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UNIVERSITY of DEBRECEN

International Review of Applied Sciences and Engineering

DOI:
10.1556/1848.2025.00870

Water hyacinth biomass-based biochar: Preparation and characterizations for sustainable soil amendment

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Received: May 27, 2024 • Accepted: January 10, 2025

ORIGINAL RESEARCH PAPER

ABSTRACT

This study investigates the utilization of biochar (WHBC) from water hyacinth biomass (WHBM) for sustainable soil amendment to improve soil quality. WHBM and WHBC are prepared and characterized with thermogravimetric analysis (TGA). For that, physiochemical, proximate, ultimate, and elemental analyses are done and characterized by using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), scanning electron microscope (SEM), and energy-dispersive X-ray spectroscopy (EDAX) to identify the suitability of soil amendment. WH biomass is carbonized with a limited air supply in a muffle furnace, and the study found that 300–664 °C temperature is the optimum condition for producing biochar from TGA. XRD of WHBC displayed more crystallinity than WHBM. FTIR of WHBC showed higher carbon stability increment than WHBM. The SEM micrograph of WHBM showed that compact, and fibril structures and WHBC revealed macroscopic changes that can significantly improve the soil properties. EDAX analysis of WHBM and WHBC proved that various soil nutrients can be helpful for plant growth. The study shows that WHBM can be utilized as a soil quality amendment material by converting it to biochar and an effective material for carbon storage in soils.

KEYWORDS

water hyacinth biochar, biomass, SDG6, biochar, characterization-TGA, XRD, FTIR, SEM and EDAX, sustainable soil amendment

1. INTRODUCTION

In present-day society, there has been an increase in the global population, making it necessary for the agricultural sector worldwide to produce more food to satisfy the rising need [1–7]. Global food security must secure enough healthy and nutritious food for a healthy life without the risk of hunger and child malnutrition. In order to avoid this, alternative methods need to be found as soon as possible to cultivate more raw ingredients for food efficiently and sustainably [8–11]. Unfortunately, arable lands are decreasing for cultivation and farming [12] due to urbanization and soil degradation [13]. For instance, more than 8 billion people have only 1.407 billion hectares of land to harvest their food, which poses an increasing challenge to achieving food security [14]. In addition, soil degradation is a significant concern in modern agriculture, and it can result from continuous cultivation of crops, soil erosion, and over-irrigation [15]. Soil nutrients continuously deplete, and soil fertility is lost, resulting in lower crop yields [16]. On the other hand, excessive chemical fertilizers and pesticide additions in farming land degrade soil quality by altering pH, killing beneficial microbes, affecting the ecosystems, contaminating groundwater, depleting natural resources, and contributing to climate change [17]. Also, chemical fertilizers and pesticides create threats to the wholesomeness of living organisms. Therefore, sustainable agriculture is a salient approach to addressing these challenges and can minimize the environmental impacts, conserve resources, and maintain the quality of the land for future generations [18].

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Sustainable agriculture is a farming approach that prioritizes long-term environmental and soil health while enhancing agricultural productivity [19, 20]. Adding plant biomass and biochar to soil can contribute to sustainable agriculture by improving soil health, water-holding capacity, and nutrients, stabilizing organic carbon, and modulating microbial activity [21–24]. Water Hyacinth Biomass (WHBM) as a soil conditioner can be an effective application to improve the productiveness of the soil and eradicate this invasive weed [25, 26]. Water hyacinth is the biosphere's utmost noxious, dreadful marine weed that reproduces yearly with 14×10^7 daughter plants and forms thick solid mats on top of water bodies, coupled with its adaptability to various environmental conditions [27, 28]. It can grow at a pH of 4–10, and air humidity of 15%–40%. Numerous ecological and economic problems are caused by water hyacinths, including oxygen depletion, pH alteration, mosquito breeding, obstruction of waterways, and interference with irrigation systems [29]. Therefore, to achieve the sustainable development goal (SDG), it is important to seek sustainable approaches for aquatic invasive weed disposal and management, particularly, water hyacinth must be appropriately disposed of and used for soil amendment [30]. The removal of WHBM from waterbodies responds to Clean Water and Sanitation (SDG6) by improving water quality and controlling eutrophication. However, it is essential to understand its characteristics to apply in agricultural soil because WHBM can be a possible foundation of valuable plant subsistence, such as nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg) and silica (Si) [31]. Furthermore, WHBM incorporated into the soil enhances the soil morphology, fertility, and carbon content. Nevertheless, raw biomass quickly decomposes, releasing carbon dioxide back into the atmosphere which contributes one-third of carbon dioxide and leads to global warming, but biochar can persist in the soil for centuries [32]. WHBM has an average content of cellulose (18–31%), hemicellulose (18–42%), and lignin (7–26%) with rich carbon content [33]. Therefore, conversion of the WHBM to biochar can modify carbon stability and support extended storage of soil carbon and a potential feedstock for biochar production, which is a profitable path to produce soil amendments for sustainable agriculture from invasive weeds [34–37].

