



Designing, Developing and Testing of a Pyrolysis System: A Case Study of Biochar and Pyroligneous Acid

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Abstract: Pyrolysis being an efficient process through which biomass materials are converted to biochar and pyroligneous acid can be easily achieved by using an efficient pyrolysis system. These pyrolysis products can be used as source of energy for cooking, soil amendment or as biopesticide/biofertilizer. The aim of this study was to design, develop and test a pyrolysis system in production of biochar and pyroligneous acid from forest wastes (twigs of acacia, eucalyptus, and black wattle). Testing of the developed pyrolysis system was based on the production and quality of biochar and pyroligneous acid. The biochar quality was based on its moisture content (MC), volatile matter (VM), ash content (AC), fixed carbon (FC) and pH while for pyroligneous acid, this was based on the pH and density (ρ). The pyrolysis system designed and developed had a carbonization kiln (diameter = 0.5 m and height = 1 m) and pyrolysis smoke condensation system (surface area = 1.16 m², radius = 0.16 m, 2 number of coiling tubes, height = 1 m, outer chimney/pipe diameter = 0.18 m). The developed pyrolysis system resulted into an average biochar production of 37.31% and 24.90% of pyroligneous acid. The biochar produced had an average MC = 9.1%, VM = 28.8%, AC = 6.9%, FC = 55.2% and pH = 6.7 while the pyroligneous acid had an average $\rho = 1.02$ gcm⁻³ and pH = 3.08. This approach of carbonizing agroforestry materials using the developed pyrolysis system enhances diversification of products by capturing what would otherwise be wasted to produce biofuel, bio-fertilizer, and bio-pesticide. This would result in environmental conservation and serve as source of livelihood when these products are marketed.

Keywords: Pyrolysis, Carbonization Kiln, Pyrolysis Smoke Condensation System, Biochar, Pyroligneous Acid, Environmental Conservation

1. Introduction

Pyrolysis is a process through which biomass materials are thermally decomposed in absence of oxygen to produce biochar and pyroligneous acid [8]. There exist different techniques of converting biomass materials into a usable products like biochar and pyroligneous acid. These includes but not limited to gasification, fermentation, and anaerobic decomposition. Gasification can be defined as the process by which electricity is generated through the application of heat to organic material in the presence of less oxygen. Fermentation, on the other hand, is a process that involves the use of organic materials to produce alcohol to generate

power for automobiles while anaerobic decomposition is a process by which biogas is generated from biomass in absence of oxygen [22]. Considering the biomass conversion technologies, the pyrolysis process is reported to have more benefits including fewer emissions [22]. Therefore, the pyrolysis technique should be preferred to other conversion technologies when carbonizing biomass materials.

Pyrolysis process is further divided into slow and fast method. In slow pyrolysis, biomass materials are heated over a varied temperature range of 300°C to 800°C at a slower rate for a prolonged residence time (greater than 60 minutes) in absence of oxygen at a heating rate of 5°C to 7°C/min and the process generates 35% biochar, 30% bio-oil and 35% syngas [23]. Biomass materials in fast pyrolysis process is

heated at a faster rate for a shorter residence time (less than 60 minutes) in absence of oxygen at a heating rate of 300°C/min resulting to 15% - 20% syngas, 10% - 30% biochar and 50% - 70% bio-oil [23].

The pyrolysis system comprises of kiln and the smoke condensation system and the process is influenced by several factors which are related to the physical characteristics of the entire system [19]. Different types of pyrolysis systems have been developed in countries like Brazil and China. Development of the pyrolysis kiln is influenced by factors like simplicity and flexibility, auto thermal operations, maximization of the solid products fraction, affordability, feedstock material density, availability of equipment and material to be used and ease of operations [17]. The smoke condensation system commonly known as heat exchanger is a heat transmission device that enables the transfer of heat between two different fluids which are at different temperatures in which the transfer of heat occurs from a higher temperature to a lower temperature fluid [3].

In the production of pyrolygneous acid, the pyrolysis smoke has to be condensed to obtain the product. The current study designed and developed a Shell-and-Tube Heat Exchanger (STHX) which is a type of condenser in which hot and cold fluids are separated by the tube walls where one fluid flows in the cylindrical pipe while the other outside the pipe commonly known as the shell. The system achieves the heat transfer from hot fluid to the cold fluid through conduction and convectional effects as a result of temperature differences [6]. The STHX poses features like ease of manufacture, convenient installation and flexibility in its disassembling as reported by Chen et al [6].

