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Elemental Composition of Biochar Obtained from Agricultural Waste for Soil Amendment and Carbon Sequestration

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Abstract: For an agricultural country such as Thailand, converting agricultural waste into biochar offers a potential solution to manage massive quantities of crop residues following harvest. This research studied the structure and chemical composition of biochar obtained from cassava rhizomes, cassava stems and corncobs, produced using a patented locally-manufactured biochar kiln using low-cost appropriate technology designed to be fabricated locally by farmers. The research found that cassava stems yielded the highest number of Brunauer-Emmett-Teller (BET) surface area in the biochar product, while chemical analysis indicated that corncobs yielded the highest amount of C (81.35%). The amount of H in the corncob biochar was also the highest (2.42%). The study also showed biochar produced by slow pyrolysis was of a high quality, with stable C and low H/C ratio. Biochar's high BET surface area and total pore volume makes it suitable for soil amendment, contributing to reduced soil density, higher soil moisture and aeration and reduced leaching of plant nutrients from the rhizosphere. Biochar also provides a conducive habitat for beneficial soil microorganisms. The findings indicate that soil incorporation of biochar produced from agricultural crop residues can enhance food security and mitigate the contribution of the agricultural sector to climate change impacts.

Keywords: biochar; pyrolysis; thermochemical; biorefinery; biomass; soil amendment; carbon sequestration; climate change; agriculture

1. Introduction

Biorefining is the term given to the sustainable processing of biomass into a spectrum of marketable products and energy [1]. A wide range of technologies are available to separate biomass such as agricultural residues into their respective components (e.g., carbohydrates, proteins, triglycerides, etc.). These components can then be further converted to value-added products such as biofuels and fine chemicals. Biorefineries use a range of methods to convert biomass to value-added products and/or energy. Products typically take the form of chemical intermediates such as biohydrogen, bioethanol, biomethane, biodiesel, pellets, lignin, charcoal [2–4] that may then serve as feedstocks for other industrial processes.

Biorefineries can be categorized by feedstock, type and status of technology (e.g., first- or second-generation biorefinery and intermediate, e.g., syngas platform, sugar platform) [5,6]. At global level, biorefineries generally focus on three main products: biochemical [7], bioenergy (e.g., [8–11]), biofuels (e.g., [12–16]), and applications in the food and polymer industries (e.g., [17–21]). However, biorefineries can also produce biochar, a high-value marketable product with benefits for the environment and sustainable agriculture [22,23]. Biorefineries use thermochemical processes (pyrolysis and carbonization) to convert biomass into biofuels and other bio-energy products [24,25]. Major thermochemical technologies for biochar production include slow and fast pyrolysis, gasification, torrefaction and hydrothermal carbonization [24].

Slow pyrolysis of biomass can be used to produce biochar, whose properties depend on feedstock properties as well as the reaction temperature and duration [22–26]. The chemical and physical properties of biochar (and thus its value) can be fine-tuned by modification of these reaction conditions [25]. The utility of biochar has been demonstrated in reducing the need for agrochemicals, increases in productivity, long-term improvement in soil conditions and reduction in greenhouse gas emissions through soil sequestration as well as indirectly through increasing the efficiency of fertilizer use [22–26].

Asia's agricultural sector generates large volumes of agricultural residues every year [26]. Crop residues contribute to 80% of the global production of biomass dry matter (8201 Tg/year) of which 3137 Tg/year are potentially available after pyrolysis [27]. The use of agricultural residues as a feedstock for biochar production is therefore of interest for use as a soil amendment, with potentially significant environmental, production and economic benefits. Thailand's economy relies on agricultural products. The country's agricultural sector generates a large volume of crop residues including paddy husks, sawdust, corncobs, cassava stems and cassava rhizomes. Production data collected by the Department of Agricultural Extension between 2006–2007 indicated that Thailand produced 4.40 million tons of corn and 17.6 million tons of cassava of which 0.84 million tons were corncobs, 2.11 million tons were cassava stems and 1.76 million tons were cassava rhizomes [28]. Normally, agricultural wastes are simply left in the field to decompose or burned. Burning crop residues adds to GHG emissions, resulting in severe impacts on air quality, biodiversity and human health. Although burning is convenient, quick and cost-effective, and allows fast preparation of the field for the next rotation, some farmers nevertheless choose to incorporate crop residues into the soil to maintain long-term soil fertility. Soil incorporation of biochar from crop residues offers an attractive alternative to open field burning. Instead of burning, farmers can deal with their large volumes of crop residues by converting it into biochar using slow pyrolysis. The biomass is heated at 500–600 °C in a reduced oxygen or fully anoxic atmosphere [29,30]. Compared with other methods, pyrolysis has proved effective in converting residues into biochar as a highly stable solid [31]. Moreover, several studies confirm that biochar is effective as a soil ameliorant and can even increase crop yields [32–34].

