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A closed drum carboniser for converting ligno-cellulosic residues to biochar pellets: A Nigerian study

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Abstract: This paper describes an innovative technology that provides an alternative to management of wastes arising from grass cuttings, weeds and agro-forestry residues that are usually discarded unattended. These wastes are now converted into biochar pellets using a newly designed carboniser which is highly economical and can generate employment opportunities to peri-urban and rural low income populations. We used simple spent oil drum with an attached chimney and cassava based starch or clay (e.g. kaolin) as binder to make pellets from the burnt raw materials. This process does not require any moving parts, electricity or any additional fuel to convert the waste into charcoal pellets. We have field tested the carboniser with elephant grass (*Pennistum purpureum*) as feedstock. Technical performance was evaluated using parameters such as Production Capacity Ratio (PCR), Reliability Ratio (RR) and Efficiency Ratio (ER). Samples of elephant grass, biochar pellets and the ash produced after the biochar used for cooking were analysed for selected chemical characteristics (viz. sulphur, carbon, hydrogen, potassium and calorific value), using standard laboratory procedures. The results obtained gave production capacity and efficiency ratio of 83%; actual production capacity of 25 kg/hour; which is 100% reliable. The differences in the chemical parameters for the three samples were significant. Potassium, carbon and calorific values were observed in increasing order: ash < elephant grass < biochar. Biochar gave lowest values of hydrogen (12.36±0.01%) and sulphur (0.67±0.0%) contents while elephant grass contained highest values of these elements (13.28±.02% and 1.38±0.00%, respectively). This technology will benefit less educated rural and peri-urban populations to develop a small scale or medium scale entrepreneurship with low financial inputs and minimal skills and the product is a good cooking fuel and environment friendly with less or no smoke.

Keywords: Agro-Forestry Residues, Biochar Pellets, Carboniser, Elephant Grass

1. Introduction

The term ‘biochar’ reflects the production of charcoal from biological materials [1, 2] and is one of the most ancient and oldest industrial technologies developed by mankind [3]. It is produced when dry and combustible organic materials are partially burnt in limited supply of oxygen (O_2). Unlike charcoal that is produced purposively for bio-energy utilization, biochar emerged in conjunction with other sophisticated uses, including organic fertilizer for soil amendment [4], carbon sequestration, water filtration and other environmental services [5]. Biochar is different from normal wood charcoal in that it has more surface area which allows it to be ignited easily and make it useful in several industrial applications. Although, biochar was described as ‘fire manure’ in an ancient Japanese book on agriculture, global interest in biochar only began in the past few years. The basis for the strong recent interest in biochar is two-fold. First, the discovery that biochar-type substances are the explanation for high amounts of organic carbon [4] and sustained fertility in Amazonian Dark Earths locally known as Terra Preta de Indio [6].

Several works have carried out research-scale pyrolysis using a wider range of feedstock [7-10]. Various feed stocks used earlier include: wood chips and wood pellets, tree bark; crop residues, straw, nut shells, rice hulls; switch grass; organic wastes, paper sludge, sugarcane bagasse, distillers grain, olive waste [11]; chicken litter [9], dairy manure, and sewage sludge [12]. Turning waste biomass into biochar reduces methane generated by the natural decomposition of organic waste and thus reducing the release of CO_2, which is a greenhouse gas into the environment. This technology thus is carbon-negative and has the potential in mitigating climate change effects, food insecurity, energy crisis and waste management [13, 5]. It also has potential to reduce over dependency of African rural and peri-urban communities on wood fuel [14, 15].

In Nigeria, traditional methods of making charcoal are inefficient in addressing the issues of environmental pollution, ease of production and exposure of workers to inhalation related risks. In view of this problem, an improved form of biochar production was developed by us. The technology converts agro-forestry residues which are either thrown out or ploughed back into soil or allowed to decay on soil into charcoal which emits little or no smoke when used by the communities for cooking purposes. A closed drum carboniser for biomass conversion to char pellets was designed, fabricated and demonstrated using elephant grass (*Pennistum purpureum*) as a test feedstock. Elephant grass (*Pennistum purpureum*) is one of the most common weeds found in Nigeria, especially in abandoned government quarters, roadsides, footpaths and vacant plots. It is also known as Napier grass or Uganda grass and is a tall grass that originally came from Africa in 1913 [16]. It grows in dense clumps of up to 3m tall. In the savannahs of Africa it grows along lake beds and rivers where the soil is rich. It has low water and nutrient requirements, and therefore can make use of otherwise uncultivated lands [17]. Historically, this wild species has been used primarily for grazing [18] and pest management. Other beneficial uses have been minimally explored in Nigeria. In other countries like China [17], it was earlier subjected to thermal pyrolytic conversion to produce charcoal, biogas and bio-oil. Although this technology is not currently in use in Nigeria, a more locally adaptable technology of biochar production could be implemented as a means of providing energy to peri-urban and rural communities, while managing the problem of spread of the grass as a weed and protecting the environment.