Biochar is a solid product that is being produced from pyrolysis of biomass materials which is used as a source of energy for cooking or as a soil amendment while pyrolygneous acid is a natural distillate extracted from pyrolysis process through condensation of pyrolysis smoke and used as a bio-pesticide or bio-fertilizer [7]. In production of biochar and pyrolygneous acid, different factors influence the yield and the quality of the products. Feedstock materials which consist of different composition of cellulose, hemicellulose and lignin content affect the production and quality of biochar and pyrolygneous acid [15]. Other parameters such as feedstock moisture content and pyrolysis residence time also influence the yield and the quality of biochar and pyrolygneous acid [7]. Furthermore, the yield and the quality of the pyrolysis products (biochar and pyrolygneous acid) depends mainly on the type of pyrolysis, pyrolysis system, biomass material and operating parameters such as pyrolysis temperature, heating rate, sweep gas flow rate, feedstock type and pyrolysis residence time [11].

In this study, a pyrolysis system consisting of a carbonization kiln and a pyrolysis smoke condensation system was designed and developed. The system was tested using twigs of acacia, eucalyptus, and black wattle and its mixture in a ratio of 1:1:1 in production of biochar and pyrolygneous acid. The feedstocks were preferred because they were readily available and commonly used as firewood

as acacia is capable of accumulating large quantities of biomass within a very short period time and produces good quality biomass which can be used for generating energy [2], eucalyptus is suitable for charcoal making due to its rusticity, high productivity and good wood density [13] while black wattle is suitable for producing bio-oil and other valuable chemicals like pyrolygneous acid [5]. Therefore, the objective of this study was to design, develop and test a pyrolysis system in production of biochar and pyrolygneous acid. Biochar quality was based on pH, moisture content (MC), volatile matter (VM), ash content (AC) and fixed carbon (FC) while pyrolygneous acid was classified using pH and density.

2. Materials and Methods

2.1. Designing and Development of a Pyrolysis System

The pyrolysis system designed and developed consisted of a carbonization kiln and a pyrolysis smoke condensation system. In designing and developing a carbonization kiln (Equations 1 and 2) were used. The volume of the carbonization kiln was designed using (Equation 1).

$$V = \frac{M}{\rho} \quad (1)$$

Where;

V = Volume of the carbonization kiln (m³)

M = Mass of the feedstock (kg)

ρ = Bulk density of the feedstock material (kgm⁻³)

The height and the radius of the carbonization kiln was designed using (Equation 2).

$$V = \pi R^2 H \quad (2)$$

Where;

V = Volume of the carbonization kiln (m³)

R = Radius of the carbonization kiln (m)

H = Height of the carbonization kiln (m)

In designing and developing a pyrolysis smoke condensation system, the formulae used by Chen et al [6] was employed as outlined below. The mass flow rate of condensing water was determined using (Equation 3).

$$\dot{m} = \rho q \quad (3)$$

Where;

\dot{m} = Mass flow rate (kgs⁻¹)

ρ = Density of water (kgm⁻³)

q = Water flow rate (m³s⁻¹)

The heat transfer in the system was computed using (Equation 4).

$$Q = \dot{m} c \Delta t \quad (4)$$

Where;

Q = Heat transfer (kW)

C = Specific heat capacity (kJ/kg K)

\dot{m} = Mass flow rate (kgs⁻¹)

Δt = Temperature difference (K)

The final temperature of the condensing water, Δt was computed using (Equations 5, 6 and 7).

$$R_1 = \frac{(T_{tin} - T_{tout})}{(T_{sout} - T_{sin})} \quad (5)$$

$$P_1 = \frac{(T_{sout} - T_{sin})}{(T_{tin} - T_{tout})} \quad (6)$$

$$F = \frac{\sqrt{(R_1^2 + 1)} \ln\left(\frac{1 - P_1}{1 - P_1 R_1}\right)}{(R_1 - 1) \ln\left(\frac{2 - P_1(1 + R_1 - \sqrt{R_1^2 + 1})}{2 - P_1(1 + R_1 + \sqrt{R_1^2 + 1})}\right)} \geq 0.75 \quad (7)$$