Biochar is highly stable, comprising more than 65% carbon. Chemical composition is highly dependent on feedstock and pyrolysis conditions [35–38]. Biomass subjected to pyrolysis is converted to biochar with high fixed carbon content and high stability. Biochar's stability in soil is crucial to its long-term environmental benefits. Because of its long-term stability, biochar can be used for carbon sequestration, mitigating climate change by locking carbon in the soil. The stability of biochar ensures longevity of expected benefits for soil, crops, water resources and climate change mitigation [39]. Biochar also regulates and increases availability of cationic plant nutrients such as P, K, Na, and Mg [27]. In addition to its direct agronomic benefits (enhanced fertilizer use efficiency, higher yields and improvement in soil fertility), biochar delivers three primary environmental benefits: sequestrating carbon in soils, reducing greenhouse gas emissions [39,40] and reducing pollution via runoff of fertilizers and pesticides into waterways and groundwater.

This research studied the composition, structural characteristics and morphology of biochar obtained via slow pyrolysis from three different types of biomass. The three biochar products were analyzed and compared to identify the most suitable biochar for soil amendment. This pilot study focused on using locally-produced crop residues wastes as feedstock. The biomass was heated in a controlled temperature biochar retort, manufactured locally using low-cost appropriate technology and designed to be fabricated by farmers themselves.

2. Materials and Methods

2.1. Biochar Production

The three sources of crop residues used as feedstock were corncobs, cassava rhizomes and cassava stems. Before heating the biomass, the materials were prepared to similar size distributions and moisture content. The cassava stems and corncobs were cut to less than 15 cm in length, while the cassava rhizomes were cut into lengths shorter than 10 cm. The materials were subjected to slow pyrolysis for 12–24 h in the Controlled Temperature Biochar Retort for Slow Pyrolysis Process (Patent Number 110100118, registered by Thavivongse Sriburi) (Figure 1). The retort was designed to comply with the respective FAO guidelines [41]. In order to control temperature, temperature data were collected from inside the biochar retort and the end of the chimney at different times throughout the heating process [22]. During the pyrolysis process, the materials were heated to a maximum 500–600 °C for 30 min. The ratio of biomass volume to fuel volume was 1.0:0.6, i.e., the mass of fuel should represent 60% of the total biomass weight in order to achieve optimal conditions for pyrolysis [34,41].

The Controlled Temperature Biochar Retort for Slow Pyrolysis Process is cost-efficient and can be built easily by farmers themselves for less than $US 50 using locally available materials and- most importantly- can use locally available biomass as feedstock [22,34,42,43]. The patented design allows control over pyrolysis conditions under limited oxygen availability inside the retort, including air intakes and exhaust holes. The design is critical to produce high-quality biochar—the outer furnace with eight drilled holes and the inner steel biochar retort with four drilled holes, all with a diameter of 2.5 cm—showed a highest yield of biochar and used the least amount of fuel. Moreover, the diameter of the holes must be exactly proportioned as incorrect hole diameter could lead to excessively high temperatures, which may adversely affect the quality of the biochar produced.

