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Experimental Study of Biochar Production Process Using a Pilot Carbonization Kiln as a Biofuel's Properties Improvement Module

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Pyrolysis is a thermo-chemical process of biomass conversion to a carbon neutral or better fuels and materials from biomass. It is a thermal decomposition of organic material in a controlled (insufficient) oxygen at a high temperature thereby producing solid (biochar), liquid (oil) and gaseous products. Biochar produced during this process is a very valuable material that can be utilized as soil additive and in carbon sequestration, where the carbon can be stored (locked) in the

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soil. The result is improved soil structure, pH, water and nutrient retention and the mitigation of climate change. Biochar can also be utilized as biofuel in energy generation directly or converted to biomass briquettes thereby, improving its energy and economic value. Therefore, the present study, involved the production of biochar from an improvised 100 litres volume pilot carbonization kiln and experimentally studied the biochar yield. The result showed a yield of 2505g at average charring ratio of 33.9 % from 7396g of composite wastes, comprising of 1844g of mixture of Maize cob and coconut husk, 1030g of mixed vegetable stem and discarded fruits (sundried watermelon and fruits, 3321g of peeled yam, cassava peels, potatoes peels and discarded food materials, and 1201g of plantain bunches and peels. This results is an indication of good performance outcome of the carbonization kiln in biochar production for soil nutrient improvement and (or) for energy supply applications as refuse derived fuels (RDF).

Keywords: Biomass; biochar; pyrolysis; carbonization; kiln; yield; agro-waste; municipal solid waste; soil sequestration; energy supply.

1. INTRODUCTION

1.1 Background of Study

The material of plants and animals, including their wastes and residues, is called biomass. It is organic, carbon-based, material that reacts with oxygen in combustion and natural metabolic processes to release heat.

“Thermo-chemical conversion of biomass includes processes like combustion, gasification and pyrolysis. Combustion refers to the conversion of biomass to heat and power by directly burning it, as occurs in boilers. Gasification is the process of converting solid biomass with a limited quantity of air into producer gas, while pyrolysis is the thermal decomposition of biomass in the absence of oxygen” [1-2].

In pyrolysis, biomass (e.g., crop and forestry residues, agricultural, municipal and industrial wastes) is decomposed at temperatures higher than 400°C, in the complete or near absence of oxygen.The products of pyrolysis are biochar, condensable liquid and gaseous products.

Pyrolysis: Biomass + heat → biochar, gas and oil

“Carbonization is a pyrolytic process by which lightweight black solid residues with increasing content of the element carbon are formed from organic material usually after pyrolysis in an inert atmosphere” [3].

The product of Biomass Carbonization is biochar which is environmentally friendly. Note that volatile flue gases are expelled during this process. This increases the heating value of biomass and stabilizes the thermal properties. Biomass is considered as environmentally friendly as fuel or as soil additive and contains little sulfur and nitrogen. Biomass can also be co-fired with coal in steam turbines [4].

According to Ralebitso-Senior and Orr [5], “the main resulting characteristics when biomass is converted to biochar are increased stability of the organic carbon (C), a porous structure, and high surface area. Biochar consists of relatively stable aromatic compounds, moderately labile aliphatic compounds, and ash. Their relative proportion is influenced by the feedstock used and production conditions such as temperature, heating rate, and oxygen (O_2) supply”.

Biochar produced during this process is a very valuable material that can be utilized as soil additive through sequestration, where the carbon can be stored in the soil, thereby improving soil structure, pH, water and nutrient retention. It is used in soil amendment to improve soil quality by improving soil physical and chemical properties. These lead to increasing soil fertility and productivity. Biochar is also used to sequester carbon. It is a useful tool for locking up carbon dioxide in the soil and mitigating climate change. Also, biochar as a biofuel can also be utilized in energy generation directly or converted to biomass briquettes thereby, improving its energy and economic value.

“Summarily, biochar has high potential to scale up and has a direct impact on crop yield, water purification (for domestic and industrial application), alternative fuels (clean solid fuel for cookstove), air purification, catalyst, biogas production, purification, and storage” [6].