Where;

R_1 = Ratio of thermal capacities

P_1 = Ratio of temperatures

F = Correction factor

T_{tin} = Inlet temperature of the hot pyrolysis smoke in the tube ($^{\circ}\text{C}$)

T_{tout} = Outlet temperature of the cooled pyrolysis smoke in the tube ($^{\circ}\text{C}$)

T_{sin} = Inlet temperature of the cold water in the shell ($^{\circ}\text{C}$)

T_{sout} = Outlet temperature of the hot water in the shell ($^{\circ}\text{C}$)

The heat transfer coefficient of the system was determined using (Equation 8).

$$k = \frac{Q}{A\Delta T} \quad (8)$$

Where;

k = Heat transfer coefficient ($\text{Wm}^{-2}\text{k}^{-1}$)

Q = Heat transfer (kW)

A = Area of the shell (m^2)

ΔT = Temperature difference (K)

The ΔT was computed using (Equation 9).

$$\Delta T = F \times \Delta T_m \quad (9)$$

Where;

F = Correction factor

ΔT_m = Logarithmic mean temperature difference (K)

(Equation 10) was used for computing the ΔT_m .

$$\Delta T_m = \frac{(T_{tin} - T_{tout}) - (T_{sout} - T_{sin})}{\ln\left(\frac{T_{tin} - T_{tout}}{T_{sout} - T_{sin}}\right)} \quad (10)$$

Where;

ΔT_m = Logarithmic mean temperature difference (K)

T_{tin} , T_{tout} , T_{sin} and T_{sout} remains the same as in (Equations 5 and 6)

The radius of the shell and the diameter of the tube to be used, was determined using (Equations 11 and 12).

$$A = 2\pi r^2 + \pi dh \quad (11)$$

Where;

A = Area of the shell (m^2)

r = radius of the shell (m)

d = diameter of the shell (m)

h = height of the shell (m)

$$n_t = \frac{A}{\pi d_o l_t} \quad (12)$$

Where;

n_t = number of tubes in the shell

A = Area of the shell (m^2)

d_o = outer diameter (m)

l_t = length of the tube in the shell (m)

2.2. Testing of the Pyrolysis System

2.2.1. Biochar and Pyroligneous Acid Production

Feedstock materials (twigs of acacia, eucalyptus, black wattle and their 1:1:1 mixture) were weighed according to the selected types. First, 100 kg of the acacia twigs at 20% moisture content was fed into the developed carbonization kiln where it was carbonized for the desired residence time of 180 minutes. Carbonization was carried out at the pyrolysis temperature of approximately 400°C and chimney inclination angle of 30° . During the carbonization, the yield of pyroligneous acid was recorded after every 15 minutes. After the carbonization, the developed carbonization kiln was cooled to room temperature so that the products can be removed and stored. The same procedure was repeated for eucalyptus, black wattle and their mixtures. Biochar and pyroligneous acid produced were then weighed using an electric weighing balance to determine their production. The biochar and pyroligneous acid production was determined using (Equations 13 and 14), respectively.

$$BC_p = \frac{M_{BC}}{M_{FM}} \times 100 \quad (13)$$

Where;

BC_p = Biochar Production (%)

M_{BC} = Mass of the Biochar Produced (kg)

M_{FM} = Mass of the Feedstock Material fed into carbonization kiln (kg)

$$PA_p = \frac{M_{PA}}{M_{FM}} \times 100 \quad (14)$$

Where;

PA_p = Pyroligneous Acid Production (%)

M_{PA} = Mass of the Pyroligneous Acid Produced (kg)

M_{FM} = Mass of the Feedstock Material fed into carbonization kiln (kg)

2.2.2. Biochar and Pyroligneous Acid Quality

The biochar produced from each feedstock material and their mixture (1:1:1) was stored in 50 kg capacity sacks marked and labelled appropriately. The quality of the biochar was determined using ASTM D1762-84 procedure. A 1 g mass of biochar produced from each feedstock was weighed and fed into a crucible and heated in a muffle furnace for 2 hours at a temperature of 105°C as recommended by Igalavithana et al [10]. The product and the crucible were then removed and weighed where the mass of the biochar obtained was subtracted from the total mass obtained after weighing them. The moisture content was then calculated using (Equation 15).