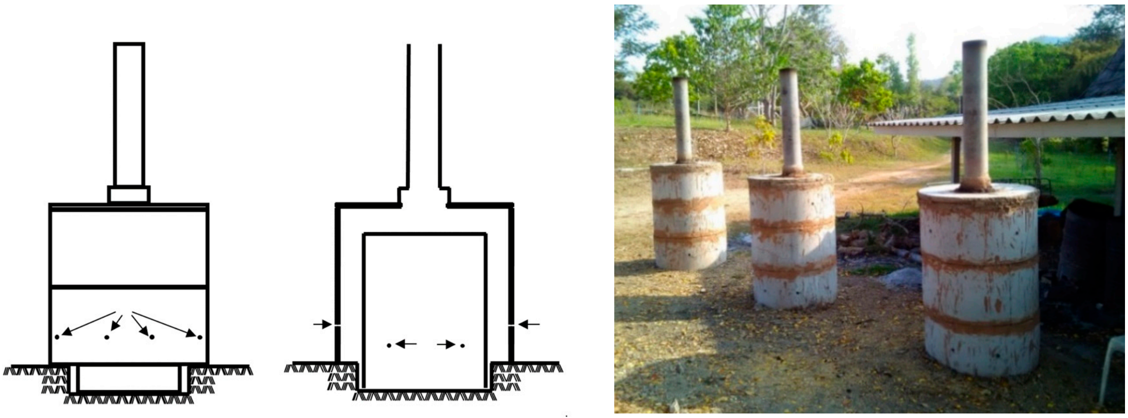


Figure 1. The Controlled Temperature Biochar Retort for Slow Pyrolysis Process.

The retort was designed for farmers in rural areas. It is simple to build and easy to use. The retorts were introduced to local farming communities via projects initiated by organizations under the Royal Project Foundation, including the Huay Sai Royal Development Study Center and Padeng-Biochar Research Center (Pd-BRC).

Pyrolysis temperature in the biochar retort can be controlled in the range of 500–600 °C. Slow for pyrolysis at a moderate temperature (350–550 °C) in the absence of O_2 and a longer residence time resulted in approximately 30% higher biochar yields than fast pyrolysis or gasification [24]. Higher yields of biochar are obtained, (up to 58–60 wt% of feedstock) as compared with similar oven designs. Intagun et al. (2018) [44] found the yield of corncob biochar produced in a "Kon Tiki" flame reached only 34.2 wt%. Cornelissen et al. (2016) [45] found similar low biochar yields of 22 ± 5 wt% from Eupatorium, wood and rice husk feedstocks using Kon Tiki kilns at Farmer Scale. These yield levels were consistent with those found by Pandi et al. (2017) [46] who reported an average biochar yield of only 19.5 ± 05% from Eupatorium feed stock in a Kon Tiki flame curtain and four subtypes of kilns (deep-cone metal kiln; steel shielded soil pit; conical soil pit and steel small cone). O'Toole et al. (2013) [47] produced biochar from wheat-straw with a yield of around 24 ± 4.7%. Beis et al. (2000) [48] studied biochar yield from walnut shell using a Heinze retort with controlled temperature between 400–700 °C. The optimal temperature for their study was 500 °C and the highest biochar yield achieved was 28.9%. The controlled temperature biochar retort used in the current study can achieve yields of approximately double those achieved using other kiln designs.

The biochar produced from the controlled temperature biochar retort for slow pyrolysis process is equivalent in quality to that produced under controlled laboratory conditions and was found in on-farm trials to contribute to soil improvement and boost yields in rice [34], soybean [49] and vegetable farms [23].

2.2. *Analysis Methodology*

The composition of the biomass samples was analyzed before and after pyrolysis to characterize their texture and morphology. Major parameters for the study were surface area and total pore volume. These parameters were influenced by both type of biomass material and pyrolysis operating conditions. The surface area was analyzed by the Brunauer-Emmett-Teller (BET) method [50–52] and total pore volume and average pore diameter were analyzed by the Barrett-Joyner-Halenda (BJH) method [51]. An Autosorb-1 Surface area and pore size analyzer was employed to measure the surface areas, total pore volume and average pore diameter. The morphology characterization was conducted using a Scanning Electron Microscope (SEM) [50,52] on the JEOL JEM-5410LV SEM machine to determine the surface morphology and surface characteristics.

Analysis of elemental composition of the final material (C, H, N and O) was undertaken to establish the weight fractions of these elements. C, H and N were analyzed using the Elemental Analyzer (CHN), Leo TruSpec CHN model. O was calculated from the difference between percentages of biochar composition (100%) and percentages of other nutrients: C%, H% and N% [53]. The H/C, O/C, C/N molar ratios were also calculated [54]. These ratios provided an indication of the properties of biochar and the transformation efficiency during the slow pyrolysis process.