2. BIOMASS PYROLYSIS PROCESSES

"The Traditional biomass pyrolysis to produce char involves placing biomass in a pit or mound, igniting the matter and covering the pit or mound with earth to allow the hot biomass to decompose. The disadvantage is that this process is fairly inefficient and difficult to control with most kiln operators gaining a knowledge of the process through years of experience. Modern day pyrolysis has progressed, with specialized reactor designs developed to enable improved process control and a designated product output" [7-8].

"Biochar yield is dependent among other things on the nature of the feedstock used (woody or herbaceous), operating conditions and the environment of the pyrolysis units (low vs. high temperature, residence time; slow vs. fast pyrolysis, heating rate and feedstock preparation)" [9-10].
Biomass pyrolysis processes are classified as fast, slow, or intermediate pyrolysis conditions, depending on the residence time and heating rate of the material in the reactor. Fig 1 shows the properties of each process.

"Fast pyrolysis temperatures can range between 450-550°C (Scott et al., 1999). Only particles of very small size (< 1mm) can be pyrolyzed using this method" [11-13].

Slow pyrolysis is performed at very low heating rates 0.1 K/s. The particle size during slow pyrolysis is between 2 and 10 mm.

"The extreme ends of slow pyrolysis are carbonization and torrefaction. Carbonization occurs when pyrolysis conditions are such that the biomass feed is very slowly heated to favour maximum char production" [7,11-12].

"Intermediate pyrolysis is performed at medium heating rates. This kind of pyrolysis is preferred for biomass in the particle size range of 1–5 mm. During the intermediate pyrolysis, there are huge thermal gradients within the particle itself" [14].

Fahmy et al. [15] outlined "various types of biomass used for pyrolysis are encompassed, e.g., wood, agricultural residues, sewage. Emphasis is laid on current and future trends in biomass pyrolysis, e.g., microwave pyrolysis, solar pyrolysis, plasma pyrolysis, hydrogen production via biomass pyrolysis, co-pyrolysis of biomass with synthetic polymers and sewage, selective preparation of high-valued chemicals, pyrolysis of exotic biomass (coffee grounds and cotton shells), comparison between algal and terrestrial biomass pyrolysis. The authors predict that combining solar pyrolysis with hydrogen production would be the eco-friendliest and most energetically feasible process in the future. Since hydrogen is an ideal clean fuel, this process may share in limiting climate changes due to CO2 emissions".

Mia et al. [16] developed and tested "biochar production kilns for farmers with a dimension of 50.8 cm × 38.1 cm (height × diameter), using three different setups for optimizing oxygen (O2) limitation and syngas circulation: airtight with no syngas circulation (Model I), semi-airtight with external syngas circulation (Model II) and semi-airtight with internal syngas circulation (Model III). A comparative assessment of these biochar production kiln models was made considering biochar pyrolysis time, fuel to biomass ratio, biochar to feedstock ratio and thermogravimetric index (TGI). Among the models, the best quality biochar (TGI = 0.15) was obtained from Model I kiln taking the longest time for pyrolysis (12.5 h) and the highest amount of fuel wood (1.22 kg kg^{-1} biomass)".

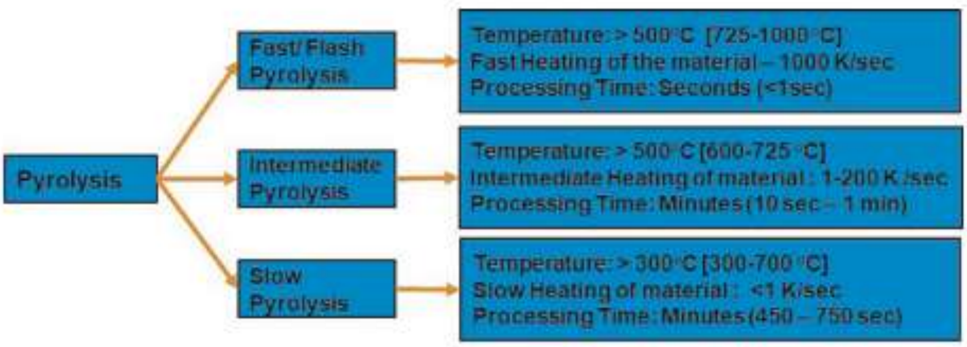

Fig. 1. Different types of pyrolysis and their operating conditions [14]

Zarzycki and Jędras [17] presented "the problem of heat exchange in the biomass carbonisation reactor with cyclic operation. Based on the actual parameter of the biomass carbonisation reactor, a geometrical model was developed, and the computation of the heating process was conducted for two cases: an empty reactor and a filled reactor. Its result demonstrated that for the analysed configuration of the reactor, the process of heating biomass in the containers is limited by the capability of heat transfer to the biomass in the container. The results suggested opportunities for the improved heat exchange in the reactor and, accordingly, shortening heating time through installation of the system that forces circulation of hot air inside the reactor".