$$MC = \left[\frac{w_1 - w_2}{w_1} \right] \times 100 \quad (15)$$

Where;

MC = Moisture content (%)

w_1 = Weight of the air-dried sample (kg)

w_2 = Weight of the sample after being heated at 105°C (kg)

The product was then heated in a furnace for 6 minutes at a temperature of 950°C. The crucible and product were then removed and cooled in a desiccator for 1 hour before its mass was determined. After obtaining the mass of the biochar, (Equation 16) was used in determining its volatile matter.

$$VM = \left[\frac{w_2 - w_3}{w_2} \right] \times 100 \quad (16)$$

Where;

VM = Volatile matter (%)

w_3 = Weight of the sample after being heated at 950°C (kg)

The product was then again returned to the furnace where it was heated for 6 hours at a temperature of 750°C and weighed after cooling the crucible in a desiccator for 1 hour. The ash content of the product was then determined using (Equation 17).

$$Ash (\%) = \left[\frac{w_4}{w_2} \right] \times 100 \quad (17)$$

Where;

w_4 = Weight of the residue after being heated at 750°C

The fixed carbon for biochar products from each sample was then determined using (Equation 18)

$$FC = \left[\frac{w_2 - w_3 - w_4}{w_2} \right] \times 100 \quad (18)$$

Where;

FC = fixed carbon (%), all the other variables remain as defined in (Equations 15, 16 and 17) above.

The biochar product from each feedstock was then mixed with deionized water in the ratio of 1:5 (solid: water) and then agitated frequently where it was allowed to mix and settle for 24 hours as recommended by Song and Guo [21]. The solution obtained was then tested using a pH meter to determine its pH.

The condensate obtained contained three layers of the products arranged as water, pyroligneous acid and tar from top to the bottom. A syringe was used to pierce an opening on the lowest part of the second layer of the product that contained pyroligneous acid in the storing container to collect the product without mixing it with water and the tar. The pyroligneous acid obtained from each feedstock was weighed to determine its mass and the volume was determined using a graduated cylinder. The density was then calculated from the ratio of its mass to the volume as shown in (Equation 19). A pH meter was then used to determine the pH of the product.

$$PA_p = \frac{M_{PA}}{V} \quad (19)$$

Where;

PA_p = Pyroligneous Acid Density (gcm^{-3})

M_{PA} = Mass of the Pyroligneous Acid Produced (g)

V = Volume of the Pyroligneous Acid Produced (cm^3)

2.3. Data Analysis

Analysis of Variance (ANOVA) at $\alpha = 0.05$ level of significance was used in analyzing the results obtained from the experiment and the significance of each term was calculated using the F -values and the p -values.

3. Results and Discussion

3.1. Designing and Development of a Pyrolysis System

A pyrolysis system comprising a carbonization kiln and the smoke condensation system was designed and developed based on basic principles of insulation to conserve heat, sealing to exclude oxygen after ignition and start of pyrolysis, smoke cooling and condensation and ease of operation and transportation of the system. The diameter of the carbonization kiln was designed to be 0.5 m based on the availability of the material and the space. From (Equation 1) by using 100 kg as the mass (m) of the feedstock to be carbonized for each experiment, considering the densities of the acacia, eucalyptus and black wattle, the volume (V) of the kiln obtained was 0.14 m^3 . The height (H) of the carbonization kiln was then determined using (Equation 2) and it was 0.73 m. The overall kiln height was 1 m after allowing a firing zone of 0.27 m height to the carbonization chamber of 0.73 m.

In developing the smoke condensation system, (Equations 3 to 12) were used. The heat transfer coefficient of the system (k) was taken to be 800 $\text{W/m}^2\text{K}$ as indicated by Rajesh et al [18]. The carbonization smoke inlet temp (T_{in}) (due to heat losses from the system as compared to pyrolysis temperature of 400°C) was assumed to be 200°C and inlet temperature in the shell (T_{sin}) was taken as 21°C since it was the room temperature of the water during the research period. The friction factor (F) of the system was assumed to be 0.75 since the required (F) should be greater or equal to 0.75 [18]. In determining water and the smoke outlet temperature after condensation, Equations 2.5, 2.6 and 2.7 were used and T_{sout} and T_{tout} was 24.66°C. The ΔT and ΔT_m was 33.28 K and 44.37 K, respectively and was obtained from (Equations 9 and 10).