2.3. *Statistical Analysis*

Data were displayed as the mean ± SE, derived from four replicates. Turkey's multiple comparison test was used to analyze the mean variance and compare the significance of the difference between means using the Statistical Package of the Social Science (SPSS) software.

3. Results and Discussion

The aim of this study was to analyze the elemental composition and structural characteristics of high quality biochar derived from different feedstock types as a means of improving soil quality, enhancing crop productivity and sequestering carbon in the soil. The raw materials for biochar production were made of agricultural wastes such as corncobs, cassava rhizome, waste fruits peeling and weeds and also wood branches such as *Albizua myriophylla* Berith, *Cornbretum punetatum* Blume, *Leucaena leucocephala* (Lamk), *Samantha saman* (Jacq) or even hard wood as *Streblus ilicifolius*.

The Controlled Temperature Biochar Retort for Slow Pyrolysis Process is cost-efficient and can be built easily using locally available materials and-most importantly-can use locally available biomass as feedstock [22,34,42,43]. The biochar invented oven was low cost and used raw materials from the local area. It is about 50 US dollars [22]. The biochar was produced from the controlled temperature biochar retort for slow pyrolysis process could have a good product and successfully to soil improvement and higher products in rice [34], soybean [49] and vegetables farm [23]. The controlled temperature biochar retort for slow pyrolysis process can control the temperature between 500–600 °C. The invented oven can control air that passes through inside by pyrolysis condition depending on the size and position of pores around it. Biochar yield depends greatly on thermochemical technology. Slow pyrolysis was most effective; a longer residence time and moderate temperature (350–550 °C) in the absence of O_2 resulted in higher biochar yield (+30%) than the fast pyrolysis (12%) or gasification (10%) [24]. The process of the Controlled Temperature Biochar Retort for Slow Pyrolysis Process can produce high Biochar yields of around 58–60% from raw materials when compared to other similar ovens. Intagun et al. (2018) [44] studied the yield of biochar kiln which was produced from corncob in "Kon Tiki" flame curtain and found the yield to be only 34.2 wt%. So, in this study the invented oven can gave a 1.76-fold higher yield than their experiment. Cornelissen et al. (2016) [45] studied biochar from Eupatorium, wood and rice husk using Kon Tiki kilns on Farmer-Scale and found that the average biochar yield was only 22 ± 5%. Pandi et al. (2017) [46] found an average biochar yield from Eupatorium feed stock of only 19.5 ± 05% by using "Kon Tiki" flame curtain (four subtypes of flame curtain klins: deep-cone metal kiln; steel shielded soil pit; conical soil pit and steel small cone). O'toole et al. (2013) [47] produced biochar from wheat-straw; the yield is around 24 ± 4.7%. Beis et al. (2000) [48] studied biochar yield from walnut shell using Heinze retort with the controlled temperature between 400–700 °C. The best temperature for their study was 500 °C and the highest biochar yield from walnut shell was 28.9%. All experiments' biochar yields were still up to two times less than the yield from the invented oven with the controlled temperature biochar retort for slow pyrolysis process in this study. Therefore, the oven and the process for produce biochar from corncobs, cassava rhizomes and cassava steams can show the high quality of the biochar by measuring element of C, H, N, and O contents between 62.95–81.35, 2.24–2.73, 1.22–1.65 and 15.23–33.44% by dry weight, respectively. Moreover, surface area and total pore volume of the biochar were higher than raw materials. Total pore volume of corncobs, cassava rhizomes and cassava steams of biochar increased 1091.18, 560.47 and 2001.72%, respectively.

Chemical analyses of the feedstock biomass before conversion into biochar (Table 1) revealed that corncobs contained the highest amount of C at 41.66%, while cassava rhizomes contained the lowest (37.60%). Corncobs contained the highest amount of H (6.84%) and cassava stems contained the lowest (6.04%). However, cassava stems contained the highest amount of N (1.27%) and the lowest in corncobs (0.74%). The cassava rhizomes had the highest level of O (55.37%), while corncobs contained the lowest levels of O (50.76%). The results of analysis following transformation of the feedstocks into biochar (shown in Table 2) revealed that corncob biochar contained the highest levels of C and H (81.35% and 2.42%, respectively) while the amount of C and H was similar for the other two biochar types: 64.25% and 2.73% for cassava rhizomes and 62.95% and 2.24% for cassava stems, respectively. Cassava stem biochar contained the highest O content (33.44%) while corncobs contained the lowest (15.23%).

