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Highlights:

- Sewage sludge biochar as a sustainable and safe heating fuel.
- Low environmental and health impact carbonized sewage sludge and saw-dust briquettes.

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Keywords: sewage sludge, Biochar, Burning characteristics, wastewater management, Potential Ecological Risk

ABSTRACT

Dried sewage sludge is an appealing biomass fuel for industrial kilns, because of its availability, affordability and has a positive effect on improving the symbiotic sustainable circularity of liquid waste treatment plants. The study investigated the fuel characteristics (efficiency, environmental and human safety) of biochar produced from sewage sludge for utilization as heating energy and compared the fuel performance to charcoal produced from wood sources using the Water Boiling Test method and X-ray Fluorescence Spectroscopy. Biochar briquette with equal ratio of carbonized sludge and wood shavings grants a solid fuel with good quality in terms of the burning rate (10.51 g/min.), specific fuel consumption (107.13 g/l) and emission levels of CO (59.64 g/kg of fuel) and $PM_{2.5}$ (4.76 g/kg of fuel). This fuel compared favourably with other biomass fuels used in Ghana. Also, no adverse impact on the environment and human health was observed in the use of the biochar with the low air quality index (35.23) recorded when the fuel is used in a well-ventilated cooking environment as well as showed low potential ecological risk (121.54) in terms

of the heavy metals in the residual ash when disposed of in the soil. The positive energy balance (2.35 MJ/kg) of the production is indicative the potential carbon savings.

1 INTRODUCTION

Energy consumption accounts for a large proportion (75.6%) of anthropogenic greenhouse gas emissions leading to global warming. Though energy poverty in sub-Saharan Africa is high and the region's total contribution to annual carbon dioxide ($CO_{2)}$ emission is among the lowest globally, the high dependence on woodfuel as a source of energy feedstock for cooking heating leads to significant depletion of global CO_2 sink. Approximately 2 billion people, mainly in mainly in Africa, Latin America and Asia, rely on fuelwood, charcoal, or animal waste for cooking and heating (Department of Economic and Social Affairs 2017). Traditional sources of energy feedstock like biomass continue to play a significant supplementary role in the energy requirements of most developing countries like Ghana.

Biomass is any potential renewable energy resource obtained from living or recently living organisms (Kemausuor, et al. 2014) (Fernande and Costa 2010). Biomass used for cooking and heating acts as a net zero addition to the carbon cycle because it absorbs CO_2 during growth and releases it in combustion (Oduro, et al. 2019). Thus, it is a relatively cleaner source of energy than coal and fossil fuels (Mengesha, Angassa and Fito 2022).

Biomass, however, has a relatively low energy density because of high volatile matter content, high moisture content and low fixed carbon, which may reduce thermal efficiency during plant operation (Jeong, Lee and Kim 2020). The energy quality of the biomass can thus, be improved significantly through the carbonization of biomass to produce charcoal. Carbonization is the thermochemical process of biomass treatment under low oxygen and slow heating conditions to reduce the content of moisture and volatile matter. The resulting solid product, biochar (charcoal from biological sources) is the preferred source of household cooking fuel. This is because of the significant reduction in exposure to particulate matter associated with the smoke density when charcoal is used instead of non-carbonized biomass.

In Ghana, for example, 44% of urban households use charcoal as their primary fuel for cooking (Ghana Statistical Service 2019) and its consumption is expected to increase from 773 ktoe in 2020 to 905 ktoe in 2030 (representing an annual average growth rate of 1.6%), due to the expected continuous reliance on woodfuel for cooking and increase in the number of urban households

(Energy Commission 2021). This may have a huge impact on the environment and reverse gains in climate mitigation action aimed at addressing global warming if the sources of biomass are not diversified to include other regenerative sources.

The design of environmentally resilient energy systems, therefore, requires technological solutions that diversifies energy feedstock by exploiting other regenerative carbon sources to prevent overreliance on traditional biomass feedstocks. Various types of biomasses such as agricultural crop residues, forest residues, wood waste, organic portion of municipal solid waste (MSW) and animal manures have been proposed as feedstocks for biochar production (Akolgo, et al. 2018). Sewage sludge, a product from the treatment of municipal liquid waste can be a sustainable source of biomass. Dried sewage sludge is an appealing biomass fuel for industrial kilns, as its availability does not fluctuate seasonally, it does not have an established market value (Ward, Tesfayohanes and Montoya 2014), its use does not require the removal of natural carbon sinks, and has a positive effect on improving the symbiotic sustainable circularity of liquid waste treatment plants. The industrial waste from the liquid waste treatment plant (stabilized faecal sludge) becomes a valuable starting material for a biochar production plant.

