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Research Article

Agronomic Potential of Avocado-Seed Biochar in Comparison with Other Locally Available Biochar Types: A First-Hand Report from Ethiopia

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Biochar is a promising option for improving soil fertility and agricultural productivity. The potential of biochar for specific purposes depends on its physical and chemical characteristics. The avocado seed is widely available as a leftover after the fleshy part is used for food and as a byproduct of avocado-oil producing agro-industries in Ethiopia. Its potential as a biochar for an agronomic purpose has not been studied. The objective of this study was to compare the agronomic potential of avocado-seed biochar (ASB) type in comparison to other biochar types produced from locally available feedstocks at two selected pyrolysis temperatures (450 and 550°C). It was identified that on a mass-base, the produced biochar yields were in a range of 29.68 to 47.45%, higher for ASB pyrolyzed at 450°C. The scanned images of the biochar types showed a remarkable surface morphology for bamboo biochar (BB) and ASB. The bulk density of the biochars were in the range of 0.21 to 0.49 g/mL. The highest volatile matter was measured for BB-450°C, fixed carbon for BB-550°C, and ash content for BB-450°C. The mean pH values were in the range of 9.1 to 11.3. The ASB-450 and 550°C exhibited higher nutrient content. The highest cation exchange capacity (CEC) was recorded for ASB-450°C; organic carbon (OC) for corncob biochar (CCB) was followed by ASB-450 and 550°C. The calcium carbonate ($CaCO_3$) content of ASB-550°C was the second-highest value next to coffee husk biochar (CHB). In this study, ASB and BB were found to have important qualities for improving degraded agricultural soils in terms of soil acidity, nutrient content, and soil fertility. Therefore, ASB-450°C and BB-450°C can be suggested to be promising candidates for reclaiming acid-soils and for improving nutrient-depleted infertile soils into agriculturally productive soils.

1. Introduction

Biochar is a solid material obtained from the thermo-chemical conversion of biomass (feedstock) in oxygen-free or limited conditions [1]. It can be produced from almost any organic feedstock obtained from plant and animal sources [2, 3]. The important physical characteristics of biochar which is able to tune its potential for specific use include production yield, surface morphology, bulk density, and fixed carbon [4]. Moreover, its chemical properties, such as pH, electrical conductivity (EC), elemental analyses, cation exchange capacity (CEC), and calcium carbonate contents are also the most important features of the biochar which are mainly determined by the feedstock type and the pyrolysis temperature applied [5].

Several previous biochar studies at a global scale have been carried out from plant sources, mainly from wood biomass, and crop residue [6]. However, biochar from other sources including sludge and municipal organic waste [7, 8], and grasses and weeds are less common [6]. Moreover, biochar from plant sources, particularly wood biochar has been widely characterized for application of agronomic purposes than biochar from animal sources and sewage sludge, because of the risk of contamination of heavy metals and other pollutants [9]. In addition, most biochar characterization studies have been carried out for agronomic purposes [10–12] including reclamation of degraded soils and enhance carbon sequestration to mitigate climate change [13], for the generation of bio-oil and energy [14], and for removing pollutants [15–17]. However, the characterization studies of avocado seed biochar have not been conducted to assess its impact on soil properties and crop production.

The lack of sufficient information and knowledge, attitude, and experience limited farmers and agronomists to apply biochar in agriculture because its agronomic values in terms of crop response and soil health benefits have yet to be well-quantified [18, 19]. It has been revealed that depending on the type of feedstock source and the pyrolysis conditions when biochar is applied to degraded soil, it provides multiple agronomic benefits for growing crops. However, the physicochemical characteristics of the biochar type have to be determined before the application of the biochar into the degraded soil, because once the biochar is added to the soil it is difficult to reverse. Thus, the characterization of biochar types is used as a guide for the application of the produced biochar for the intended purpose. It also guides which feedstock to be pyrolyzed at what temperature shall be applied for a given degraded and nutrient-depleted soil type. However, this kind of study is lacking in Ethiopia, and even in Africa, in spite of severely degraded and impaired agricultural land exists. According to FAO [20], the world's population will reach 9.1 billion by 2050, 34 percent higher than today. Remarkably almost all of this population increase will occur in developing countries.

Ethiopia, the second most populous developing country in Africa has been entertaining a contradictory scenario for the last several decades. The livelihood of the overwhelming majority (more than 85 percent) of its population and the basis of the country's national economy depends on agriculture [21]. Whereas, the agricultural soil is severely impaired by soil infertility and nutrient loss for several decades [22]. Again, the average annual growth rate of the major food grains in the country has been 0.6 percent, while the population growth rate is over 2 percent [23, 24]. As a result of these, food insecurity is almost endemic in Ethiopia for long years back [25]. To combat this scenario, reclamation of degraded soils using biochar has been suggested as the best alternative by several studies. However, studies reported on the characterization of biochar are seriously scanty locally in Ethiopia, even at the level of Africa, while feedstock sources are plenty. For example, avocado seed biomass is abundantly available from municipal and agro-industrial waste in the study area (first-hand report, never characterized for agronomic purposes locally or at a global scale), bamboo biomass, native to Ethiopia (the study region) with prodigious rates of growth, and eminently renewable; corncob, coffee husk, and other agricultural wastes are abundantly available in the study region as a potential sustainable source. Nevertheless, more biochar studies have been conducted in the developed countries than developing countries [6]. Moreover, Agegnehu et al. [6] also reported that most of the biochar studies reported were produced in small kilns and traditional techniques than biochar produced in modern pyrolysis units. These two conditions triggered the authors of this study and initiated this research, where the characterization of biochar carried out in this study was performed using a locally available feedstock source and a modern pyrolysis machine. If the municipal and agricultural wastes are left in position it results in enhanced greenhouse gas emissions, which may lead to a loss of valuable nutrient resources and cause severe health problems.

Therefore, the major objective of this study was to compare the physicochemical characteristics of six biochar types made from four feedstock and two pyrolysis temperatures (450 and 550°C), based on selected parameters relevant to reclaiming degraded agricultural soil. The finding from this study will serve as a baseline for the subsequent greenhouse and field experiments which will assess crops growing on biochar-treated viz-a-viz untreated soil.

2. Material and Methods

2.1. Description of the Study Area and Sampling Sites. This study was conducted in Sidama National Regional State, located at 275 km South of Addis Ababa, the Ethiopian capital (Figure 1). Geographically the study area is located at 6°0′0″ to 7°0′0″N latitude and 38°0′0″ to 39°0′0″E longitude covering a total area of 6,538.17 square kilometers [26]. It lies in an area varying from lowland to highland, cold to hot with a mean annual temperature of 10 to 20°C and precipitation of 1000 to 1800 mm. According to EthioSIS [27], the pH of the soils in the study area ranged from alkaline (Awassa-Zuriya) to strongly acidic at the Hula district. The organic carbon (OC) of soils is low [28] and the soils are classified as Nitosols [27].