Table 1. Properties of biomass feedstocks.

	Corncob	**Cassava Rhizome**	**Cassava Stem**
C (wt%)	41.66 ^{a} ± 1.12	37.60 ^{a} ± 2.22	41.55 ^{a} ± 0.92
H (wt%)	6.84 ^{a} ± 0.36	6.15 ^{a} ± 0.58	6.04 ^{a} ± 0.13
N (wt%)	0.74 ^{b} ± 0.02	0.88 ^{b} ± 0.04	1.27 ^{a} ± 0.14
O (wt%)	50.76 ^{a} ± 0.89	55.37 ^{a} ± 1.64	51.14 ^{a} ± 1.18
H/C ratio	1.97 ^{a} ± 0.17	1.96 ^{a} ± 0.27	1.74 ^{a} ± 0.06
O/C ratio	0.91 ^{a} ± 0.05	1.10 ^{a} ± 0.09	0.92 ^{a} ± 0.05
C/N ratio	65.63 ^{a} ± 1.89	50.16 ^{b} ± 3.86	39.30 ^{b} ± 3.53
Molecular formula	$CH_{1.97}O_{0.91}$	$CH_{1.96}O_{1.10}$	$CH_{1.74}O_{0.92}$
Surface area (m^2/g)	2.54 ^{b} ± 0.41	2.78 ^{b} ± 0.23	2.51 ^{a} ± 0.03
Total pore volume (cm^3/g)	0.0034 ^{b} ± 0.0007	0.0043 ^{b} ± 0.0004	0.0058 ^{a} ± 0.0006
Average pore diameter (Å)	31.05 ^{c} ± 0.75	69.57 ^{b}± 5.58	83.34 ^{a} ± 1.79

Note: Data are shown as the Mean ± SE. ^{a}, ^{b}, ^{c}, Means followed by a different letter are significantly different at the 0.05 level ($p < 0.05$).

Comparing the chemical composition of each type of feedstock with its biochar product, the analyses of all three samples confirmed an increase in the proportion of C in biochar compared with the original biomass. The amount of C in corncobs increased by the highest percentage (39.69%), followed by cassava rhizomes (26.65%) and cassava stems (21.40%). For H and O the opposite trend was observed.

The distinct chemical composition of biochar resulted from a slow pyrolytic conversion of the biomass feedstock. Biomass is made up of three main components: hemicellulose, cellulose and lignin. In general, these components are represented at levels of 20–40%, 40–60% and 10–25%, respectively, as lignin wt% of the lignocellulosic biomass [55,56]. The slow pyrolysis process dissociates bonds between C and functional groups on the surface area of the biomass, including -OH, aliphatic C-O and aliphatic C-H groups [57–59]. The high temperature drives off volatile compounds and gases including CO_2, CO, H_2O, and volatile hydrocarbons [31,59–61]. Higher temperatures lead to increased amount of volatile matter which in turn boost the content of aromatic structures, especially when the temperature exceeded 400 °C [58,62,63]. Elevated levels of aromatic compounds contribute to enhanced stability of the biochar structure. The H/C molar ratio indicated formation of aromatic compounds. The O/C molar ratio decreased during carbonization, leading to dehydration reactions which reduced the hydrophilicity of the surface of the biochar material [63–65]. These characteristics give biochar long-term stability, allowing it to endure in soil for hundreds of years [66–68].