Carbonization of WHBM involves heating it in a controlled environment with limited oxygen to convert it into carbon-rich biochar for the application of soil amendment [38]. In addition, the most suitable temperature for carbonization of WHBM must be determined to produce high-quality biochar with stable carbon and nutrients for soil amendment application, which will help improve soil quality, fertility, soil structure, and water retention and provide a habitat for beneficial microorganisms [39]. The performance of water hyacinth biochar (WHBC) depends on the properties of WHBM that need accurate characterization and their thermal decomposition [40]. In recent years, thermogravimetric analysis (TGA) has provided reliable results and an efficient method for assessing biomass properties that help to find the decomposition temperatures of manufacturing eco-friendly biochar from cellulosic carbons to more stable aromatic carbons [41, 42].

The primary focus of this research is to determine WHBM and WHBC properties and the possibility of amending the material for agricultural soil as a soil fertilizer, with the following aims: 1) To study the characteristics of WHBM before making biochar to investigate the capability of biochar production, 2) To determine the optimum temperature for production of biochar using water hyacinth by TGA analysis, 3) To study the characteristic changes of water hyacinth after making biochar using advanced microstructural characterization techniques and suggest the suitability for agricultural application.

2. MATERIALS AND METHODS

In this study, WHBM was collected and prepared for biochar production. Thermogravimetric analysis of WHBM was performed to identify the suitable temperature for biochar preparation. Then, biochar was prepared and evaluated using proximate and ultimate analyses to identify chemical and elemental compositions and determine biochar stability. To determine the suitability of biochar as a soil amendment for agricultural use, XRD, FTIR, SEM, and EDAX analyses were used to analyze the structural properties, crystallographic nature, functional groups, and surface morphologies of WHBM and WHBC, along with their elemental compositions.

2.1. Collection and preparation of WH biomass

The WHBM were collected from the Sengulam lake (9°30′40.6″N 77°38′18.3″E) at Srivilliputtur, Virudhunagar, India and cleaned many times with water and then washed in distilled water, air-dried [43]. The dried WHBMs were powdered (particle size <1.50 mm) and kept in polythene bags for further analysis. The powdered WHBM was processed to achieve a uniform particle size using a sieve with a mesh size of 1.5 mm. Figure 1 shows the preparation of powdered WHBM from raw water hyacinth.

2.2. Thermogravimetric analysis of WH biomass

A thermogravimetry analysis and derivative gravimetry (TGA/DTG) were performed on the WHBM powder sample from 30 °C to 800 °C at a heating rate of 20 °C min^{-1} under air to observe the thermal degradation of different weight percentages of the powder sample as a function of weight loss [44]. This analyzer is accompanied by a furnace with a crucible and N gas (20 mL min^{-1}) is supplied to the furnace. The MTG software recorded mass loss and temperature data every five seconds, which was analyzed on Origin. The differential thermogravimetric (DTG) weight-loss profiles help to determine the stages of decomposition [45].

2.3. Preparation of biochar

WHBC is prepared in a muffle furnace and pyrolyzed in a limited-air atmosphere. For this, WHBM powder was kept

Fig. 1. Preparation of water hyacinth biomass

in a closed container and carbonized at 300 °C, for a time of 30 min. Figure 2 shows the production of WH and prepared WH biochar.

2.4. Proximate and ultimate analysis of WHBM and WHBC

The moisture content (MC), ash (AC), fixed carbon (FC), volatile matter (VM) and pH of WHBM and WHBC are carried out by following standards: ASTM D3173, ASTM D3175, ASTM D3174 respectively. The WHBM and WHBC were oven-dried at 105 °C up to mass stability had attained to determine their moisture content. WHBM was heated to 950 °C for 7 min in a muffle furnace to determine the volatile components. Samples were heated to 750 °C for six hours to measure the amount of AC present. Total carbon (TC) was determined by subtracting the total MC, VM, and AC from 100 [46]. Biomass pH was measured in WHBC suspension (1% wt/wt) [43]. The compositional analysis using Elementar Vario EL III CHNS analyzer for C, H, N and S to assess WHBM as a significant source for biochar production [47].

2.5. Microstructural characterization of WHBM and WHBC

WHBM and WHBC were studied using a BRUKER D8, XRD, and the conforming patterns (10–80°) were recorded to determine their crystalline nature. The vibrations of functional groups of the WHBM and WHBC were studied using a Fourier transform infrared spectrometer (FTIR, IR Tracer 100) in the frequency range 400–4,000 cm^{-1}. Scanning electron microscopy (SEM) is used for studying the surface morphology and microstructure of WHBM and WHBC [48, 49]. SEM, ZEISS EVO18 CARL helps to study the morphology microstructure of WHBM and WHBC and Energy-Dispersive X-ray Spectroscopy (EDX) is employed to determine elemental composition [50].