In the study area, perennial crops such as coffee (*Coffea arabica*), avocado (*Persea americana*), bamboo (*Arundinaria alpina*), and "enset" (*Ensete ventricosum*), and annual crops such as maize (*Zea mays*), tomato (*Solanum lycopersicum*), sweet potato (*Ipomea batatas*), and haricot bean (*Phaseolus vulgaris*) are widely grown. The feedstock samples were collected from 8 districts in the study area (Figure 1). They were selected on the basis of their abundance, wide availability, renewability, and low cost in the area. Avocado fruit tree is grown widely in Wondo Genet, Malga, Dale districts, and around Hawassa City. People are accustomed to utilizing avocado fruit in dietary at home and in juice houses; as a result, the seed is abundantly found in the municipal waste of Hawassa City (Capital of Sidama Regional State). Avocado fruit is also a major raw material for oil production in Yirgalem integrated agro-industrial park, located at the Dale district. The integrated agro-industrial park, after processing the fruit produces a pile of avocado seed waste which can be collected for biochar production. Bamboo biomass is selected because the plant is easily grown and abundantly cultivated in the highlands of the region, Hula (Hagere Selam) and Arbe Gona districts. These districts are among the major bamboo production areas in the country [29]. The region is also identified as the leading coffee growing and processing area in the country (Dale and Aleta Wondo districts) [30] where the coffee husk is

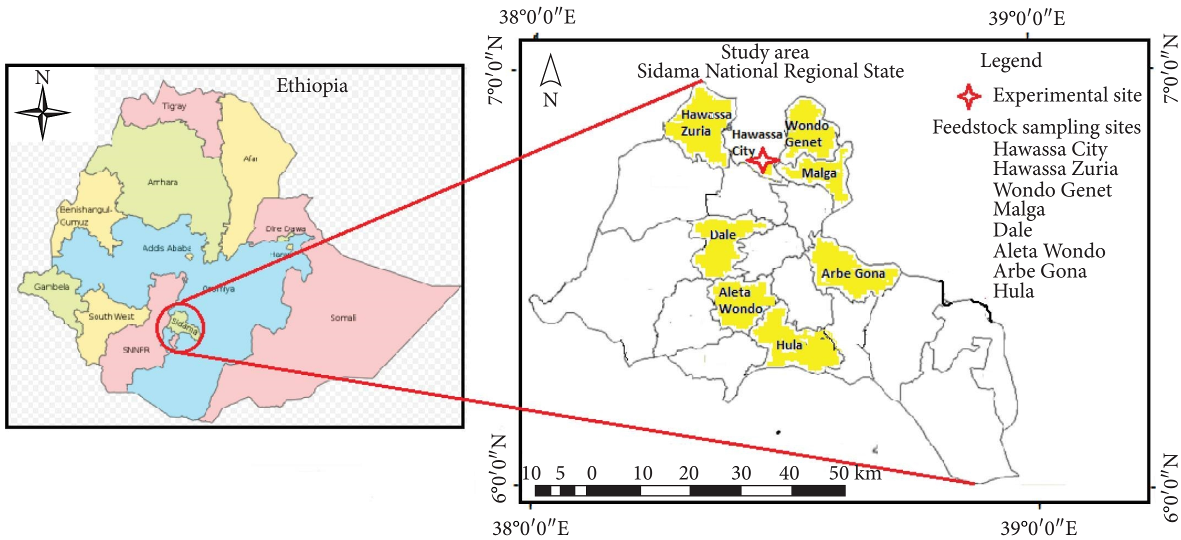

Figure 1: Map of the study area, Sidama National Regional State, Ethiopia.

abundantly found for biochar production. Farmers in the study area, particularly at the Hawassa Zuria district produce maize for their livelihood and for the market; as a result, the byproduct corncob is found abundantly, which can be used for biochar production.

The experimental site is located at the regional capital, Hawassa City, found at the Northern tip of the region as shown in Figure 1.

2.2. Biochar Production. The biochar production comprised of four different feedstocks (avocado-seed, bamboo, coffee husk, and corncob). The collected feedstocks were initially cleaned of debris and unwanted materials. All feedstocks, except coffee husk, were separately chopped to approximately 20 mm by 25 mm pieces and formed cylindrical granules to ensure uniform charring. The granules were air-dried to constant weight. The dried feedstocks were weighed and separately put in the pyrolysis furnace for biochar production.

The pyrolysis temperatures applied were 450°C for CCB and CHB, whereas 450 and 550°C for ASB and BB. The reason for the application of two pyrolysis temperatures for ASB and BB was: (i) characterization of ASB for agronomic purpose is not reported anywhere on the globe so far, therefore it requires more than one production for comparison; (ii) to see trends of different physicochemical characteristics of ASB in at least two temperature variations; (iii) the feedstock used for BB is native to Ethiopia which is not widely studied locally or overseas for agronomic purpose. Whereas, CCB and CHB were analyzed at a pyrolysis temperature of 450°C in this study, as they have been reported in different parts of the world with a wider range of pyrolysis temperatures.

The pyrolysis was carried out at Jimma University, College of Agriculture and Veterinary Medicine, Ethiopia. The pyrolysis machine was equipped with stainless steel and the set-up consisted of a well-operating digital system, capable of regulating temperature, a condensation system with a residence time of 4 hrs, a heating rate of 3°C/min, and a 1 hr holding time. The produced biochar was allowed to cool down to room temperature. Finally, the biochar was ground and sieved with <2 mm mesh size for analysis.

2.3. Physical Analysis. The image scanning of the biochars, determination of their bulk density, and proximate analysis were carried out at the laboratories of Hawassa University, College of Agriculture.

2.3.1. Biochar Yield. The weights of the precursors/feedstock before and after charring were measured using a digital balance. The purpose of measuring the weight was to estimate the production of biochar yield at different pyrolysis temperatures and different feedstock types. Each biochar yield was calculated based on the following equation [31]:

$$\text{Biochar Yield}\,(\%) = \frac{Wb}{Wo} X\ 100, \quad (1)$$

where Wb = mass (kg) of produced biochar and Wo = the dry mass (kg) of the precursors/feedstock.

2.3.2. Surface Morphology and Pore Size Determination. Biochar samples were first cut into thin slice sections to fit the instrument. Then, the surface morphological changes of each biochar sample were investigated using a scanning microscope, (LEICA-M205-C-01-UM-mc-NOR-EN-SP-0001) at Hawassa University, College of Agriculture imaging center.

2.3.3. Bulk Density. The bulk density of each biochar was produced according to Ahmedna et al. [32] and Stella Mary et al. [33]. A cylinder (25 mL) was filled to a specified volume with 40 mesh powder biochar and dried in an oven at 80°C overnight; then, the cylinder was tapped for 1-2 min to compact the char, and the bulk density was calculated and presented as g/mL in the following equation:

$$\text{Bulk density} = \frac{Wd\,(g)}{Vd\,(\text{mL})}, \quad (2)$$

where Wd = weight of biochar (g) and Vd = volume of the packed dry biochar (mL).

2.3.4. Proximate Analysis. The proximate analysis including moisture content, volatile matter, ash content, and fixed carbon were measured according to Singh et al. [4].

Moisture Content Measurement. One g of biochar was placed in a preheated crucible (covered) placed in an oven and heated at 105°C for 18 hrs, then moisture content was measured as

$$\text{Moisture Content}\,(\%) = \frac{Wi - Wd}{Wi} X\ 100, \quad (3)$$

where Wi = initial biochar weight before oven dried; Wd = weight after oven dried at 105°C.

Volatile Matter Determination. The weight of the dried crucible and cover were measured alone and with 1 g biochar and placed in an oven at 105°C for 18 hrs. Then, the covered crucible with the samples were transferred to the desiccator, and the sample weight together with the crucible and cover were measured approximately to 0.1 mg. Then, the sample with the covered crucible were placed in a preheated furnace at 950°C for exactly 10 mins. After being cooled to ambient temperature for about 10 mins were transferred to a desiccator, the sample weight together with the crucible and cover was measured approximately to 0.1 mg.