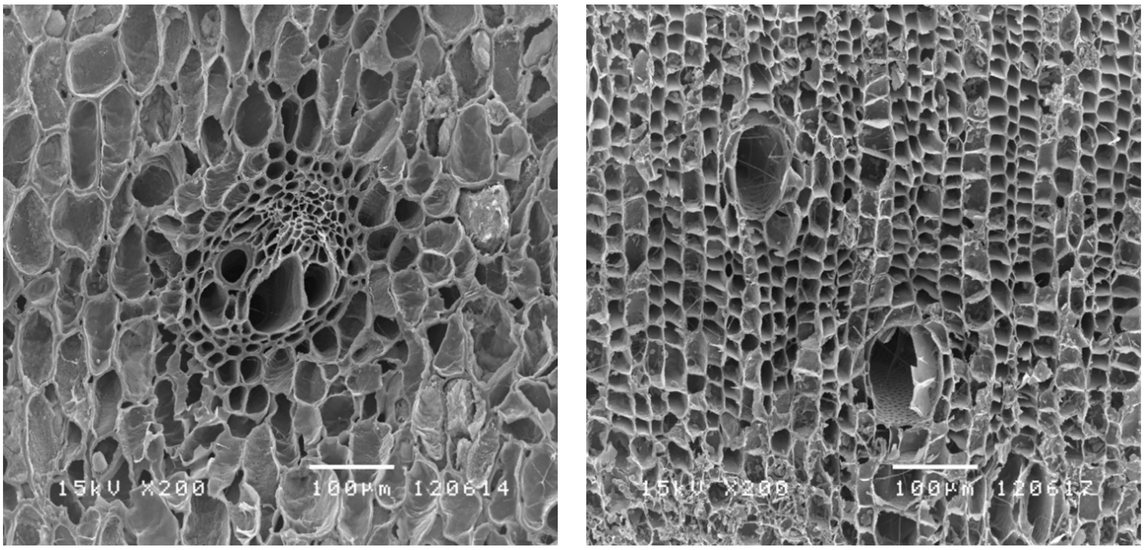
Table 2. Properties of biochar product.

	Corncob	Cassava Rhizome	Cassava Stem
C (wt%)	81.35 ^{a} ± 1.42	64.25 ^{b} ± 1.53	62.95 ^{b} ± 3.71
H (wt%)	2.42 ^{a} ± 0.17	2.73 ^{a} ± 0.17	2.24 ^{a} ± 0.12
N (wt%)	1.22 ^{b} ± 0.14	1.65 ^{a} ± 0.08	1.37 ^{ab} ± 0.06
O (wt%)	15.23 ^{b} ± 1.27	31.80 ^{a} ± 1.27	33.44 ^{a} ± 3.81
H/C ratio	0.36 ^{a} ± 0.02	0.43 ^{a} ± 0.12	0.42 ^{a} ± 0.01
O/C ratio	0.14 ^{b} ± 0.015	0.37 ^{a} ± 0.02	0.39 ^{a} ± 0.08
C/N ratio	80.60 ^{a} ± 8.41	45.72 ^{b} ± 2.34	54.08 ^{b} ± 4.51
Molecular formula	$CH_{0.36}O_{0.14}$	$CH_{0.51}O_{0.37}$	$CH_{0.43}O_{0.40}$
Surface area (m^2/g)	56.35 ^{b} ± 0.79	18.38 ^{b} ± 2.21	200.46 ^{a} ± 26.18
Total pore volume (cm^3/g)	0.0405 ^{b} ± 0.0041	0.0284 ^{b} ± 0.0029	0.1219 ^{a} ± 0.01
Average pore diameter (Å)	28.72 ^{b} ± 2.29	61.69 ^{a} ± 1.64	24.35 ^{b} ± 1.82

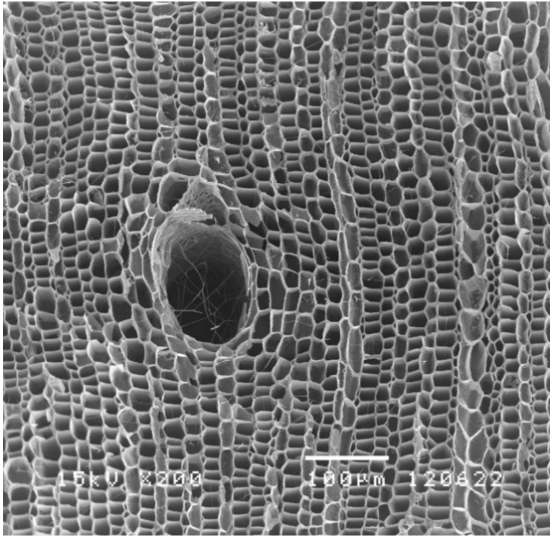
Note: Data are shown as the Mean ± SE. ^{a}, ^{b}, Means followed by a different letter are significantly different at the 0.05 level ($p < 0.05$).