2. Materials and Methods

2.1. Materials

Materials required for fabrication and operation of the carboniser consist of three 120 litre used oil drums, a metal cover, filling material to trap the smoke on its way in the pipe that leads to the chimney, waste holder with chimney (stainless drum is preferred but expensive), tripod stand, product holder with lid (cap), smoke and particle recovery drum; metal plate; welding tools- welding machines, electrodes, iron cutter, vice; heat resistant chemical; water; medium sized stick; lighter (or safety matches); wetting-can; tripod stand (stone may be used); heavy duty hand glove, nose cover, other PPE as may be applicable; mold (different shapes); binder: stove; plastic containers and stirrer; nylon sheet; and Compressing plate.

2.2. Fabrication of the Carboniser

Figure 1 shows a line diagram of the carboniser. It consists of three spent oil drums and chimney that is packed with smoke/particle adsorption materials. The first drum with perforations serves as kiln or furnace where burning of biomass takes place. It is coated with anti-radiant or heat resistant material to improve its strength in withstanding high temperature. The second drum is where the smoke escaped is trapped and adsorbed on coconut fibre. The third drum was used to collect the char powder produced after burning and to be mixed with necessary binding agents to make char pellets. These drums are chosen because they are easily available for low income communities at an affordable cost.

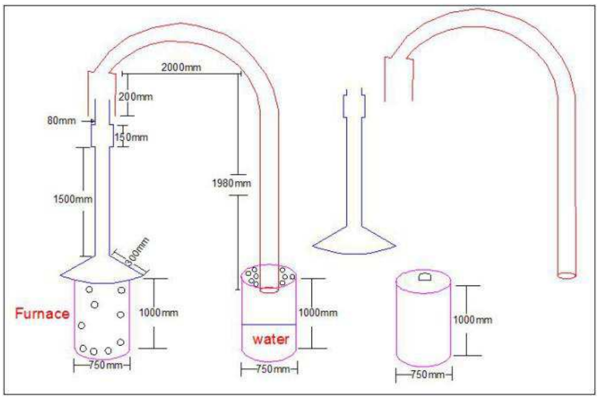

Figure 1. *A sketch of the drum carboniser*

2.3. Raw material or Feedstock

A variety of feed stocks were test run. These were: crop residues, agro-forestry wastes, and grass clippings from fence and lawns. However, a common grass chosen in this study was elephant grass (*Pennistum purpureum)* which is a problem grass that grows abundantly on roadside, river banks and other uncultivated areas. Indeed it is a trouble grass on highways and agricultural lands.

2.4. Operation of the Plant

The waste holder is first placed on tripod stand. Waste biomass (e.g. grass, stover, stems, leaves and twigs of the shrubs, sugarcane bagasse, corn stalks fallen leaves, rice husk, ground nut shells and weeds) is selected, dried and carefully packed into waste holder. Waste in the furnace (Drum 1) is ignited with matches without putting any fuel to initiate or aid burning. Waste holder is closed with the chimney and the chimney is opened 3 to 4 times in the cycle of burning to turn the waste for uniform burning. The time taken for burning takes about one hour or more depending on the biomass. High lignin biomass takes longer time whereas cellulose rich biomass takes less time. At the point when the material turns black (Figure 2) the fire inside the drum is quenched by sprinkling water and the content is emptied into product holder (Drum 3), compressed and covered with lid. After cooling it is molded into pellets (Figure 2), sun dried and stored for use. The pellets are made by compressing the powdered charcoal manually or in a compressor. A binding agent low in carbon may be helpful. Time taken for complete burning depends on the type and quantity of the feedstock**.**

2.5. Technical Evaluation of the Carboniser

The technical performance of the carboniser unit was evaluated in terms of: Production Capacity Ratio, Reliability Ratio and Efficiency Ratio.

i. The production capacity ratio was calculated as the ratio of the average actual plant production capacity to the design capacity of 25 kg/hr for 8 hours of production time per day.
ii. The reliability or availability ratio of was measured as the ratio of average of the actual plant operation time per day to the designed operation time of 8 hrs per day.
iii. The efficiency ratio was calculated as the product of the production capacity ratio and reliability ratio. That is, Production Capacity Ratio x Reliability Ratio.