Akom et al. [18] examined "the yield and cost of biochar produced using a locally developed reactor. Biochar yield of 540 kg was obtained from 1460 kg of wood shaving feedstock used. The average charring ratio and feedstock were 37% and 122 kg respectively. A total of 988 kg of firewood was used to produce the biochar in 35 days. The biochar was produced in 12 batches in 35 days with 988 kg of firewood. The yield of biochar obtained in their study was claimed to be consistent with a report on woody biomass under slow pyrolysis".

Chiaramonti et al. [10] investigated "the technological opportunities for small scale charcoal making systems and proposed a small scale application suitable for the Italian farmers by designing a pilot plant".

3. METHODOLOGY

3.1 Biochar Production Process

Gathering of Biomass waste materials → Drying to expel moisture → Carbonization by Pyrolysis

3.1.1 Gathering biomass waste material

The biomass wastes materials will be gathered mainly municipal solid wastes, agricultural wastes comprising vegetable stems, fruits, yam peels, coconut peels, plantain bunch etc.

Fig. 2. Feedstocks

3.1.2 Drying of feedstocks

Drying the feedstock before charring also improves the pyrolysis process efficiency as fairly large energy input would be required for drying during the pyrolysis process. High moisture content also leads to reduction in biochar yield [20-21].

3.2 The Structure of the Improvised Kiln and Carbonization Process

Fig. 3 is the concept diagram of the improvised pilot carbonization kiln for biochar production. The following steps are followed in actualizing the process.

i. Two holes of 100mm diameter were be created on an empty mild steel drum of 820 mm height and 660 mm diameter as shown in Fig. 3
ii. A metallic cylinder of 100mm diameter was then attached such that it projected 200mm above the drum.
iii. The drum was placed on top of a partially lagged biomass powered stove, such that the 100mm cylinder act as a chimney.
iv. The drum was filled with the sun dried biomass waste, totaling 7396g of Composite waste.
v. It was then covered and sealed with a clay making the drum airtight.
vi. The stove was fed with dry biomass majorly leaves, woods, waste paper and other combustible materials, and it combusted between 400 °c 500°c for heating the kiln (airtight drum) for one hour. At this temperature, pyrolysis takes place. A thermocouple was used in determining the temperatures.
vii. The kiln was then removed from heating and was cooled below 35^{o}C by sprinkling water on the body of the drum, to avoid reignition or scalding when exposed to air.
viii. The biochar was then poured out and was allowed to continue cooling, as seen in Fig. 5.
ix. The biochar was then packed, ready for agricultural applications or to be densified to briquettes.