Table 2 summarizes the analyses of the structure and morphology of biochar made using different feedstocks. The results revealed that surface area and total pore volume of cassava stem biochar were the highest at 200.46 m^2/g and 0.1219 cm^3/g, respectively, followed by corncob biochar (56.35 m^2/g and 0.0405 cm^3/g) and cassava rhizome biochar (18.38 m^2/g and 0.0284 cm^3/g). As for average pore diameter, cassava rhizome biochar had the widest pore diameter at 61.69 Å, followed by corncob biochar (28.72 Å) and cassava stem biochar (24.35 Å), respectively.

Using scanning electron microscopy (Figure 2), analysis of morphology of the three biochar products revealed that biomass type influenced morphology under identical pyrolysis conditions in the same retort. Moreover, biochar obtained from different parts of the same plants also demonstrated different morphological characteristics and structures. Biochar produced from cassava rhizomes and cassava stems have a higher pore density than corncob biochar, while corncob biochar has a high pore size distribution than biochar produced from cassava rhizomes and stems. These results are consistent with measurements of their respective surface areas and total pore volumes.



(**a**) Corncob (**b**) Cassava Rhizome



(**c**) Cassava Stem

Figure 2. Scanning Electron Microscopy (SEM) images showing differences in morphology of biochar produced from different biomass feedstocks.

The physical structure of biochar was dependent on the types of biomass feedstock as well as pyrolysis conditions [69–71]. After pyrolysis, the easily decomposed C in the original biomass can be stored "permanently" (>100 years) as biochar [72,73]. The high pyrolysis temperatures lead to dissociation of organic aromatic C bonds, resulting in production of amorphous C [37,58,62,63,74]. The C in biochar appears mostly in the form of amorphous C in which C atoms are connected in aromatic rings [75–77]. Slow pyrolysis results in the release of volatile organic matter, hemicellulose, and lignin, and was associated with overall shrinkage, melting, and cracking, resulting in the highly heterogeneous and complex structure of biochar, with many pores of different diameters [78–81]. These results highlight the importance of biomass type as one of the most important determinants of final biochar properties.

The analysis shows that surface area is directly related to total pore volume, which gives biochar an elevated capacity to adsorb cations across its surface [62,82–84]. A higher matrix surface area increases ion exchange with nutrients at the surface. Therefore, mixing biochar into the soil can increase the soil's cation exchange capacity [84–86]. Moreover, surface area and total pore volume both influence biochar's ability to retain nutrients and water within the pore matrix, thus stabilizing their availability within the soil to support crop growth [58,87].

The results indicated that biochar with high average pore diameter influenced the volume of water and nutrients retained in the pore matrix; biochar with larger pores is able to retain larger amounts of solution and nutrients and subsequently release them for root uptake.

This study revealed that chemical composition of biochar (C, H, O and N), H/C ratio, O/C ratio, the chemical structure (aliphatic and aromatic structures) as well as the product's physical characteristics (surface area, total pore volume and pore size) are associated with biochar's higher cation ion exchange capacity [58,88,89]. Pyrolysis temperature is an important determinant of physical and chemical properties of biochar, since it governs the extent of cleavage of chemical bonds within key components of the biomass (lignin, cellulose, hemicellulose). At 200–300 °C volatile fractions are transformed into low molecular weight liquids and gases instead of biochar [90,91]. Meanwhile, the dehydration of hydroxyl groups and thermal degradation of cellulose and lignin become increasingly significant at higher temperatures [91,92]. During pyrolysis, hemicelluloses decompose first at temperatures ranging from 200 to 260 °C; cellulose breakdown begins at 240–350 °C, and decomposition of lignin begins from 280–500 °C [93]. A dramatically increased surface area in the biomass char is observed to begin at 400–500 °C [94]. When the temperature is increased to 500–600 °C, aromatic organic compounds (mainly amorphous carbon, the main component of biochar) begin to break down [37,74]. The amorphous carbons are structured as aromatic rings, giving biochar its characteristic stability [75–77]. Pyrolysis temperature is therefore a key determinant of biochar yield as well as pore size and volume [80,81].