Figure 2. *A: Elephant grass, B: Closed drum carboniser, C: Semi-finished product and D: Finished product (pellets)*

2.6. Laboratory Analysis

To ascertain the effects of the pyrolytic process on the chemical characteristics of the feedstock and products, composite samples of dry grass, biochar produced and the ash by-product obtained after utilisation of the biochar pellets for cooking were analysed. Organic carbon was determined by Walkey Black wet oxidation method; total Kjeldahl-nitrogen by Macro-Kjeldahl method and potassium content by sodium tetraphenyl boron volumetric method, as described earlier [19]. Analyses of sulphur, and hydrogen were carried out, following Motsara and Roy [20] procedures and calorific value by American Society for Testing Materials (ASTM) [21]. Determination of lead (Pb), nickel (Ni), cadmium (Cd) and manganese (Mn) in the samples was done by weighing 1g of ground sample into a conical flask. To this, 5ml of digestion reagent (2:1 of concentrated HNO_3 and concentrated H_2SO_4 were added and heated until brown peroxide and white perchloric acid evaporated. The resulting residue was dried. The procedure was repeated until a white precipitate remained in the flask. This was then filtered through a Whatman filter paper No 1 into a 100ml volumetric flask. The filtrate was diluted with 0.1N HNO_3 (p.a) to 100ml. The digested samples were then analysed for the heavy metals with atomic absorption spectrophotometer (GBC 902).

Furthermore, methods by Association of Official Analytical Chemists [22] were used to assess proximate composition of the biochar (crude protein, moisture content, ether extract, ash, oxygen and crude fiber) for its quality. The data collected were subjected to statistical analysis of variance and significant differences among the treatment means were evaluated using Duncan’s Multiple Range Test (DMRT) at 5 % probability level.

2.7. Results and Discussion

From the literature search, previous designs of small scale biochar and charcoal plants available globally are listed in Table1. Most of these designs do not capture smoke released into the atmosphere during their operations.

Table 1. *Some earlier designs of biochar/charcoal plants across the world*

S/N	Name of Inventor and Country	Name of the Plant
1	Kobus Venter (South Africa)	Trans-Portable Kiln
2	Adam (Kenya)	Improved Charcoal Production System (ICPS) or (Retort kiln)
3	Companies: Vuthisa Technologies(South Africa)	3- Drum Biochar Retort
4	R. Diermair	Two Barrel TLUD Construction
5	Bates, Albert (USA)	Drum kiln
6	Bhaskar Reddy (India)	Magh Biochar Retort
7	Frogner (Mongolia)	JR Biochar Ovens
8	Wilson, Kelpie (USA)	Japanese Cone Kiln
9	Bhaskar Reddy (Andhra Pradesh, India)	Biochar Pit Kiln
10	Karve (India)	Single Barrel Charcoal Kiln
11	Folke Gunther	Simple charcoal kiln
12	Bakary Jatta, (BwiamVilliage, Gambia)	Jatta Charcoal Retort
13	Tom Miles (New Delhi)	Bamboo-based Charcoal Plant
14	Wondwossen B. (2009) (Ethiopia)	Carbonizer
15	Odesola I. F and Owoseni T. A (2010).(Nigeria)	Biochar Reactor

2.8. Features of the Current Design

The uniqueness of our Carboniser design are:

1 The entire unit is completely covered to reduce gaseous emissions into the atmosphere during burning.
2 Heat loss is reduced to increase the temperature of furnace and burning potential of the carboniser.
3 The technology has potential for recovering smoke that can as well be recycled into other useful products.
4 The unit can be operated safely at any convenient place such as backyard of a house or school as the gaseous emissions are minimal,
5 The unit is portable and can be shifted easily to locations where there is availability of biomass.
6 The unit is packed with particle adsorption materials for smoke and particulate matter removal.
7 The biochar produced can be molded manually or by simple locally fabricated machines of different shapes.

