, elucidate long-term field performance, and assess potential environmental effects including solubilization, toxicity, and biosorption to maximize its full potential.

Competing Interests

The authors declare that there are no conflicts of interest.

Availability of Data and Material

All the data generated in this research work has been included in this manuscript.

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