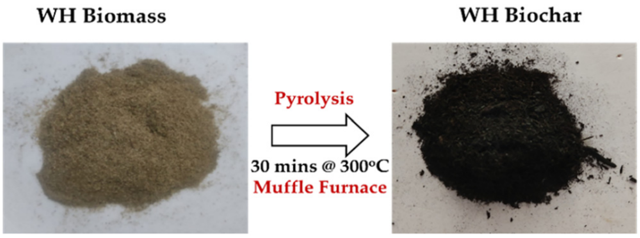


Fig. 2. WH biochar preparation

2.6. Cation exchange capacity of WHBC

The cation exchange capacity (CEC) of WHBC is measured using a modified ammonium acetate displacement method [51], which helps to identify nutrient retention. WHBC (1 g) was placed in a 50 ml polypropylene tube with deionized water (20 ml). WHBC was filtered using a vacuum filtration system with a μG glass membrane after 3 days of agitation and filled with sodium ions with 20 ml of a sodium acetate solution, with a concentration of 1.0 mol L^{-1} and a pH level of 8.2. This mixer underwent washes using 20 ml portions of 90% ethanol to eliminate sodium ions. The resulting leachates were diluted to 100 mL with deionized water in a flask. The concentration of sodium, in the leachate was then determined using a flame photometer. The CEC was calculated as the amount of sodium absorbed per unit mass of WHBC and expressed in cmol kg^{-1}.

2.7. Water retention capacity of WHBC

Water Holding Capacity (WHC) is determined by mixing 0.50 g of WHBC with deionized water (20 ml) and vibrating for 3 days. The biochar-water mixture was filtered, dried, and weighed after full saturation. The WHC is calculated using equation (1).

$$WRC(\%) = \frac{Weight\ of\ saturated\ WHBC - Weight\ of\ dry\ WHBC}{Weight\ of\ dry\ WHBC}\ \text{X}\ 100 \tag{1}$$

3. RESULT AND DISCUSSION

3.1. Primary analysis of WH biomass

The pH of WHBM is slightly alkaline. Therefore, any pre-treatment is not necessary to use as feedstock for biochar preparation. Table 1 shows that the received WHBM has a high MC of 85% while the dried water hyacinth has a low of 4%. A MC of around 10% is desired for biochar production [52]. In biomass, 39 wt.% of VM represents a potential for high yields of biochar. The results of AC (19%) show the amount of inorganic substance present in the water hyacinth

Table 1. The physicochemical character and proximate analysis of WH biomass

Sl. No	Characters	Percentage
1	pH	7.5
2	Moisture content (as received)	85%
3	Moisture (dry basis)	4%
4	Volatile matter	39%
5	Ash Content	19%
6	Fixed Carbon	42%

that would remain after the complete combustion of the WHBM. Low AC is beneficial for biochar products with good quality. Furthermore, biochar yield is subject to the FC of WHBM. WHBM has FC (42%) which shows potential for higher biochar yield [29].

According to the elemental composition from CHNS analysis of the WHBM sample from Table 2, the carbon content is 39.96% and the hydrogen content is 6.14%. In particular, carbon-rich biomass is ideal for the production of biochar since it can store carbon in soil for a long time [53]. WHBM can also supply the essential nutrients nitrogen (2.34%), potassium (0.7%) and phosphorous (3.56%) to the soil. The sulfur content was not detected in the collected WHBM which shows it is not accumulated in the plant dry matter.

3.2. TGA of WH biomass

Thermal stability of WHBM and hemicellulose, cellulose, and lignin content were determined using TGA [54]. TGA study provided the mass loss of WHBM with temperature increment and Fig. 3 shows the pyrolytic decomposition of WHBM in inert atmospheres occurs at mild temperatures for hemicelluloses (up to 230 °C) followed by cellulose (230–360 °C) and finally lignin (360–664 °C) and DTG curve weight change of WHBM concerning temperature. Moreover, the TGA/DTG curve indicates that the optimum temperature for biochar production is from 230 °C to 664 °C which lies in the lignocellulose phase so it is a suitable temperature for WHBC preparation. In this study, the 300 °C temperature can produce biochar with a higher yield.

3.3. Characterization of WH biochar

The elemental composition of the WHBC exposed that medium C content was 29.86% followed by nitrogen at 2.07% shown in Table 3. The study revealed that WHBC is carbon-rich (29.86%) with nitrogen content, suitable for sustainable soil amendments [55, 56]. The H/C (0.026) of WHBC was very low which was extremely carbonized with a highly aromatic structure that can persist in soil for a longer time [57]. In addition, WHBC can retain essential nutrients such as N, P, and K. Therefore, WHBC can improve soil productiveness and plant growth.