The heat transfer (Q) of the system was determined using (Equation 4). The mass flow rate of the water (\dot{m}) was 2 kgs^{-1} which was determined from (Equation 3) since the flow rate (q) of the system used was 2 l/s (supply cooling water flow rate determined using a flow meter). By using the specific heat capacity (C) of water as 4.2 kJ/kg K , Q obtained was 30.74 kW. The area (A) of the system required was 1.16 m^2 which was determined from (Equation 8) and the radius (R) obtained was 0.16 m determined from (Equation 11) by assuming a height of 1 m (due to ease of loading and offloading). The outer diameter (D) of the smoke chimney was 0.18 m which was determined from (Equation 12) by assuming two u-tubes in the shell of the smoke condensation system. The computation for the design of the pyrolysis system is as shown in (Table 1).

Table 1. Pyrolysis System Design Computation.

Carbonization Kiln				
Determinant	Formulae	Assumptions	Parameter Value	System Dimensions/ Values
V (m ³)	$V = \frac{M}{\rho}$	Feedstock material with low density was used Mass of the feedstock material was 100 kg	$M = 100 \text{ kg}$ $\rho_{\text{acacia}} = 800 \text{ kgm}^{-3}$ $\rho_{\text{eucalyptus}} = 700 \text{ kgm}^{-3}$ $\rho_{\text{blackwattle}} = 740 \text{ kgm}^{-3}$	0.143m ³
H (m)	$V = \pi R^2 H$ $H = \frac{V}{\pi R^2}$	$D = 0.5 \text{ m}$	$V = 0.143 \text{ m}^3$ $R = 0.25 \text{ m}$	0.73 m
Pyrolysis Smoke Condensation System				
T _{sout} and T _{tout} (°C), ΔT and ΔT _m (K)	$k = \frac{Q}{A\Delta T}$ $\Delta T = F \times \Delta T_m$ $F = \frac{\sqrt{(R_1^2+1)\ln\left(\frac{1-P_1}{1-P_1R_1}\right)}}{(R_1-1)\ln\left(\frac{2-P_1(1+R_1-\sqrt{R_1^2+1})}{2-P_1(1+R_1+\sqrt{R_1^2+1})}\right)} \geq 0.75$ $R_1 = \frac{(T_{tin}-T_{tout})}{(T_{sout}-T_{sin})}$ $P_1 = \frac{(T_{sout}-T_{sin})}{(T_{tin}-T_{tout})}$	$k = 800 \frac{W}{m^2K}$ $F = 0.75$ $T_{tin} = 200^\circ C$ $T_{sin} = 21^\circ C$	$R_1 = 47.9$ $P_1 = 0.0206$	$T_{sout} = T_{tout} = 24.66^\circ C$ $\Delta T_m = 44.37K$ $\Delta T = 33.28K$
Q (kW)	$Q = \dot{m}c\Delta t$ $\dot{m} = \rho q$	None	$\rho = 1000 \text{ kgm}^{-3}$ $q = 2 \text{ ls}^{-1}$ $c = 4.2 \text{ kJ/kgKl}$ $\Delta t = 3.66 \text{ Kl}$ $Q = 30.74 \text{ kW}$ $\Delta T = 33.28K$	30.74 kW
A (m ²)	$A = \frac{Q}{k\Delta T}$	$k = 0.8 \frac{kW}{m^2K}$	$Q = 30.74 \text{ kW}$ $\Delta T = 33.28K$	1.16m ²
R (m)	$A = 2\pi r^2 + \pi dh$ $A = 2\pi r^2 + 2\pi rh$	$h = 1 \text{ m}$	$A = 1.16 \text{ m}^2$	0.16 m
D _{outer} (m)	$n_t = \frac{A}{\pi d_o l_t}$ $d_o = \frac{A}{n_t \pi l_t}$	$n_t = 2$ $l_t = 1 \text{ m}$	$A = 1.16 \text{ m}^2$	0.18 m

The pyrolysis system designed and developed is as shown in (Figure 1).