8 Replication and promotion are easy and cost effective; this can be adopted for various types of biomass.
9 This technology uses no electricity or moving parts and does not require any extra fuel.
10 It can be operated by the rural populations without any formal education or skills.
11 Total closure enhances energy efficiency and can be effectively used even for soft wood.
12 Moderate investment costs and a simple construction with locally available materials.

2.9. Technical Evaluation of the Carboniser

Results of technical performance of the carboniser are shown in the Table 2. The plant has production capacity and efficiency ratio of 83% each; actual production capacity of 25 kg/hour; and it is 100% reliable. The performance of the carboniser is comparable to earlier small-scale designs by Wondwossen [23] and Johannes and Stephen [24] with a similar output of 15 kg/25mins each. The carbonisers were designed for agricultural wastes, grass, sugarcane trash and dry leaves. Also, the present design has more efficiency and production capacity than the type reported by Odesola and Owoseni [25] with 79.9% output and production capacity of per kg of 18.3 kg per day when used for cocoa pod husk. Generally, research and pilot-scale pyrolysis has been undertaken at a rate of 28–300 kg/hour [10].

Table 2. *Technical performance of the plant*

Performance Criteria	Measurable Parameter		Value
Production Capacity Ratio	Design capacity(kg/hour) = 30	Actual production capacity (kg/hour) = 25	0.83
Reliability Ratio	Design operation time(hour/day) = 8	Average operation time(hour/day) = 8	1.00
Efficiency Ratio	Production capacityRatio = 0.83	Reliability ratio = 0.83	0.83

Table 3 shows chemical composition and calorific values of feedstock (elephant grass), biochar pellets and ash samples. The differences in the values of parameters for the three samples were significant. Carbon and calorific values were observed in increasing order: ash (3.29 ± 0.03% and 3.65 ± 0.02%) < elephant grass (88.46 ± 0.04% and 34.27 ± 0.01%) < biochar (91.87 ± 0.02 % and 35.37 ± 0.01 %), indicating responsiveness of carbon to high calorific and cooking values of the pellets obtained in this study. According to Johannes and Stephen [24], the carbon content of briquette charcoal could be varied from 80% to as high as 82% or above by adjusting the carbonisation condition, which depends on the amount and dryness of the feedstock. Biochar and ash gave lower values of sulphur (0.67 ± 0.0%; 0.64 ± 0.01%) contents respectively while elephant grass contained highest values of this element (13.28 ± 0.02 %). Low content of sulphur indicated good performance of the carboniser. Feedstock loses its smoke inside the carboniser during the pyrolytic process and so, biochar briquette does not have smoke and burns cleanly due to very low sulfur content [24].

Results of hydrogen and carbon contents in the samples showed similar characteristics as reported in earlier studies [26, 27]. As reported by FAO [28], hydrogen and carbon were primarily associated with plant organic matter and the degree of carbonisation was described by the H/C ratio. As carbon content of biochar increases, oxygen and hydrogen content decreases with increasing temperature. The energy content of biochar therefore depends on its feedstock which may reach 30 and 35 MJ /kg [29]. The calorific value obtained for biochar sample (35.37±0.01 kg/kg) fell in this range and was the highest among the three samples. This value is far higher than 3.8 kJ/kg obtained in a previous study by Odesola and Owoseni [24] from cocoa pod, using the Choi and Okos model.

Biochar can serve as substitute for traditional low efficient wood fuel that causes environmental degradation. Fuel wood covered nearly 90% of energy used in rural households and 40% of energy used in urban households [30]. In regions that rely on biomass energy, as is the case for most of rural Africa as well as large areas in Asia and Latin America, pyrolysis bioenergy provides opportunities for more efficient energy production than wood burning [31]. According to Johannes and Stephen [24], heating value of the biochar briquette varies from 7,150 to7, 300 kcal with a density of 970 kg/m^3 and since it has a good heating value and higher density while briquetting it burns for about 2–3 hrs while a stove can cook three meals at a time using 100 g biochar pellets.