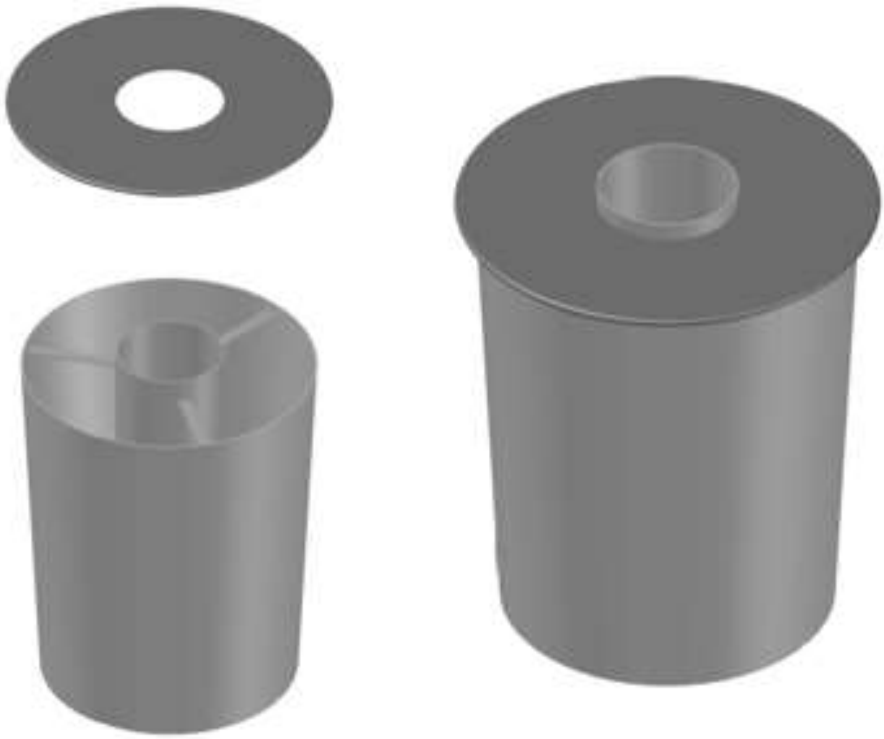

Fig. 3. Concept diagram of the improvised pilot carbonization kiln

Fig. 4. The Pilot Carbonizatin Kiln

Fig. 5. Biochar

4. RESULTS AND DISCUSSION

The Yield of Biochar after Pyrolysis:

Mathematically,

$$\text{Yield}_{\text{biochar}} = \frac{\text{M}_{\text{biochar}}}{\text{M}_{\text{biomass}}} \times 100\%$$

Where;
$\text{Yield}_{\text{biochar}}$ = percentage yield of biochar in %
$\text{M}_{\text{biochar}}$= mass of biochar in kg
$\text{M}_{\text{biomass}}$ = mass of raw biomass in kg

A total Biochar yield of 2505g was produced from 7396g of Composite waste comprising of 1844g of mixture of Maize cob and coconut husk, 1030g of mixed vegetable stem and fruits, 3321g of peeled yam, cassava peels, potatoes peels and discarded food materials, and 1201g of plantain bunches and peels. The yield in this study is consistent with [18,22-23], as good yield for herbaceous feedstocks. The major factors that determine yield are the nature of feedstock (waste) used (herbaceous or woody) and operating conditions in the pyrolysis chamber which are viz, low or high temperature, residence time (slow or fast pyrolysis), heating rate and feed preparation, Laird et al. 2011.

We adopted slow pyrolysis at low temperature because it is known to produce better yield [18, 24]. Harbaceous feedstocks produce lesser yield when compared to woody feedstocks. This can be explained by high cellulosic content in the harbaceous feedstocks, which were converted into volatile matter during pyrolysis. Meanwhile, woody feedstocks had high lignin content and biomass density (high carbon content per unit volume), which resulted in high biochar yield [25].

5. CONCLUSION

Fabrication of a pilot carbonization kiln has been carried out using a locally available materials and the kiln was successfully deployed in biochar production. Biochar yield of 2505g at average charring ratio of 33.9 % was produced from 7396g of composite wastes, comprising of 1844g of mixture of Maize cob and coconut husk, 1030g of mixed vegetable stem and discarded fruits (sundried watermelon and fruits, 3321g of peeled yam, cassava peels, potatoes peels and discarded food materials, and 1201g of plantain bunches and peels. Therefore, the pilot carbonization kiln can be fully deployed in converting bio-municipal solid wastes and agricultural wastes generated in the locality into a biochar for soil or energy applications.

Table 1. Biochar feedstocks and yield

Feedstock	Sample	Mass of biomass ($\text{M}_{\text{biomass}}$) (in g)	Mass of Biochar ($\text{M}_{\text{biochar}}$) (in g)	Biochar Yield / Charring Ratio (in %)*
Maize cob, coconut husk	A	1844	596	32.3
Mixed vegetable stem and fruits	B	1030	302	29.3
Peeled yam, cassava peels, potatoe peel, discarded food items	C	3321	1307	39.3
Plantain bunches and peels	D	1201	300	25.0
Average		1849	626	33.9
Total		7396	2505	33.9

*On wet basis

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COMPETING INTERESTS

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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