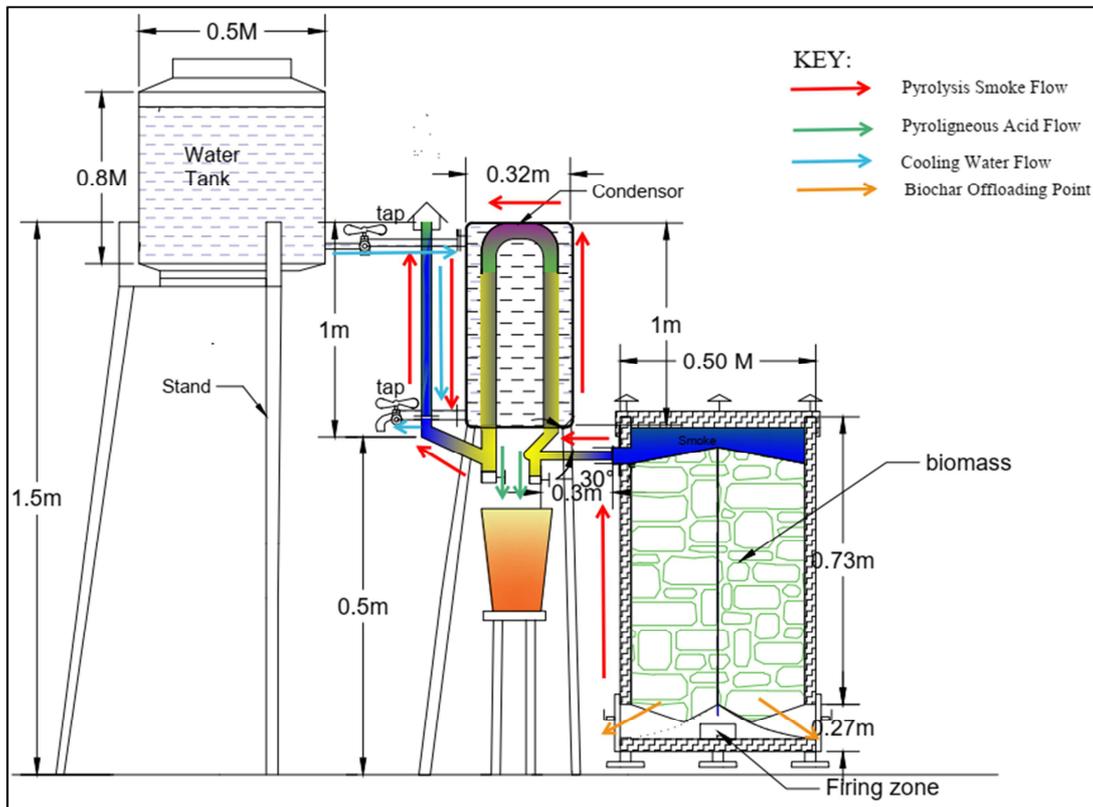


Figure 1. The Developed Pyrolysis System.

3.2. Testing of the Designed and Developed Pyrolysis System

3.2.1. Biochar and Pyroligneous Acid Production

Each feedstock material carbonized resulted in a different production of the biochar and pyroligneous acid as presented in (Table 2).

Table 2. Pyrolysis products from selected feedstocks.

Feedstock material	Mean biochar and pyroligneous acid production (%)	
	Biochar	Pyroligneous acid
Acacia	39.46 ^a	29.89 ^a
Black wattle	37.11 ^b	22.71 ^c
Eucalyptus	34.97 ^c	21.65 ^c
Mixture (1:1:1)	37.69 ^b	25.34 ^b
Average	37.31	24.90

Means followed by the same letter (s), (a, b, c), are not significantly different at $\alpha = 0.05$, LSD = 0.74 for biochar and 1.13 for pyroligneous acid

The yield of the biochar obtained was 39.46 kg, 37.11 kg, 34.97 kg and 37.69 kg being 39.46%, 37.11%, 34.97% and 37.69% for acacia, black wattle, eucalyptus and their 1:1:1 mixture, respectively. The yield was slightly higher than what Wu et al [24] obtained (35%) due to the difference in feedstock material even though for eucalyptus it was slightly less. This might be due to the difference in pyrolysis temperature.