Table 2. The elemental composition and nutrient profile of WHBM

Sl. No	Elements	Percentage
1	C	39.96
2	H	6.14
3	N	2.34
4	S	ND
5	O	3.56
6	P	3.56
7	K	0.7

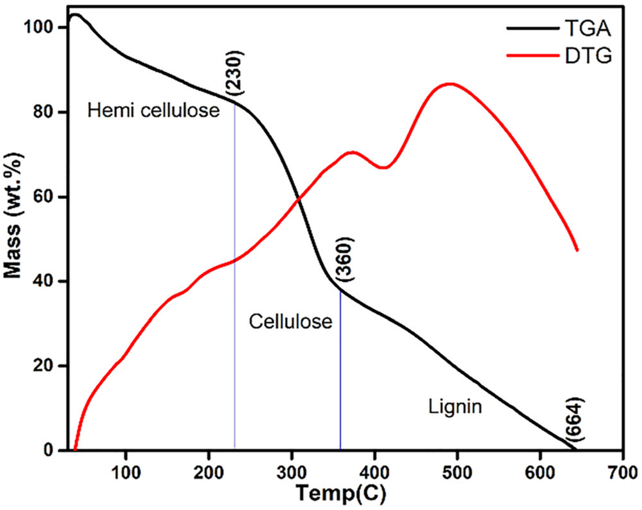


Fig. 3. TGA/DTG profiles for WHBM

This technique has produced effective WHBC with a 65% yield (Table 4) after 30 min at 300 °C. The WHBC had an alkaline pH of 8.2 and this relatively high alkaline biochar is suitable for amending acidic soils. The WHBC has a VM of 27% due to the decomposition of volatiles and evolved in aliphatic, aromatic fragments, and carbohydrate products [58].

Table 3. The proximate analysis and major nutrition profile of WH biochar

Sl. No	Elements	Percentage
1	C	29.86
2	H	0.78
3	N	2.07
4	S	ND
5	O	11.56
6	P	0.7
7	K	1.6
8	H/C	0.026

Table 4. The physicochemical character and proximate analysis of WH biochar

Sl. No	Characters	Percentage
1	Yield	65%
2	pH	8.02
3	VM %	27%
4	AC %	14%
5	FC %	59%

The AC (14%) is caused by inorganic constituents and organic matter residues present in WHBM. During pyrolysis of WHBM, organic material decomposes under thermal conditions in the absence of oxygen, leaving behind inorganic residues contributing to ash content. The organic content of the biomass includes compounds such as cellulose, hemicellulose, and lignin besides inorganic elements such as potassium, calcium, magnesium, and silica that were embedded in the organic matrix. With increasing temperature through pyrolysis, the organic matrix decomposes and releases volatile compounds, which include water vapour, carbon dioxide, carbon monoxide, and hydrocarbons. It also makes minerals structurally bound to the organic substance available. Together with free inorganic elements originally found in the biomass, these minerals stay in the residue in the solid phase after the organic components have volatilized. Oxides and salts of potassium, calcium, magnesium, and silica comprise the residue ash. The FC (59%) is due to polymerization, which leads to the production of more structured carbon [59].

3.4. XRD

The amorphous and crystalline phase was determined from XRD analysis in WHBM and WHBC. The diffraction pattern of WH biomass and WH biochar is shown in Fig. 4, which shows WHBM perfectly well-defined crystalline indicated at 2 theta of 14.98° (110) and 21.2° (200) for cellulose groups I and IV [60]. In WHBM, the C=O function is seen due to the presence of hemicellulose.

In the XRD of WHBM, two broad peaks of cellulose at sharp 2θ angles of 14° and 21°. Nevertheless, on WHBC, peaks were removed due to the distraction of cellulose and new peaks revealed in WHBC with 2θ 28°, 41°, 50°, and 58° correspond to calcite quartz and dolomite, which can improve WHBC crystallinity and also has potential use for soil amendment purposes for the enrichment of soil nutrients [61].

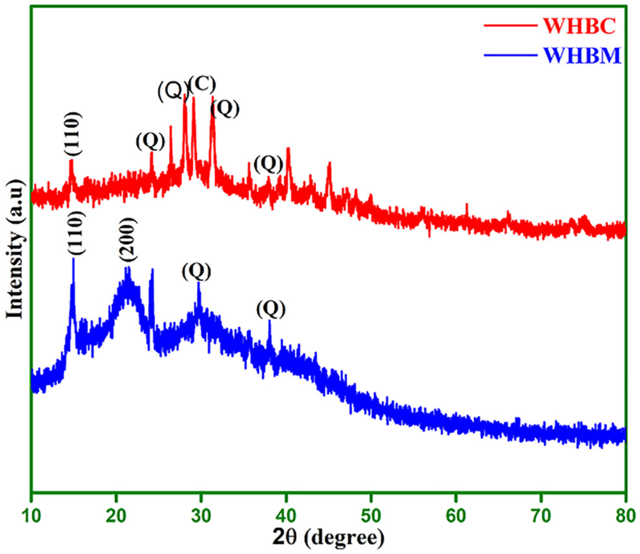


Fig. 4. XRD of WHBM and WHBC

3.5. FTIR

The FTIR spectra of WH biomass and WH biochar are displayed in Fig. 5. The WHBM's cellulose, hemicellulose, lignin, and chemical functional groups are known by the various wavelength spectra [62]. Also, FTIR spectra showed hydroxyl, carbonyl, carboxyl, and aromatic functions in WHBM. The peaks 3,714, and 3,603 cm^{-1} show the H–OH stretching of the carboxyl group and the 2,978 cm^{-1} peak affirms the asymmetric C–H stretching of an aliphatic group due to cellulose and lignin [63].