The bonds between aromatic compounds define the structure and properties of biochar. The main surface functional groups are hydroxyl, methyl, carboxylic and alkene groups [91]. However, Kim et al. (2012) [74] found that carboxyl and carbonyl group originating from carbohydrates appeared with the highest intensity at 300 °C and then decreased at higher temperatures. In contrast, other functional groups were concentrated or formed during decomposition. Aromatic skeletal vibration and aromatic C-H deformation increased until the temperature reached 500 °C [94–96]. As temperature increased, the char became progressively more aromatic and carbonaceous. The hydroxy, aliphatic C-H, carbonyl and olefinic CC groups were lost at higher temperatures. The aromatization process begins at ~350 °C and continues to higher temperatures [97]. Many chemical interactions between biochar and the environment are directly related to its surface chemistry. The presence of surface functional groups such as carboxyl influences cation exchange capacity and the efficacy of biochar as an adsorbent of nutrients [98].

These functional groups facilitate ion exchange and nutrient adsorption over the surface of the biochar [23,34,99,100]. The combined high surface area of biochar and its high CEC leads to higher ion exchange between nutrients in the soil solution [23,101]. The findings provide further evidence to support the utility of biochar as a nutrient source [58,77,102–105], as a soil enhancement to increase soil water holding capacity [58,66,77], supply the plant available silicon pool [106,107], for water retention [58,77] and as a habitat and refugia for soil microorganisms [66,77,105].

Biochar's value as a soil amendment has been widely reported; soil incorporation can increase and enhance crop yields in terms of quality as well as quantity [32,33,105,108–112]. These findings have been documented in a variety of crops such as corn [108–111,113,114], soybeans [22], sorghum [105], cowpeas and peanuts [111]. In vegetables, benefits have been shown in lettuce (*Lactuca sativa*), cabbage (*Brassica chinensis*) [115], Chinese kale [23], tomato [116] and rice [32,34,87,88,105]. Growing crops in soil incorporated with biochar resulted in higher crop yields and improved quality [49,105,110,114,115]. Moreover, the stability of biochar allows it to remain in the soil for a long period. Biochar absorbs and retains plant nutrients from both organic and chemical fertilizers, reducing the leaching of nutrients and potentially reducing the total amount of fertilizers needed, thus reducing production cost [22,87,105,114]. Ultimately, increased productivity and quality of produce will contribute to higher net farm income [43].

Biochar is also an effective soil amendment that can increase soil quality in terms of its physical and chemical composition. Biochar incorporation improves soil aeration and increases the porosity of clay and shale soils [34,88,105,108,117]. Biochar also enhances soil aggregation. Incorporation of biochar into sandy loam soils also improves pH [34,58,66,88,104,115], water holding capacity [88,110,117], cation exchange capacity [89,105,110,111,115] and populations of beneficial soil microorganisms [112]. Moreover, biochar contributes to carbon sequestration [32,39,85,108,118–120], both directly by mixing the biomass into the soil [29,58,104] and indirect sequestration by retaining carbon stocks within the biomass [23,49,55,76]. Biochar can thus contribute to reducing carbon emissions from agriculture [32,90,108,113,117,121].

4. Conclusions

This research aimed to study chemical composition and morphology of biochar produced from three different biomass types: corncobs, cassava rhizomes and cassava stems. These feedstocks underwent slow pyrolysis, reaching maximum temperatures ranging from 500–600 °C. The results show that biochar obtained from these three sources of biomass differed significantly in their elemental composition and morphological structures, with corncobs having the highest amounts of carbon compared to other biomass feedstocks. Analysis of surface area, total pore volume and pore size confirmed prior findings that increased surface area and total pore volume are associated with higher ion exchange capacity and ability to retain water and nutrients. Larger pore diameter may also contribute to more conductive habitats for soil microorganisms. Cassava stem biochar had the highest surface area and total pore volume. Biochar's chemical composition, morphology and texture indicated that biochar obtained from biomass feedstocks through slow pyrolysis yielded a biochar product with chemical composition and morphology suitable for soil amendment and carbon sequestration, both directly and indirectly.

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