Then, the volatile matter was measured according to the following equation:

$$\text{Volatile matter}\,(\%) = \frac{W105 - W950}{W105} X\ 100, \quad (4)$$

where $W105$ = biochar weight oven-dried at 105°C; $W950$ = weight after furnace heated at 950°C.

Determination of Ash Content. The weight of the dried crucible with cover and a 1 g sample were placed in an oven at 105°C for 18 hrs. Then, the sample weight was recorded together with the crucible and covered approximately 0.1 mg. The furnace was heated from ambient to 750°C at a rate of 5°C/min, held at 750°C for 6 hours, then cooled to 105°C, finally removed and transferred to a desiccator, then the sample weight at 750°C was recorded together with crucible and covered approximately to 0.1 mg.

Then, ash content was determined based on the following equation:

$$\text{Ash}\,(\%) = \frac{W750}{W105} X\ 100, \quad (5)$$

where $W750$ = biochar weight after furnace heated at 750°C; $W105$ = weight after oven dried at 105°C.

Fixed Carbon Content. It was quantified by mass difference. The fixed carbon content in each biochar was calculated based on the following equation:

$$\text{Fixed carbon}\,(\%) = 100\% - \text{moisture}\,(\%) + \text{ash}\,(\%) + \text{volatile matter}\,(\%). \quad (6)$$

Or, based on the following equation:

$$\text{Fixed carbon}\,(\%) = \frac{W105 - W950 - W750}{W105} \times 100, \quad (7)$$

where $W105$ = weight after oven dried at 105°C; $W950$ = biochar weight after furnace heated at 950°C; $W750$ = biochar weight after furnace heated at 750°C.

2.4. Chemical Analysis. The chemical parameters were analyzed at laboratories of Holetta Agricultural Research Laboratory and Hawassa University College of Agricultural soil analytical laboratory. The pH and electrical conductivity (EC) were determined by procedures outlined by Singh et al. [4]. The pH and EC of the biochar samples were measured independently by mixing 5.0 g of a sample with 50 mL of deionized water for each. The solutions were then shaken for an hour and allowed the suspension to stand for about 30 mins before measurement with a pH meter and EC meter separately.

Biochar elemental analyses of total nitrogen (TN), available phosphorus (Av. P), and potassium (K) were determined according to McHenry [34] and Chintala et al. [35]. The dried 0.3 g sample was added to 7.5 mL conc. HNO_3 and 2.5 mL of conc. HCl. The mixture was allowed to digest for approximately 30 mins in a microwave digestion system. The digested sample was filtered with a 0.45 μm Teflon-filter, then diluted with deionized water to 50 mL, and analyzed for TN, Av. P, and K using atomic absorption spectrometry (AAS).

The organic carbon (OC) of biochar samples were analyzed using Walkley and Black [36] method. A 10 mL 1 N potassium dichromate solution was added into a 1 g biochar sample. To this, 20 mL sulfuric acid was added and gently agitated for 1 min, allowed to stand for 30 mins. Then, the solution was diluted to 200 mL using deionized water. A 10 mL phosphoric acid, 0.2 g ammonium fluoride, and 10 drops of diphenylamine indicator were added to this solution. Then, the solution was titrated with 0.5 N ferrous ammonium sulfate solution until the color changes from dull green to a brilliant green. Using a similar method, the blank sample was also prepared and titrated. Finally, the volume of titrants in the sample (V_s mL) and in the blank (V_b mL) was recorded and the percentage of the organic carbon was calculated using the following equation:

$$\text{OC}\,(\%) = (V_b - V_s) X \frac{M_{Fe^{2+}}\ X\ 0.003\ X\ 100\ X\ 1.3}{W}, \quad (8)$$

where V_b = volume (mL) of titrant in blank; V_s = volume (mL) of titrant in sample; MFe^{2+} = concentration of standardized ferrous ammonium sulfate solution; W = weight of sample biochar (g).

For the determination of cation exchange capacity (CEC), a modification of the Gillman [37] method was applied. The biochar was washed in a 0.1 M $BaCl_2$ solution three times to exchange the exchangeable. Then, a standard 0.02 M $MgSO_4$ solution was added to replace the Ba^{2+}, and precipitation of $BaSO_4$ occurred. The CEC was calculated from the difference between the original cations with respect to the remaining in the standard solution were made. Calcium carbonate ($CaCO_3$) was determined following procedures outlined by Singh et al. [4]. The biochar sample of 0.5 g was mixed with 10 mL 1 M HCl and shaken for 2 hrs at 25°C on a reciprocating shaker stand overnight. Prepared samples were analyzed. The solution was titrated with standardized 0.5 M NaOH until a neutral pH (~7.0) was reached. The volume of the titrant (NaOH) was recorded when the titration was completed at pH 7 ("*b* mL"). Following the same procedure on the blank sample and the volume of titrant (NaOH) was also recorded ("*a* mL"). Pure $CaCO_3$ powder samples (dried at 105°C for 1 h) were used for reference. Then, %CaCO3 was calculated based on the following equation:

$$\%CaCO_3 = \frac{Mx(b-a) \times 10^{-3} \times 100.09 \times 100}{2 \times W}, \quad (9)$$

where M = Standardized molarity of NaOH (mol L^{-1}); b = Volume of NaOH being consumed (mL) by the blank; a = Volume of NaOH being consumed (mL) by the biochar sample; W = Mass of biochar (g).

2.5. Statistical Analysis. All samples were collected and processed in triplicates. The mean and standard deviation of the physicochemical parameters of the produced biochars were determined using a Statistical Package for Social Science (SPSS) version 24 (IBM Corporation, Armonk, NY, USA) and a Microsoft excel spreadsheet. Their significance differences were determined using one-way ANOVA. A posthoc comparison of means was performed using the Tukey-HSD procedure for the differences between the biochar (feedstock types) in the same temperature and with different pyrolysis temperatures of the same biochar (feedstock type). The statistical significance was set at $p < 0.05$.

3. Results

3.1. Physical Analysis. The mean yields of avocado seed biochar (ASB) produced at a temperature of 550 and 450°C, bamboo biochar (BB) at 550 and 450°C, corncob biochar (CCB), and coffee husk biochar (CHB) each produced at a temperature of 450°C are presented in Figure 2. On a mass basis, yield rates of the biochars ranged from 29.68% for BB-550°C to 47.45% for ASB-450°C. The result also showed that avocado seed pyrolyzed at 550°C produced the second highest yield next to ASB analyzed at 450°C pyrolysis temperature (Figure 2).

The scanned images of the biochars (Figure 3) and the measurements of their sizes (Table 1), both BB-550 and BB-450°C, had bigger pore sizes than CHB-450 and CCB-450°C. However, at a closer observation of Figures 3(a) and 3(b), the avocado seed biochars' pores are smaller in size (width and length) but longer in depth (mean height) (Table 1). The pore depth (mean height) of ASB-450°C is the second longest in depth next to BB-550°C (Figure 3).

In this study, the highest mean biochar bulk density value (0.49 g/mL) was measured for ASB-550°C, followed by the CHB-450°C and ASB-450°C with the value of 0.44 and 0.43 g/mL, respectively. The lowest bulk density (0.2 g/mL) was measured for CCB-450°C (Figure 4).