The peaks at 2,320 cm^{-1} and 642 cm^{-1} show the hemicellulose components of C=O and C–H respectively and 1900 cm^{-1} correlated with C–O. In WHBC, hemicellulose presence can increase its porosity and water-holding capacity, improving its properties as a soil amendment. The 1,600 cm^{-1} band is associated with C=C and stretching decreased due to carbonization temperature [64]. The peaks of 1,408 cm^{-1}, 1,028 cm^{-1} and 781 cm^{-1} show CH2 bonding of cellulosic content, C–O–H stretching, and C–H bonding of WHBC [65]. These compounds can produce pores and large surface area which improve the soil structure [41].

3.6. SEM and EDAX

WHBM and WHBC were investigated using SEM analysis to understand their structures, and surface topography to determine the water-holding capability, nurture microorganisms, and retain nutrients [66]. Figure 6(a–d) shows a layered and fibrous structure of WHBM which is attributed to chemical composition and smooth surface due to a bundle of tightly linked microfibers.

EDX Spectra (Fig. 7) explains the elemental composition of WHBM and shows the carbon content of 34.6% and the oxygen element of 46.3% on a weight basis. In addition, the WHBM has beneficial nutrients such as K, Na, Mg, Si, Ca, and P, which can provide fertility to the soil. However, the conversion of WHBC into WHBM can support maintaining