Table 3. *Elemental composition and energy values of the feedstock, biochar and the ash (Mean ±SD)*

Parameters	Feedstock (Elephant Grass)	Biochar Pellet	Ash	F test	p value (= 0.05)
% Sulphur	1.38±0.01b	0.67±0.01a	0.64±0.01a	1.26	0.00
% Carbon	88.46±0.04b	91.87±0.02c	3.29±0.03a	3.67	0.00
% Hydrogen	3.28±0.02c	2.36±0.01b	0.46±0.03a	1.15	0.00
% Potassium	0.42±0.01a	0.82±0.03b	1.27±0.01c	404.17	0.00
% Nitrogen	0.89±0.00c	0.55±0.02b	0.45±0.01a	621.84	0.00
Calorific Value (kj/g)	34.27±0.01b	35.37±0.01c	3.65±0.02a	5.33	0.00

Different letters indicate significant differences along the rows

Table 4. *Selected heavy metal content of the feedstock, biochar and final ash (Mean ±SD)*

Parameters	Feedstock (Elephant Grass)	Biochar Pellet	Ash	F test	p value (= 0.05)
Pb (mg/kg)	0.29±0.03a	38.50±0.14c	21.81±0.04b	9.74	0.00
Cd (mg/kg)	0.06±0.01a	1.13±.01c	0.95±0.02b	2.83	0.00
Mn (mg/kg)	126.65±0.49c	62.00±1.13b	56.55±0.35a	5.53	0.00
Ni (mg/kg)	53.50±0.42c	47.45±0.21b	45.70±0.14a	410.22	0.00

Different letters indicate significant differences along the rows

As the biomass obtained is wildly grown, it may accumulate heavy metals from the immediate environment. Heavy metals were either found highest in either biochar [Pb (38.50 ± 0.14 mg/L) and Cd (1.13 ±.01 mg/L)] or elephant grass [Mn (126.65 ± 0.49 mg/L) and Ni (53.50 ± 0.42 mg/L)]. Biochar had higher values for the selected heavy metals than the ash as shown in Table 4. The mechanism that concentrated Pb and Cd in the biochar was rather a complex one yet to be understood. However, the main benefit of biochar production is that pyrolysis offers clean heat, which is needed to improve cooking technology [32]. Biochar also has lower indoor pollution than wood [33]. The fact that Mn and Ni values reduced in the ash resulting from the use of biochar might mean that part of the metals were released into the environment during the process. Increase in the values of Pb and Cd may probably be due to leaching from material used for the carboniser. More researches are required to substantiate this observation.

Table 5 reveals proximate analysis of the biochar pellets. Proximate analysis is the most often used analysis for characterizing coals in connection with their utilisation. As defined by ASTM International [21], proximate analysis separates the products into four groups: (1) moisture, (2) volatile matter, consisting of gases and vapors driven off during pyrolysis, (3) fixed carbon, the non-volatile fraction of coal, and (4) ash, the inorganic residue remaining after combustion. In order to widen the potential use of the biochar, results of nutritional related parameters like crude protein, crude fibre, ether extract need to be known. In a previous study, Chhay Ty et al. [34] linked these parameters to nutritive value of Mustard green (*Brassica juncea*). They concluded that though the dry matter content of leaves and stems was not affected by the nutrient value of biochar, the crude protein content of leaves and stem increased by 30% while the crude fiber decreased by 30% as the application of biochar was increased from zero to 5 kg/m^2. Elephant grass used in the present study may exhibit similar characteristics.

Table 5. *Proximate analysis of charcoal*

S/N	Parameters	Value
1	% Crude Protein	9.85±0.02
2	% Crude Fibre	31.49±0.02
3	% Ether Extract	2.96±0.02
4	% Ash	10.40±0.03
5	% Oxygen	2.85±0.02
5	% Moisture Content	11.05±.01

3. Conclusion

The carboniser developed was shown to be effective with less smoke and gaseous emissions. The values for chemical parameters varied among the samples with carbon, calorific values, two heavy metals (lead and cadmium), crude fibre and crude protein being highest in the biochar. By simply using a fabricated metal drum, all the agro and forest residues/waste could be burnt safely, removing carbon monoxide, while retaining carbon dioxide that cooks the food. The ash which is a by-product after use in the kitchen can be further used as pesticide or mineral fertilizer beneficial for enhanced crop production. This design and process will benefit less educated rural and peri-urban populations to develop small scale or medium scale entrepreneurship with low financial inputs and minimal skills. It will in turn also benefit rural women who are specifically dependent on forest based charcoal or any cheap fuel source for their cooking needs and put ordinary manure to farms for food production.

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