The proximate analysis of six biochars in this study shown in Figures 5(a)–5(f) had the moisture content in decreasing order from 7.88 to 4.43% where CHB-450°C > ASB-550°C > ASB-450°C > BB-450°C > BB-550°C > CCB-450°C. The highest volatile matter values measured for BB, CCB, and CHB at 450°C were 48.29%, 47.09%, and 46.47%, respectively. The lowest volatile matter values measured at 550°C for ASB and BB were 33.55 and 37.12%, respectively. The fixed carbon percentages of the biochars in descending order were ASB-550°C (57.89%) > BB-550°C (55.99%) > ASB-450°C (48.79%) > CCB-450°C (46.29%) > CHB-450°C (43.19%) > BB-450°C (39.67%). Moreover, the percentage of ash content of all biochars was the lowest of all other proximate values, where BB-450°C (5.99%), CHB-450°C (2.46%), and CCB-450°C (2.19%) had the highest ash content followed by BB-550°C (1.8%) > ASB-550°C (1.32%) > ASB- 450°C (1.26%) (Figure 5). Whereas, the percentage of fixed carbon value is higher in all the sampled biochars in this study.

3.2. Chemical Analysis. The pH values of six biochars from four feedstocks of ASB and BB at 450 and 550°C, and CCB and CHB at 450°C are given in Figure 6. The mean pH ranged from 9.1 for the BB at 450°C to 11.3 for CHB at 450°C. All biochars produced in this study were in the alkaline range (pH > 7). The pH of ASB at 550°C was the second highest pH next to CHB at 450°C. The pH of ASB produced at 450°C was the third-ranked out of six produced biochars in this study. However, statistically, there were no significant differences between the mean pH values of the biochars from different feedstocks and different pyrolysis temperatures (450 and 550°C).

The effect of pyrolysis temperature and feedstock type on the macronutrient content of produced biochar is shown in Figure 7. The percentage of TN ranged from 0.35% for BB at 550°C to 1.29% for ASB at 450°C. The TN contents in decreeing order ASB-450°C > ASB-550°C > BB-450°C, and CHB-450°C > CCB-450°C > BB-550°C with percentage composition values of 1.29, 1.07, 0.42, and 0.42, 0.38, and 0.35, respectively. However, except for ASB at 450 and BB-550°C, the remaining had no statistically significant difference in nitrogen content. The two highest TN percentage contents were measured for ASB pyrolyzed at 450 and 550°C. Statistically, there were no significant differences in TN contents with increasing temperature in both ASB-450 with 550°C as well as BB-450 with 550°C.

The mean Av.P percentage composition of the biochars in this study ranged from 0.06% for CCB-450°C to 0.46% for ASB-450 and 550°C, while ASB with increasing pyrolysis temperature remains the same (0.46%) (Figure 7). Whereas,

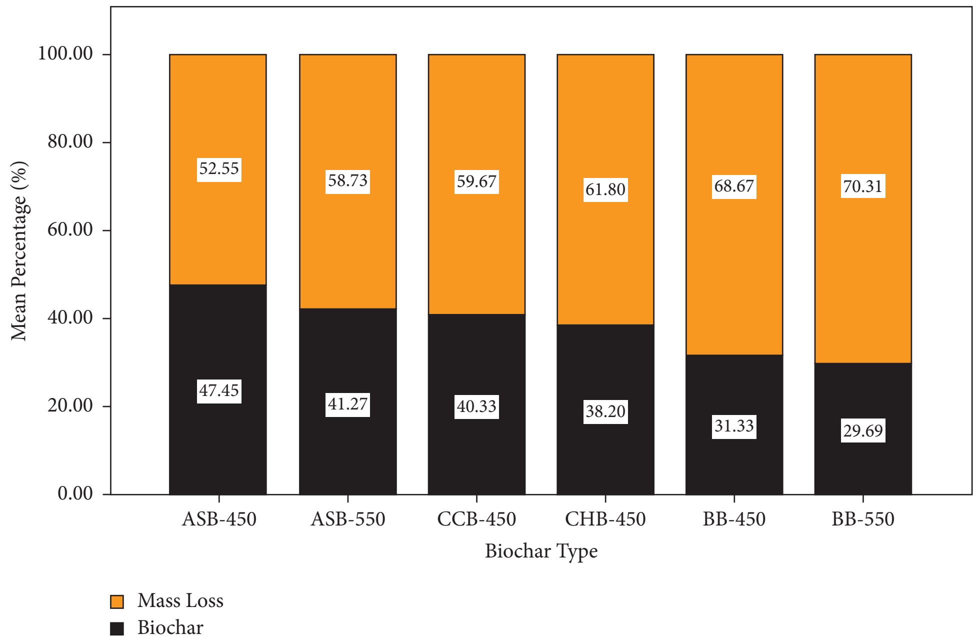

Figure 2: Effect of pyrolysis temperature and feedstock type on biochar yield.

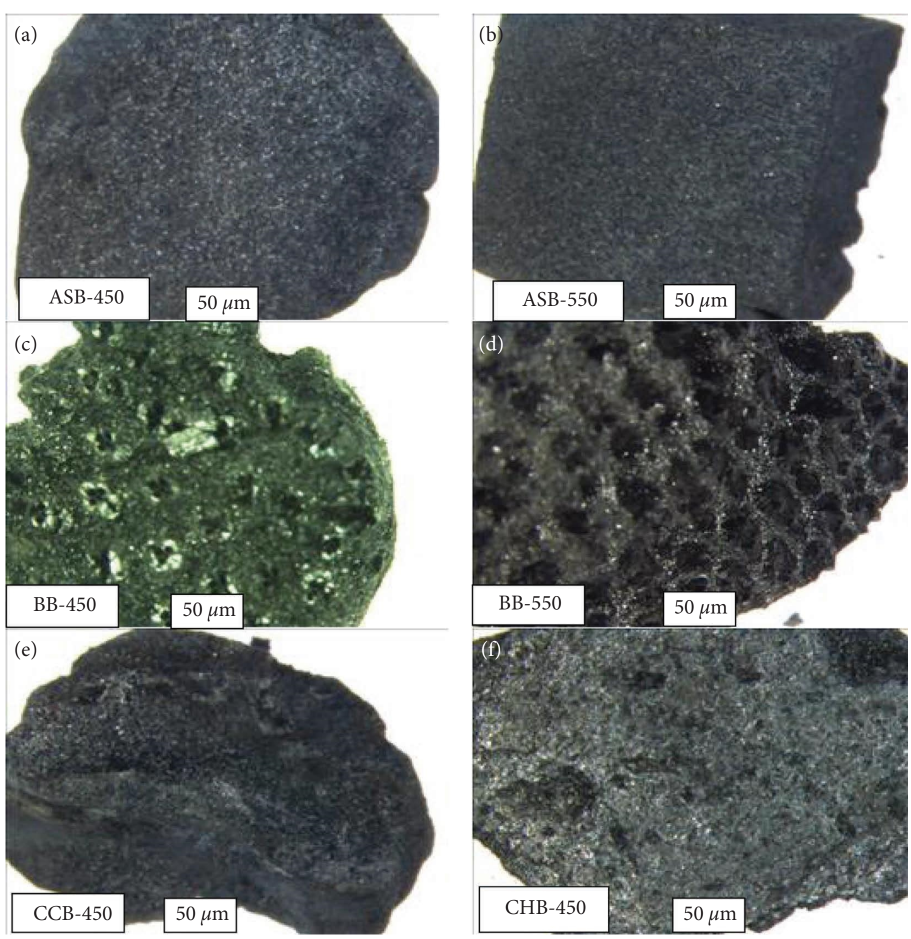

Figure 3: Image of scanned biochars. (a) Avocado seed biochar pyrolyzed at 450°C, (b) avocado seed biochar pyrolyzed at 550°C, (c) bamboo biochar pyrolyzed at 450°C. (d) bamboo biochar pyrolyzed at 550°C. (e) corncob biochar pyrolyzed at 450°C, and (f) coffee husk biochar pyrolyzed at 450°C.