The production of biochar from sewage sludge has attracted the attention of researchers in its use as a sustainable source of biomass for the production of biofuels (Bora, Gupta and Durbha 2020). However, sewage sludge by its nature, even after mechanical dewatering processes has very high moisture content and therefore requires significant heat treatment to realise an attractive heating value and merit application as a heating energy feedstock. Also, some chemical constituents of sewage sludge raise concerns about its suitability as a sustainable energy feedstock. It has noxious substances in its composition that releases offensive odour during combustion as well as heavy metals that may raise environmental concerns from uncontrolled disposal of residual ash. There is therefore, a need to assess the net positive energy credential of the process of producing biochar for fuel using sewage sludge and well as the environmental safety in its use.

Biofuels are characterized by their calorific value, elemental composition, ultimate and proximate analysis. The calorific value represents the main economic value of thermal fuels. Ash and moisture do not present any economic importance and are valueless; high contents increase transportation costs and reduce combustion efficiency. Thus, ultimate and proximate analyses indicate fuel performance as well as CO, and $PM_{2.5}$ emissions (Hafford, et al. 2018).

The study seeks to investigate the fuel characteristics (efficiency, environmental and human safety) of biochar produced from sewage sludge for utilization for energy purposes and compares its performance to typical woodfuels such as charcoal produced from neem. It also investigates the effect of co-carbonization of sludge with wood shavings for optimum fuel efficiency.

2 MATERIALS AND METHODS

2.1 Materials

Sewage sludge was obtained from the Mudor liquid waste treatment plant of the Sewerage Systems Ghana Limited (SSGL) situated in Accra which treats liquid waste comprising mainly faecal matter in a central sewer system in Accra, Ghana. The sludge was carefully collected to avoid collecting sand from the drying bed so as not to compromise the composition of the sludge into sacks. The sludge was then transported to the Council for Scientific and Industrial Research – Institute of Industrial Research (CSIR-IIR).

Wood shavings from a mixture of lumber species were collected from the waste dumping section of a wood processing plant and air dried to a moisture content of 5 wt./wt. % before storing in a polythene sack.

Cassava starch was procured and used as a binder without further treatment. Charcoal produced from neem (*Azadirachta indica*) was procured from the market and used without further treatment. Shea butter waste, coconut husk, groundnut shells, sugar cane bagasse, palm kernel shells, and coconut shells were sourced from agro-processing factories in Ghana. Commonly used wood-based fuels in Ghana were procured and used without any further treatment. Corn stalk, millet straw, corn cobs were sourced from farms in the Bono region in Ghana. Kenaf, dried bamboo and neem wood were sourced from the Eastern region of Ghana. The saw dust pellets were procured from Makers Arc Ghana Limited.

2.2 Methods

2.2.1 Carbonization

The thermal conversion of the biomass into biochar was carried out using a locally constructed liquefied petroleum gas (LPG) fired batch kiln (Fig. 1). The sun-dried sludge was dried to a constant weight in an LPG fired oven. About 0.1 kg of LPG was used to dry 20 kg of sludge at 105± 20 °C to a uniform moisture content of 6%. The total energy required for drying was calculated as 5,500 kJ.

The dry biomass material (lumpy sewage sludge or wood shavings) was loosely packed into a 0.038 m^3 stainless steel basket to allow for heat transfer through the packed bed of biomass material during the combustion process. The packing density of the sewage sludge and the wood shavings were 526.35 kg/m^3 and 263.16 kg/m^3 respectively. The temperature of the packed bed was maintained at 600 °C in an inert environment for 2 hours. The temperature in the carbonization chamber as well as the biomass bed, were observed to evaluate the conversion process with two K-type thermocouples. One was placed at the central top part of the biomass bed to measure the temperature of the biomass at the coldest possible part and the second thermocouple placed in the reactor, outside the biomass bed, at an equidistance from the bottom of the reactor where the heating source was applied. The reactor was heated at a heating rate of 15 °C per min. After 2 hours, the heating source was turned off and the samples were allowed to cool whilst in the reactor for about 48 hours to temperatures below 40 °C before removal and storage. The carbonized sludge (CS) and the carbonized wood shavings (CSD) were stored separately in polyethylene bags, labelled, and kept in a cool but dry environment.