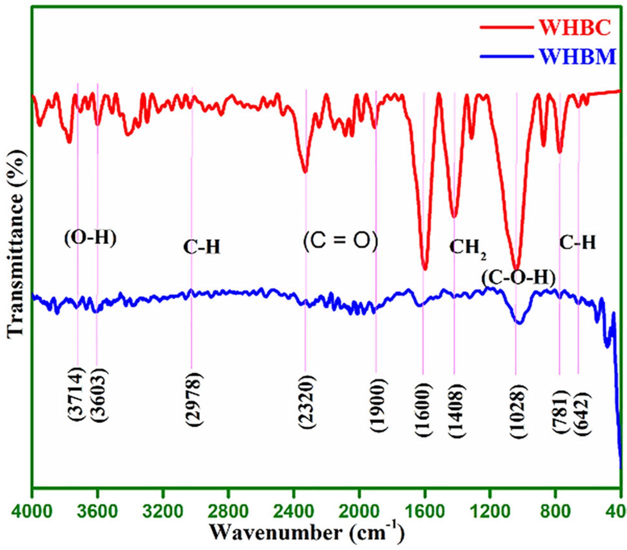


Fig. 5. FTIR of WHBM and WHBC

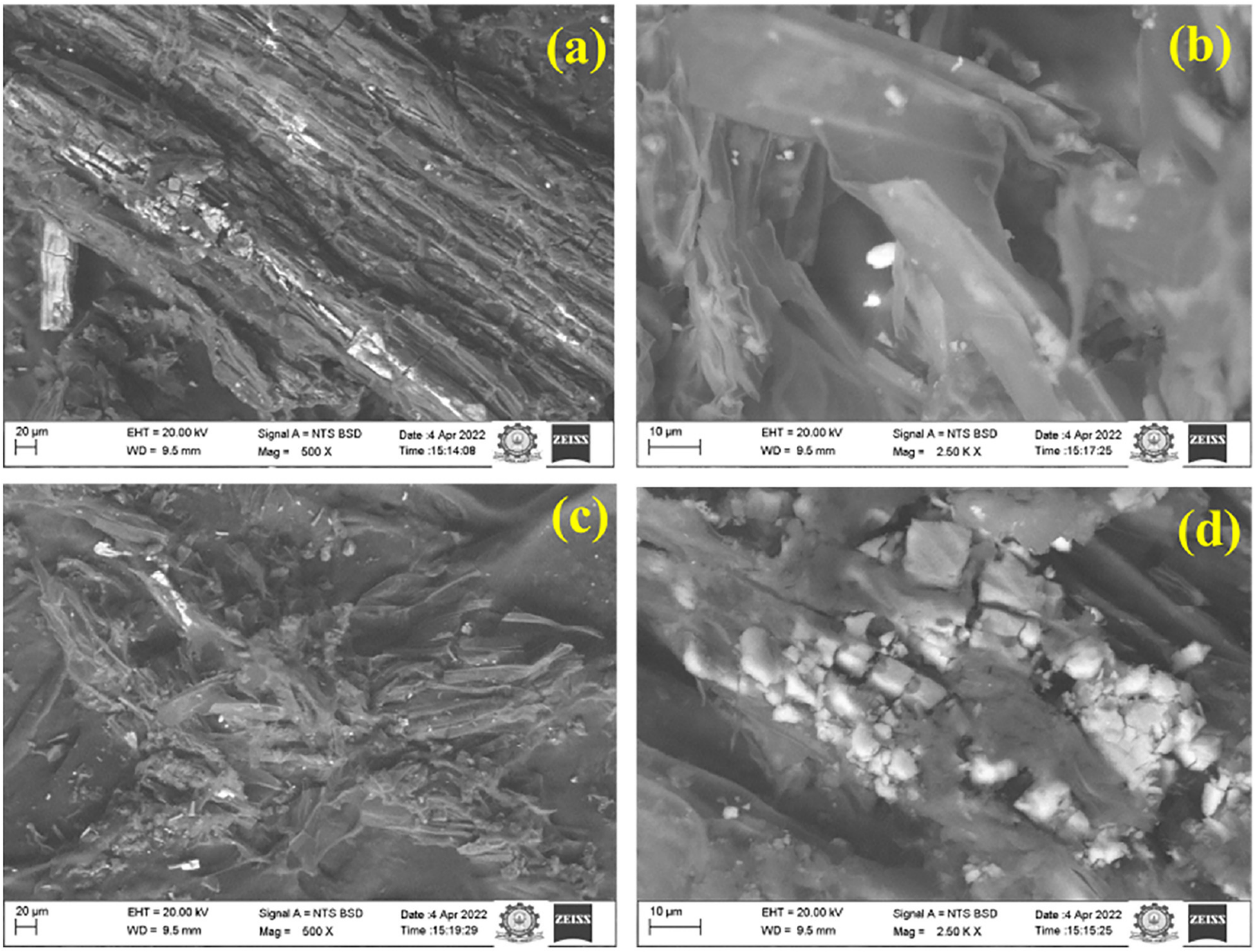
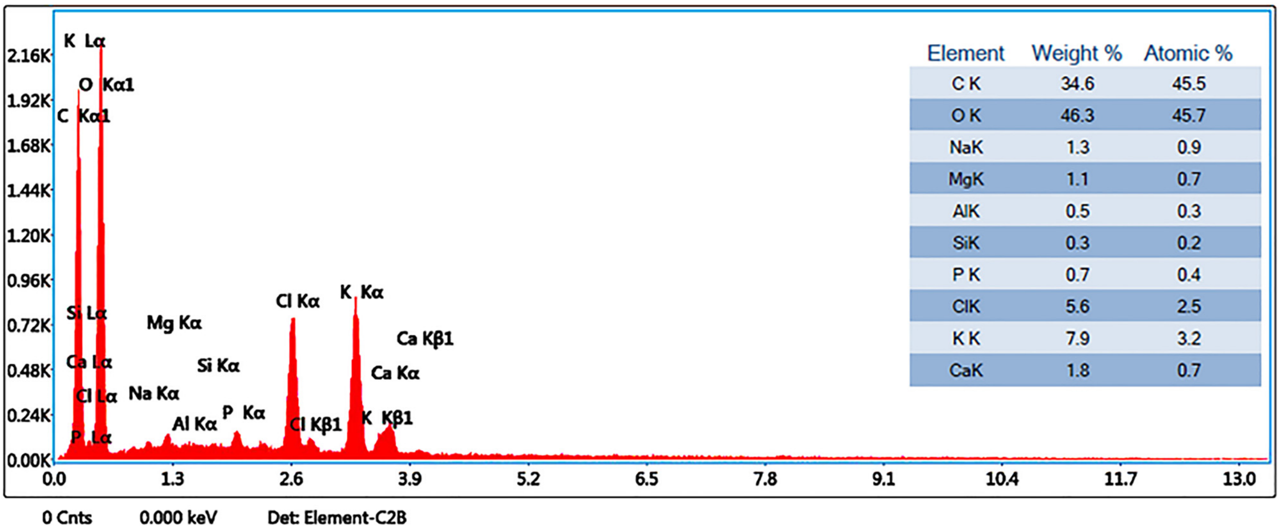


Fig. 6. SEM images of WHBM



Element	Weight %	Atomic %
C K	34.6	45.5
O K	46.3	45.7
NaK	1.3	0.9
MgK	1.1	0.7
AlK	0.5	0.3
SiK	0.3	0.2
P K	0.7	0.4
ClK	5.6	2.5
K K	7.9	3.2
CaK	1.8	0.7

Fig. 7. EDAX spectra of WHBM

soil fertility over the long term by providing a slow-release source of nutrients.

Figure 8 shows that the surface morphology of WHBC is heterogeneous rough, firm, compact and dense structure [67]. The structural alteration of WHBC from WHBM was detected in the SEM micrograph. The surface area of WHBC has improved, as identified using ImageJ software through the analysis of SEM images. This improvement is attributed