Table 1: Measurement of pore size after scanning the biochars in this study.

Biochar types	Length (μm)		Width (μm)		Height (μm)	
	Mean	Max	Mean	Max	Mean	Max
ASB 450°C	13.64 ± 9.91	24.04	5.57 ± 6.39	12.54	8.71 ± 13.27	24.04
ASB 550°C	26.82 ± 18.4	47.59	26.48 ± 18.17	47.03	4.18 ± 3.14	7.32
BB 450°C	52.16 ± 10.4	78.34	51.15 ± 10.28	77.33	8.69 ± 5.69	18.81
BB 550°C	80.78 ± 19.67	122.31	79.28 ± 19.06	122.27	11.18 ± 11.95	54.34
CCB 450°C	29.9 ± 22.85	66.91	29.26 ± 23.41	66.88	3.31 ± 2.51	6.27
CHB 450°C	35.73 ± 14.5	70.02	34.3 ± 14.27	70.02	6.27 ± 8.58	20.9

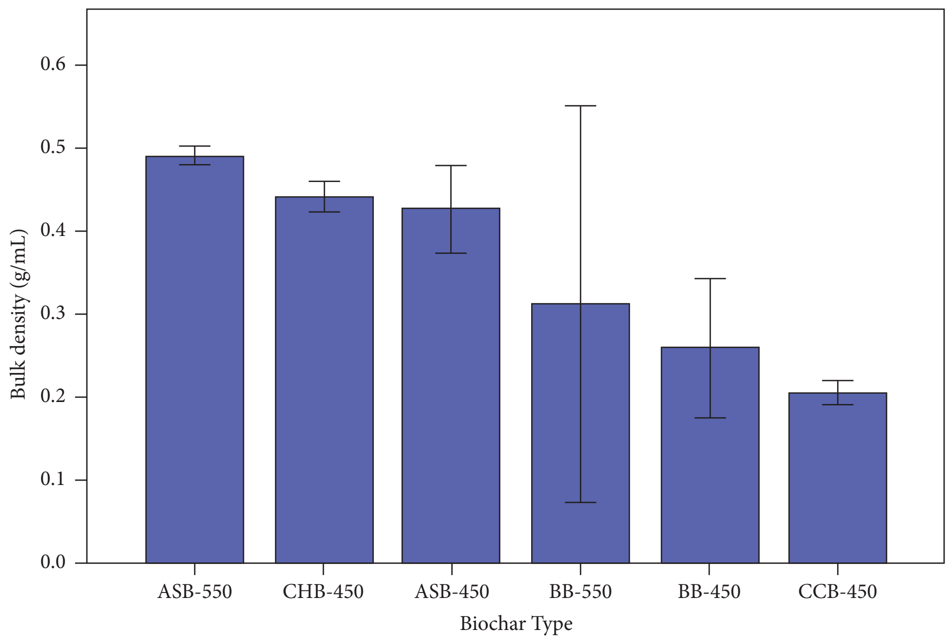

Figure 4: Bulk density of biochars.

the increase in pyrolysis temperature from 450 to 550°C for BB decreased the Av.P composition but not statistically significant ($p > 0.05$). However, the Av.P composition of ASB was significantly higher ($p < 0.05$) than the remaining biochars in this study (BB, CCB, and CHB) (Figure 7).

The K contents of biochars in decreasing order in this study were ASB-550°C (2.4%) > ASB-450°C (1.43%) > BB-550°C (1.40%) > CHB-450°C (1.21%) > BB-450°C (1.1%) > CCB-450°C (1.01%), showing that ASB (550 and 450°C) are ranked first followed by BB-550°C. However, there was a significant change in K content as the change in feedstock and declined with pyrolysis temperature, as shown in ASB-550°C (2.4%) > CHB-450°C (1.21%) > BB-450°C (1.1%) > CCB-450°C (1.01%) (Figure 7).

The EC value of CHB-450°C was significantly higher ($p < 0.05$) than the other EC values of the biochars in this study. The EC values of BB-550°C, BB-450°C, and ASB-450°C were the second, third and fourth in descending order, respectively, (Table 2). The CEC values in descending order were ASB-450°C (34.25) > ASB-550°C (25.06) > CCB-450°C (24.1) and the lowest CEC value was measured for BB-550°C (Table 2). The increased pyrolysis temperature from 450 to 550°C significantly decreased the CEC value in ASB ($p < 0.05$), but the temperature change did not result in a significant decrease in the CEC value of BB. However, the CEC values of the biochar were significantly different from the feedstock type(Table 2).

The highest OC value was measured for CCB-450°C (75%) and the lowest for BB-450°C (48%). The OC value of CCB-450°C was significantly higher than the OC value of the other biochar types. However, BB-450°C had significantly less OC value than the other biochar types (Table 2). Coffee husk biochar pyrolyzed at 450°C had the highest $CaCO_3$ content with a significantly higher value than the other biochars in this study, followed by ASB-550°C which had also a significantly higher value than ASB-450°C. The lowest $CaCO_3$ content was measured for ASB-450°C (Table 2).

4. Discussion

In our study, the effects of both pyrolysis temperature and feedstock types (Figures 2–7) have been clearly demonstrated in the physical characteristics of the biochars produced, while the effect of feedstock type was demonstrated in Tables 1 and 2. This is in agreement with the findings of previous studies [38–41] that pyrolysis temperature and feedstock type are critical factors for the creation of biochar characteristics. Biochar yield was reduced by 6.18 and 1.64%