Variation in the production of the pyrolysis products obtained was attributed to the different densities of the feedstocks as has been reported by Rodrigues and Braghini [19]. Acacia, black wattle, and eucalyptus had densities of 800 kgm⁻³, 740 kgm⁻³ and 700 kgm⁻³ with a biochar production of 39.46%, 37.11% and 34.97% while producing a pyroligneous acid of 29.89%, 22.71% and 21.65%, respectively. The biochar produced from each feedstock

material is as shown in (Figure 2).



Figure 2. Biochar produced from each feedstock material.

The amount of pyroligneous acid collected was measured in millilitres (ml) and recorded after every 15 minutes throughout the carbonization process to a residence time of 180 minutes is as shown in (Figure 3).

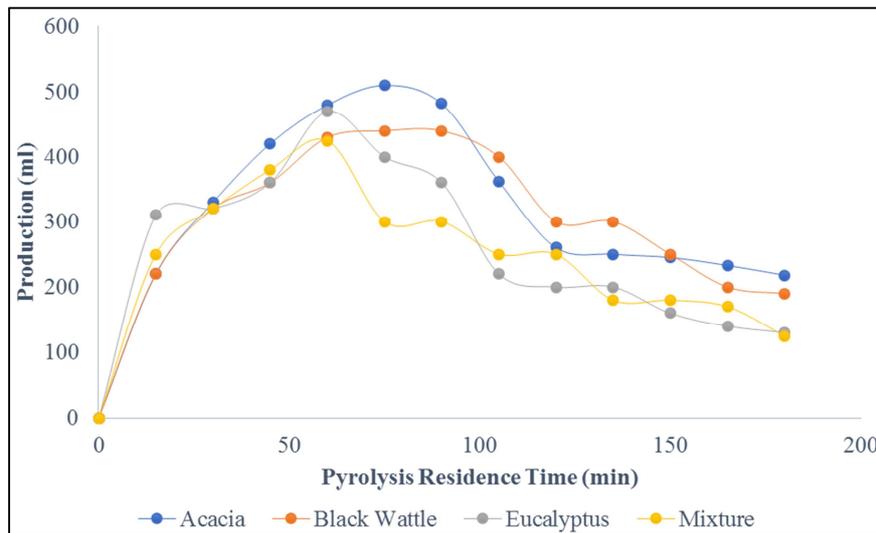


Figure 3. Pyroligneous Acid Production.

The pyroligneous acid yield increased with an increase in pyrolysis residence time for some time for each feedstock material and mixture carbonized before it starts reducing. The variation in the production was attributed to the difference in densities of the material used as has been reported by Rodrigues and Braghini [19]. An increase in the

pyrolysis residence time resulted to decrease in the yield of the pyroligneous acid due to an increase in the production of uncondensed gas [11]. The pyroligneous acid produced is as shown in (Figure 4).



Figure 4. The Pyroligneous Acid.

The maximum yield obtained was 510 ml, 470 ml, 440 ml and 425 ml at pyrolysis residence time of 75 min, 60 min, 75

min and 60 min for acacia, eucalyptus, black wattle and their mixtures, respectively. Oramahi and Diba [16] obtained the highest yield at pyrolysis residence time of 72.9 minutes after carbonizing bark of *durio* having a moisture content of 13.95% at pyrolysis temperature of 421°C. This is less than the one for acacia and black wattle but higher than that of eucalyptus and their mixtures and this is because of the difference in feedstock material, moisture content and pyrolysis temperature.

3.2.2. Biochar and Pyroligneous Acid Quality

The quality of biochar from each feedstock material was determined and different values were obtained as shown in (Table 3).

Table 3. Quality of the Biochar from Specific Feedstocks.