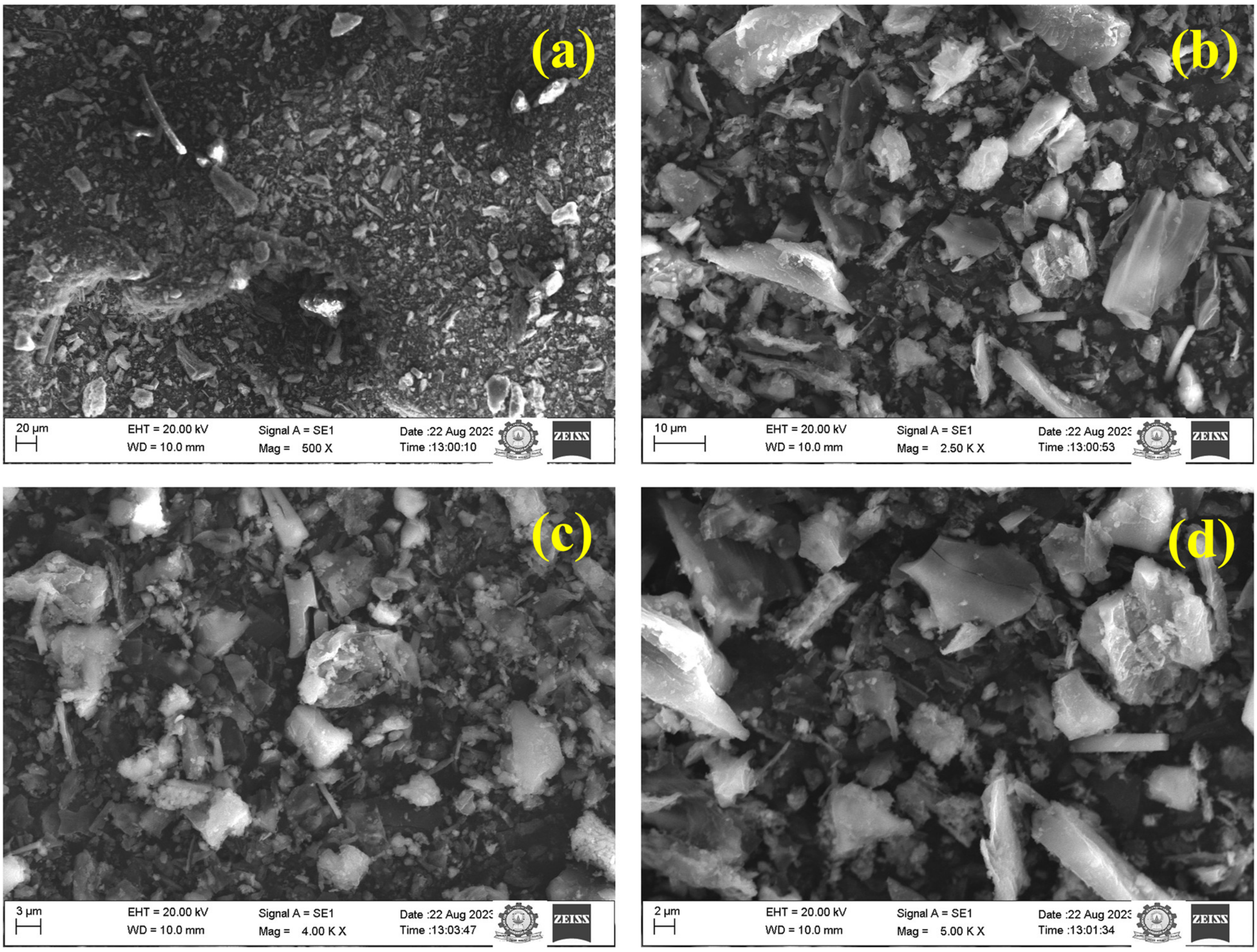
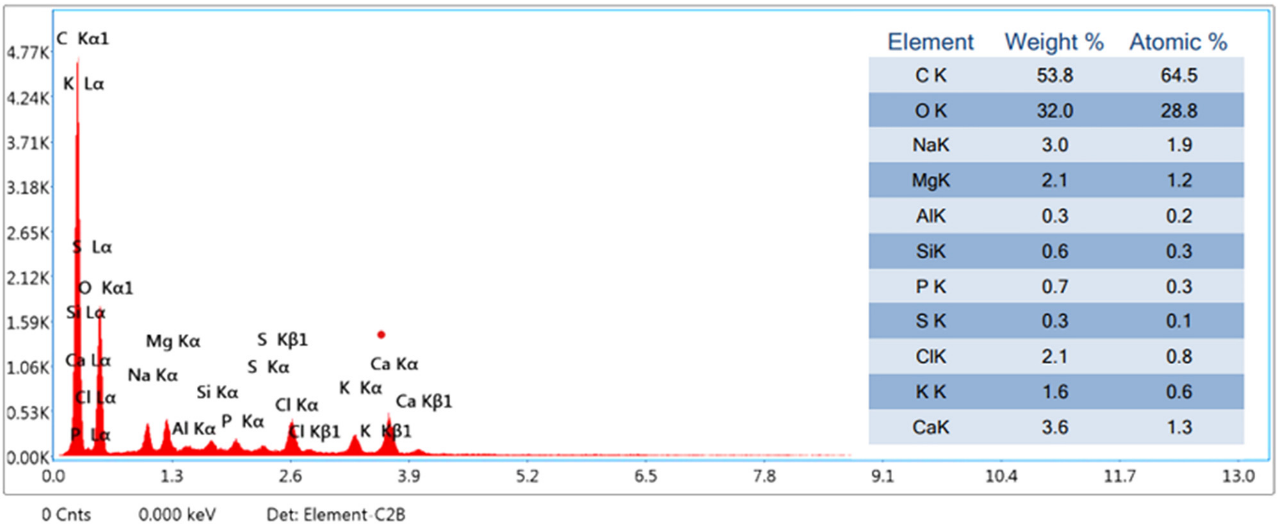