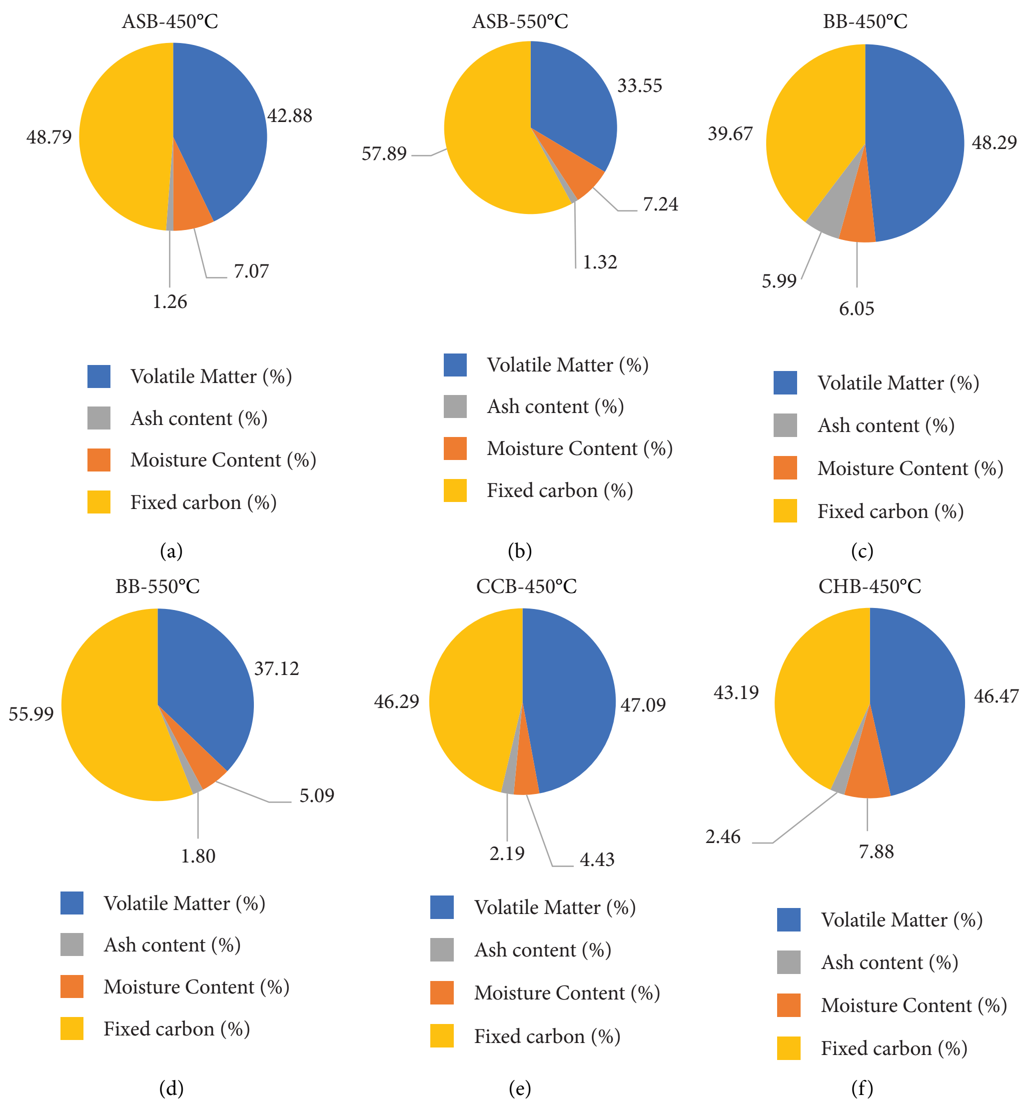

Figure 5: Proximate analysis of biochars. (a) Avocado seed biochar pyrolyzed at 450°C. (b) Avocado seed biochar pyrolyzed at 550°C. (c) Bamboo biochar pyrolyzed at 450°C. (d) Bamboo biochar pyrolyzed at 550°C. (e) Corncob biochar pyrolyzed at 450°C. (f) Coffee husk biochar pyrolyzed at 450°C.

with increasing pyrolysis temperature by 100°C (from 450 to 550°C) for both ASB and BB, respectively. The reduction was significant ($p < 0.05$) for ASB. The observed drop in biochar yield could be due to the thermal degradation of lignocellulosic structures and dehydration as described by Antal and Grönli [42]. The result is in agreement with the previous studies by Amonette and Joseph [43]; Domı´nguez et al. [44] and Judd [45] where the increase in yield of biochar at lower pyrolysis temperatures was attributed to the condensation of aliphatic compounds. The difference in percentage biochar yield between different feedstock types at the same pyrolysis temperature (450°C) was statistically significant ($p < 0.05$) and was recorded in the range of 7 to 16%. This is in line with the study reported by Nguyen et al. [40] where rice husk showed a higher biochar yield (35%) compared with bamboo biochar yield of 30%, which could be attributed to feedstock variation. The higher biochar yield of ASB-450°C than ASB-550°C in this study is mainly attributed to the lower pyrolysis temperature and the higher lignin content [17, 46] contained in its feedstock. Lignin content varies among different feedstock types, which affects the yield of the produced biochars pyrolyzed with similar temperatures [42, 47, 48]. Along with the high pyrolysis temperature and high lignin content of the avocado seed feedstock low heating rate (3°C/min) also contributed to the higher yield exhibited by ASB-450°C in this study among others. Antal and Gronli [42] reported a similar trend where a slow heating rate (5°C/min) leads to significantly a higher biochar yield compared to a high heating rate (10°C/min).

The variation in surface morphology of the studied biochars including visible wider pore size (length and width) for BB (Figures 3(c) and 3(d)); CHB (Figure 3(f)); and CCB (Figure 3(e)) were noted in this study. Deep pore heights were exhibited by ASB-450 and 550°C (Table 1). These observed differences in Figure 3 might be due to both the feedstock type and the pyrolysis temperature. Change in

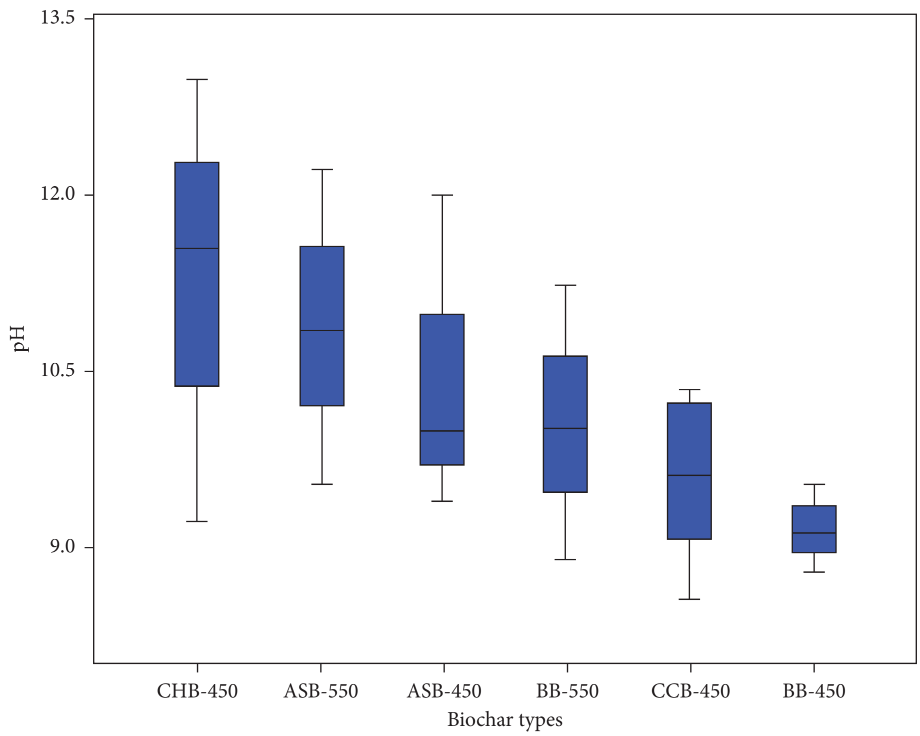

Figure 6: Effect of pyrolysis temperature and feedstock type on Biochar pH.