Feedstock material	Feedstock mass (kg)	Mean biochar quality				pH
		MC (%)	VM (%)	AC (%)	FC (%)	
Acacia	100	8.2 ^b	28.2 ^b	6.8 ^a	56.8 ^a	6.9 ^a
Black wattle	100	9.6 ^a	28.9 ^a	7.0 ^a	54.5 ^b	6.6 ^a
Eucalyptus	100	9.5 ^a	29.2 ^a	7.0 ^a	54.3 ^b	6.5 ^b
Average		9.1	28.8	6.9	55.2	6.7

Means followed by the same letter (s), (a, b), are not significantly different at $\alpha = 0.05$, LSD = 0.59, 0.72, 0.27, 0.83 and 0.30 for MC, VM, AC, FC and pH, respectively

The MC of biochar was 8.2%, 9.6% and 9.5% for acacia, black wattle and eucalyptus material, respectively. Acacia biochar had a VM of 28.2% while black wattle and eucalyptus had 28.9% and 29.2%, respectively. Ash content of the biochar for acacia was 6.8% while for black wattle and eucalyptus was 7% each. Acacia biochar resulted in 56.8% FC while black wattle and eucalyptus had 54.5% and 54.3%, respectively. The pH of the biochar obtained ranged from 6.5 to 6.9 with acacia having 6.9 while black wattle and eucalyptus had 6.6 and 6.5, respectively. The result obtained is higher than what Haddad et al [9] reported except for FC

and pH after producing biochar from raw Cyprus sawdust at pyrolysis temperature of 475°C and pyrolysis residence time of 1 hour. The biochar produced had MC = 3.6%, VM = 27.0%, Ash = 1.5%, FC = 68.0% and pH = 7.34. Results obtained from current study differs from this due to difference in feedstock material, pyrolysis residence time, particle size and pyrolysis temperature. The quality for the mixed ratio for the biochar obtained was not considered since the product was easily determined physically.

The pyroligneous acid quality from each feedstock material and their mixture obtained is as shown in (Table 4).

Table 4. Pyroligneous Acid Quality from Specific Feedstocks.

Feedstock material	Mixed ratio	Mean pyroligneous acid quality	
		ρ (gcm ⁻³)	pH
Acacia	1:0:0	1.02 ^b	3.07 ^a
Black wattle	0:1:0	1.04 ^a	3.09 ^a
Eucalyptus	0:0:1	1.01 ^b	3.07 ^a
Mixture (of the above)	1:1:1	1.02 ^b	3.09 ^a
Average		1.02	3.08

Means followed by the same letter (s), (a, b), are not significantly different at $\alpha = 0.05$, LSD = 0.02 both for ρ and pH

The density of the pyroligneous acid obtained was 1.02 gcm⁻³, 1.04 gcm⁻³, 1.01 gcm⁻³ and 1.02 gcm⁻³ while the pH was 3.07, 3.09, 3.07 and 3.09 for acacia, black wattle, eucalyptus, and the mixture, respectively. The result obtained for pyroligneous acid quality agrees with the ones obtained by Lu et al [12] after producing pyroligneous acid with a pH of 3.08 and density of 1.039 gcm⁻³.

A good quality biochar has a moisture content of less than 7% [14], volatile matter of 20%-30% [4], ash content of less than 5% [20], fixed carbon of greater than 75% [14] and a pH that ranges from 5.9 to 12.3 [1]. Doti et al [7] reported that a

good quality pyroligneous acid has a pH that ranges from 2 – 4 and a density ranging from 1.01 gcm⁻³ to 1.05 gcm⁻³. Therefore, from the results obtained in the current study, biochar and pyroligneous acid produced were within the required standard to be used as source of energy for cooking or as a biopesticide, respectively.

4. Conclusions and Recommendations

Biomass materials (both agricultural and forestry) can be easily converted to a usable product like biochar (used as

source of energy for cooking or as a soil amendment) and pyrolygneous acid (used as a biofertilizer or biopesticide) through a pyrolysis system. The developed pyrolysis system had a high production rate of biochar and pyrolygneous acid. Furthermore, the system produced a high-quality biochar and pyrolygneous acid therefore making it suitable for pyrolysis of biomass materials. It is therefore recommended to use a pyrolysis system with a smoke condensation system whenever biomass materials are being carbonized. This approach of carbonizing agroforestry materials using the developed pyrolysis system enhances diversification of products by capturing what would otherwise be wasted to produce biofuel, bio-fertilizer, and bio-pesticide. This would result in environmental conservation and serve as source of livelihood when these products are marketed. Despite the developed pyrolysis system producing a high-quality pyrolysis product, further studies are required in determining the effect of insulation properties and the number of cooling tubes in the heat exchanger on the production and quality of the biochar and pyrolygneous acid.

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