Fig. 8. SEM images of WHBC

to the structural changes occurring during the pyrolysis process, where volatile organic components decompose. However, sufficient pores are not formed in the microstructure of WHBC, which indicates WHBM needs pretreatment. In addition, this study suggests that activation of WHBC can help to produce a more porous structure and high surface area [68].

The elemental composition of the WHBC from EDAX spectra (Fig. 9) shows the presence of nutrients such as P, K, Si, Al, Ca, Cl, Mg and Na, which will help the plant growth [69].



Element	Weight %	Atomic %
C K	53.8	64.5
O K	32.0	28.8
NaK	3.0	1.9
MgK	2.1	1.2
AlK	0.3	0.2
SiK	0.6	0.3
P K	0.7	0.3
S K	0.3	0.1
ClK	2.1	0.8
K K	1.6	0.6
CaK	3.6	1.3

Fig. 9. EDAX spectra of WHBC

3.7. CEC and WRC of WHBC

CEC for WHBC is found to be 16 cmol kg^{-1}, which implies moderate nutrient retention capacity. WHBC will contribute significantly to soil fertility since these can retain important nutrients for plant growth, such as potassium, calcium, and magnesium. WHBC also recorded a WRC of 320%, which represents excellent soil moisture retention ability. WHBC, therefore, promises great potential for enhancing soil moisture-holding capacity in droughty areas by maintaining moisture levels for uptake by plant roots.

4. CONCLUSION

Based on the characterization of WHBM and WHBC, the following conclusions were made:

- Water hyacinth weed is extremely difficult to eradicate once established. So, the management of this weed is very much necessary. The findings of primary analysis showed that WHBM has high carbon content which is suitable for biochar feedstock. This study recommends that a sustainable solution for aquatic weeds is to convert biochar to solve environmental issues.
- The TGA study determined the thermal decomposition of WHBM of cellulose and lignin, and hence, the optimum temperature for biochar production is 230 °C–664 °C. Initially, The WHBC was produced at 300 °C temperature and received a higher biochar yield (65%). The proximate analysis revealed the WHBC carbon content was reduced from WHBM due to the release of more volatile content. However, macronutrients such as N, P, and K are presented in the WHBC and can be used as amending material for agricultural soil.
- The XRD analysis of WHBM confirmed the presence of cellulose and lignin content, whereas new peaks were presented in the XRD pattern of WHBC which attributed to char formation. Hence, the XRD analysis of conforming minerals presence such as quartz, calcite, and dolomite that the prepared WHBC is suitable for agriculture soil modification to enhance the productiveness of the soil and plant growth by supplying nutrients such as silica, calcium, and magnesium from quartz, calcite and dolomite minerals. The FTIR analysis showed the various functional groups associated with WHBM and WHBC. WHBC can be used as an amending material due to its aromatic structure that can store carbon in the soil and contribute to mitigating climate change.
- SEM analysis revealed that WHBC is a heterogeneous rough, firm, compact and dense structure. However, sufficient pores are not formed in WHBC's microstructure, indicating WHBM needs alkali pretreatment. In addition, this study suggests that biochar activation can produce more pores with a large surface area. The essential nutrients such as K, P, Si, Al, Ca, Cl, Mg and Na are present in the WHBC which will improve plant growth.
- WHBC retains moderate levels of nutrients, which are determined by CEC. Hence, suitable for agricultural amendment and is an appropriate material for enhancing soil fertility through vital nutrients such as potassium, calcium, and magnesium. This can also enhance soil moisture retention in drought-prone regions.
- WHBC exhibits the best properties due to its enhanced carbon stability, nutrient retention, and mineral composition, making it ideal for agricultural and environmental applications. TGA is optimized Pyrolysis temperature, volatile matter is reduced and macronutrients like N, P, and K are preserved. Minerals like quartz, calcite, and dolomite in WHBC also contribute to soil productivity by providing nutrients like calcium, magnesium, and silica.
- As a result of the aromatic structure of WHBC, identified through functional group analysis, it can sequester carbon in the long term, thus contributing to climate change mitigation and soil fertility maintenance. In addition, its firm and compact microstructure, as confirmed by morphological analysis, provides durability. Therefore, the conversion of WHBM to WHBC can contribute to sustainable agricultural practices.

ACKNOWLEDGEMENT

The author Nittin Johnson Jeyaraj is grateful to the International Research Centre (IRC), and Kalasalingam Academy of Research and Education (KARE) for providing a University Research Fellowship (URF) and instrumental research facilities.

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