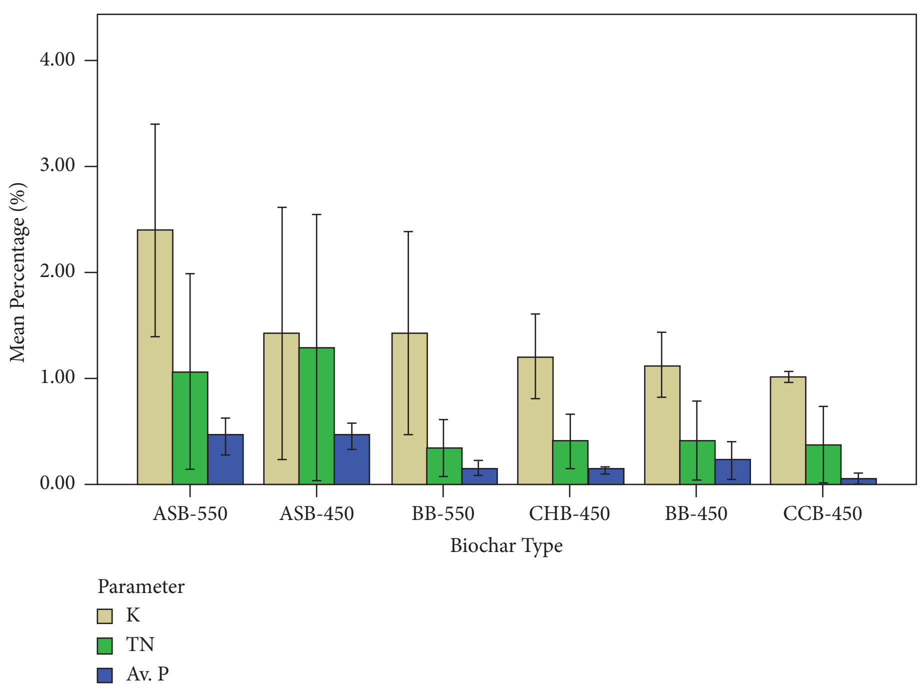

Figure 7: Effect of pyrolysis temperature and feedstock type on biochar macronutrient content.

pyrolysis temperature from 450 to 550°C resulted in a significant increment of mean length and width for ASB and BB (Table 1). The increment in mean length and width of pores with the pyrolysis temperature is in line with the reports of Bonelli et al. [49] and Kloss et al. [50] that, as pyrolysis temperature increases, the pore-blocking substances are driven-off thus increasing the external formation of pore size. Moreover, as pyrolysis temperature increase pore volume, which also increases the progressive degradation of the organic materials (cellulose, lignin) and vascular bundles and form channel structure [51, 52]. The increased pore size, therefore, plays a significant role in the application of

Table 2: Effect of pyrolysis temperature and feedstock type on biochar EC, CEC, OC, and $CaCO_3$.

Precursor/feedstock	Pyrolysis T (°C)	EC (dS m^{-1})	CEC (meq/100 g)	OC (%)	$CaCO_3$ (%)
Avocado seed	450	2.86 ± 0.26	34.25 ± 1.28	59.40 ± 2.59	3.19 ± 0.59
	550	0.34 ± 0.01	25.06 ± 1.54	59.77 ± 2.61	7.47 ± 0.54
Bamboo	450	6.59 ± 0.28	21.67 ± 1.43	48.18 ± 0.72	5.47 ± 0.65
	550	6.98 ± 0.41	17.03 ± 1.66	58.37 ± 1.04	5.22 ± 0.69
Corncob	450	0.12 ± 0.01	24.10 ± 1.46	75.92 ± 1.40	6.43 ± 0.31
Coffee husk	450	31.63 ± 0.05	22.90 ± 1.32	58.66 ± 1.11	17.14 ± 0.93

Values are mean ± standard deviation of three replicates.

biochar for agricultural purposes. For example, the pore size is critically important for water storage [53], an ecological niche for soil microbes [54], storage pool of plant available water [55–57] as well as liquid fertilizer loading sites [53] and adsorption sites for a wide variety of hazardous pollutants [47, 58].

The effect of pyrolysis temperature and feedstock type exhibited lesser variation in the bulk density of the biochars produced in this study (Figure 4) and much lower than the bulk density of agricultural soil (~1.3 g mL^{-1}) [59]. The bulk density of the biochars recorded in this study (less than 0.5 g mL^{-1}) is lower than the 0.6 g mL^{-1} reported by Blanco–Canqui [59]. Such low values of bulk densities of biochar are suitable for plant root elongation [60]; root density [61]; ease of nutrient release to plants and enhanced water infiltration [62], and reducing soil bulk density [59]. Generally, biochar application in agricultural lands reduces the bulk density of the soil by 3 to 31% [59, 63].

The typical proximate analysis of the produced biochars as described by Stella Mary et al. [33] including the moisture content, volatile matter, ash content, and fixed carbon were demonstrated in this study. As a result of the effect of pyrolysis temperature and feedstock type, variations in proximate values were observed. The variations of the proximate analysis of ASB and BB with increasing temperature were in accordance with the trend reported by Wu et al. [8]. That, volatile matter content has decreased significantly from 42.88 to 33.55% and 48.29 to 37.11% in ASB and BB, respectively, with increasing pyrolysis temperature from 450 to 550°C. This is in agreement with Paethanom and Yoshikawa [64] and Mukherjee and Zimmerman [65] that the biochar derived from relatively low-temperature pyrolysis is characterized by a high content of volatile matter that contains easily decomposable substrates. Associated with this, volatile matter content has been hypothesized to be an indicator for biochar stability [66]. In this regard, Leng et al. [67] recommended that a combination of fixed carbon and volatile matter can provide a more accurate assessment for biochar stability. Moreover, Spokas [68] more clearly estimated carbon stability using a volatile matter to fixed carbon ratio (VM/FC). Here, VM/FC ratio less than 0.88 of a biochar can have stability with a half-life of >1000 years, while a biochar with VM/FC ratio greater than 0.88 but less than 3.0 can have a half-life of 100–1000 years Spokas [68]. Based on this, ASB-450 and 550°C, and BB-550°C showed VM/FC of less than 0.88, which is predicted to be more stable with a half-life of >1000 years. While all the remaining biochars in this study have a VM/FC ratio greater than 0.88 and less than 3 indicating a biochar stability within the range of 100 to 1000 years.

Conceptually, the volatile fraction does not equate to a labile component in identical proportions, as biochars with about 40% volatile matter showed a calculated decomposition over 100 years of less than 10% [66]. Therefore, in this study, it has been identified that four types of biochars exhibit volatile matter above 40% BB-450°C (48.29%), CC-450°C (47.09%), CHB-450°C (46.47%), and ASB-450°C (42.88%). Conceptually, these biochars can be applied for soil treatment and will have a decomposition of less than 10% in 100 years. This indicates greater biochar stability that is useful in climate mitigation and also in maintaining possible positive agronomic effects over longer periods of time. Contrary to volatile matter, biochars pyrolyzed at high temperature (550°C) for both ASB and BB biochars had a significantly higher content of fixed carbon. As the pyrolysis temperature increased from 450 to 550°C the fixed carbon of ASB and BB increased from 48.79 to 57.89% and from 39.67 to 55.99%, respectively, and the ash contents of ASB from 1.26 to 1.31%.

The highest fixed carbon content was recorded at a higher temperature, owing to the presence of higher carbon content in the ASB and BB-550°C. Similar results were reported from various scholars including pyrolysis of woodchips by Masek et al. [69], pomegranate seeds by Ucar and Karagoz [70], and cherry sawdust by Gheorghe et al. [71].

Among the commonly used quality measurement of biochars, pH is an important parameter for soil treatment. Accordingly, the biochars characterized in this study were all in the alkaline range. As it has been reported by Cantrell et al. [72], the feedstock materials and the pyrolysis condition determine the key functional properties of the biochar including pH. Thus, in this study, the pH of the ASB and BB increased by 0.41 and 0.9 units, respectively, with increasing pyrolysis temperature from 450 to 550°C. Similar results were reported by Tomczyk et al. [73] that the pH of produced biochar has increased with temperature. The increment could be attributed to the loss of the acid surface of functional groups by thermal decomposition at a higher temperature, and then, the biochar become alkaline [74, 75]. Similarly, Domingues et al. [76] reported that the pH of biochars pyrolyzed at temperatures ranging from 350 to 750°C usually produced a pH in the range of 9.7 to 11.7. Overall, it has been agreed that the pH of biochars increased with increasing pyrolysis temperature [77]. It has also been agreed that there is a variation in the pH of biochars with feedstock type [73]. In this study, as a result of variation in feedstock type, the biochars pyrolyzed at the same temperature had different pH values. In this regard, the pH of bamboo was less by about 2 units compared with CHB, ASB, and CCB with the same pyrolysis temperature (450°C). This study was consistent with Tag et al. [78] who reported that biochar produced from wood biomass had an average pH value lower by 2 units than the values for other biochars formed from nonwoody biomasses under similar pyrolysis conditions. Srinivasarao et al. [79] also reported that the pH values of biochars from different feedstocks vary in the range between 6.2 and 13.0, where most of them are in the pH range from 7.1 to 10.5 [80]. Accordingly, the finding in this study is in line with these reports. The findings of this study could contribute to amending soil acidity, a significant challenge in many parts of the world which seriously impair crop productivity [81].

Significant difference was not observed in TN, Av.P, and K content with the change in pyrolysis temperature between ASB-450 and ASB-550°C as well as BB-450 and BB-550°C. A similar trend was reported in Acacia and willow biochars pyrolyzed at a temperature of 500 and 550°C, respectively, [82]. This might be attributed mainly to feedstock elemental contents than the change in pyrolysis temperature. A similar result and recommendation were also reported by Enders et al. [83] and reaffirmed by this study that Av.P concentration found in the biochars produced from ASB-450 and ASB-550°C had the same content (0.46%), whereas, the Av.P concentration of ASB-450°C is significantly higher ($p < 0.05$) than the remaining biochars in this study (BB-450°C, CCB-450°C, and CHB-450°C) (Figure 7). The chemical elements TN, Av.P, and K are important macronutrients that are widely applied in agriculture and required by plants in large amounts [4]. However, they are easily lost from the soil via runoff, erosion, or leaching in agricultural soils [84]. Therefore, the finding of this study indicated in Figure 7 has shown that ASB which is rich in macronutrients (TN, Av.P, and K) could be a promising candidate for the sustainable agronomic strategy that is able to respond to the nutrient losses across Sub-Saharan African soils. Moreover, it can be used as a soil treatment for the deficit in nutrient balance for N-41 kg, P-4 kg, and K-31 kg ha^{-1} annually across the whole of Sub-Saharan African soil treatment [85].

The EC values obtained in this study were in a very wider range between 0.12 and 31.63 (Table 2). As EC is a measure of total dissolved salts or the presence of excess ash, CHB-450°C having a higher value of EC is excessively rich in dissolved salt content. However, a contrary result to the EC content of CHB-450°C was reported by Dume et al. [86]. The lower EC value for CCB-450, ASB-450, and ASB-550°C is an indication of low salinity, which is among the expected important quality attributes of biochars for an agronomic purpose [87]. This is also recommended by Machado and Serralheiro [88] that salinity is a major constraint to crop production.

Pyrolysis temperature showed a clear effect on the CEC of biochars in this study. The CEC of biochar measures the ability to hold exchangeable cations such as Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), and Potassium (K^{+}). In this regard, the CEC of ASB and BB significantly decrease with increasing temperature. This is similar to the study reported by Harvey et al. [89] and Mukherjee et al. [74] that the CEC of biochars decreases with increasing pyrolysis temperatures. Since, pyrolysis at low-temperatures leads to the oxygenation of biochar surfaces which results in the formation of oxygen containing functional groups, including: carboxyl, hydroxyl, phenol, and carbonyl groups over the vast internal surface area of the biochar [90, 91]. These functional groups give rise to a considerable negative charge and a high CEC. However, at higher pyrolysis temperatures, a decrease in the abundance of oxygenated (acid) functional groups occurred due to lower oxygen: carbon ratio, and as a result, lower CEC is observed [89, 92]. Therefore, in this study, the highest CEC was for ASB-450°C, whereas the lowest CEC for BB-550°C, indicating a wider range of composition of exchangeable cations (Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+}) observed due to variation in pyrolysis temperature and the source materials used among others.

The biochar carbon composition is mainly of two types: easily degradable organic carbon compounds and very stable and fixed aromatic carbon (black carbon). Of the two, the fixed carbon content (OC) is an important quality parameter for biochar [93], which is observed in CCB-450°C recorded the highest (75.92%) in this study followed by the two avocado seed biochars, ASB-550°C (59.77%) and ASB-450°C (59.40%). The variation of OC content with pyrolysis temperature and feedstock type observed in this study is in line with the report made by Sohi et al. [94]. In this regard, the high values of OC in the produced biochars indicate the recalcitrance of OC in the biochars. This implies that the application of such biochars into agricultural lands increases soil OC significantly and results in higher soil quality. Consequently, high levels of soil OC accumulation can enhance nitrogen efficiency and boost crop productivity [95, 96].

The highest $CaCO_3$ content observed in coffee husk biochar in this study might be due to the highest EC composition in it, because the increase in EC is attributed to the alkalinity and $CaCO_3$ content as reported by Chintala et al. [35]. The variation in $CaCO_3$ due to feedstock type and pyrolysis temperature was observed in the range of 3.19 to 7.47, except for coffee husk which is 17.14. The two-avocado seed biochars (ASB-450 and 550°C) contained the least and highest $CaCO_3$ content in the range, respectively. This showed pyrolysis temperature has an impact on $CaCO_3$ content because increasing temperature mainly attacks the functional group of the biochars where it has influence over the $CaCO_3$ content. This is in agreement with the study reported by Singh et al. [4].

5. Conclusion

All biochars characterized in this study exhibited higher quality for soil enhancement, in terms of pH, pore profile, and low bulk density. Particularly biochars produced at low pyrolysis temperature (450°C) for both avocado and bamboo have preferably better quality. With these quality attributes and their availability in the study area, avocado seed biochar and bamboo biochar could be promising candidates for agricultural soil enhancements and carbon sequestration. Among these, a remarkable body morphology with wider pore size, high volatile matter, and high fixed carbon content were some of the important qualities of bamboo biochar exhibited in this study. In contrast, avocado seed biochar had more attributes included: higher yield, higher fixed carbon content, higher cation exchange capacity, and elemental composition as well as organic carbon and calcium carbonate content.

Therefore, the application of avocado seed biochar to a soil is an alternative strategy that improves soil physicochemical properties and the soil functioning as a component of the ecosystem as well as the whole environment on a sustainable basis.

Data Availability

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Additional Points

Core Ideas. (1) Converting avocado seed wastes into biochar is a win-win strategy, reducing waste management hassle and intellectually recycling organic wastes (carbon sequestration). (2) Biochar from avocado seed (municipal waste) had better quality in terms of biochar production, and key agronomic parameters. (3) The scanned image of avocado seed and bamboo biochars have outstanding surface morphology that can be successfully utilized for agronomic purposes.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Hibret Demissie conducted the overall activities starting from conception and design, proposal writing, literature review, data collection, statistical analysis, original manuscript write-up, reviewing, and editing. Andargachew Gedebo supervised the research and critically reviewed and commented. Getachew Agegnehu helped in biochar laboratory analysis and critically reviewed, commented, and cosupervised the research. All authors have read and approved the final manuscript.

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