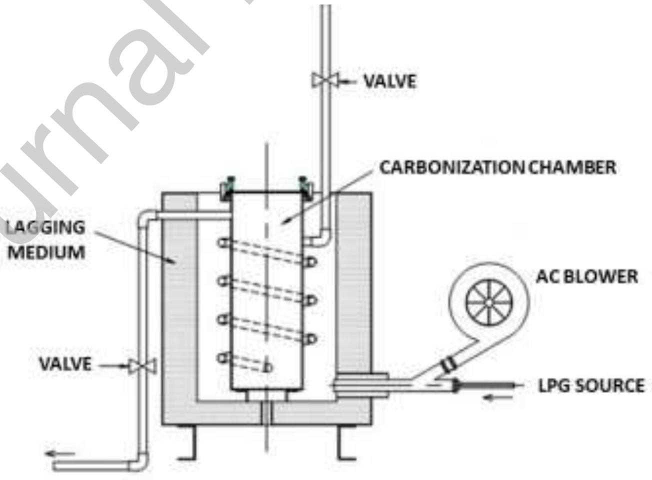

Fig. 1 Carbonization rig for the conversion of sludge to biochar

2.2.2 Formulation and briquetting

Studies have shown that the combination of diverse biomass materials can improve the quality of the compacted briquettes (Cui, et al. 2021). To improve the energy density of the biochar, a briquette formulated from a composite of carbonized sludge enriched with carbonized wood shavings was explored. Wood shavings are a by-product of wood processing industries in Ghana and was explored to enrich the carbon content of the sewage sludge. The effect of the different carbon enrichment of the biochar from sludge was investigated.

In a typical formulation, 5 g of cassava starch was added to 100 ml of water and cooked to gelatinize. Cassava starch was used because it is widely available as an industrial binder in Ghana, and it is also locally produced. 247.5 g of CS and 247.5 g of CSD was weighed accurately and added to the gelatinized cassava starch solution and mixed thoroughly to achieve a uniform wetting. 40 g of the mixture is placed into a cylindrical metal mould lubricated with automotive engine oil and pressed with a forming pressure of 2 bars using a hydraulic press. The briquette was demoulded and air dried to a constant weight to obtain a biochar composite of ratio 1:1 of thickness 20 mm and length 60 mm. The size of the mould was chosen to reflect approximately the standard size of wood charcoal on the Ghanaian market.

Table 1 shows the ratio of carbonized sewage sludge (CS) and carbonized wood shavings (CSD) in the composite biochar.

Table 1 **Composition of the composite biochar**

Weight of CSD (g)	Weight of CS (g)	Weight of binder (g)	CSD:CS
165.0	330.0	5	1:2
247.5	247.5	5	1:1
297.0	198.0	5	3:2

2.2.3 Elemental analysis of biochar

The elemental composition of the as produced biochar was investigated using an Oxford Twin-X x-ray fluorescence (XRF) spectrophotometer. The elemental composition from Na to Ca was conducted in a helium environment at 5 kV voltage and a current of 600 µA using a Focus 5 detector. The elemental composition from Sc to U was conducted in an air environment at 5 kV voltage and a current of 90 µA using a Focus 5 detector.

2.2.4 Proximate analysis of the biochar

Moisture content

The moisture content (MC), Ash content (Ash), Volatile Matter (VM) and Fixed Carbon (FC) were determined using the ASTM International Test method for chemical analysis of wood charcoal (ASTM D1762-84 2021).

2.2.5 Physical characteristics of the biochar fuel

Density

The density of the biochar briquettes as produced were determined using ASTM method for density by displacement (ASTM D792 2002).

Hardness

The hardness of the briquette was determined using the Izod impact test (ASTM D256 2023) without a notch.

2.2.6 Fuel Characteristics of the biochar

Water Boiling Test

The Water Boiling Test protocol 4.2.3 was used to evaluate the fuel characteristics. It is intended to measure how efficiently a stove uses fuel to heat water in a cooking pot and the quantity of emissions produced. The fuel characteristics considered in this study included the specific fuel consumption, burning rate and firepower. The burning rate is defined as the amount of fuel consumed per unit time (g/min), the Firepower (W) is defined as the amount of energy released by the burning fuel consumed per unit time.

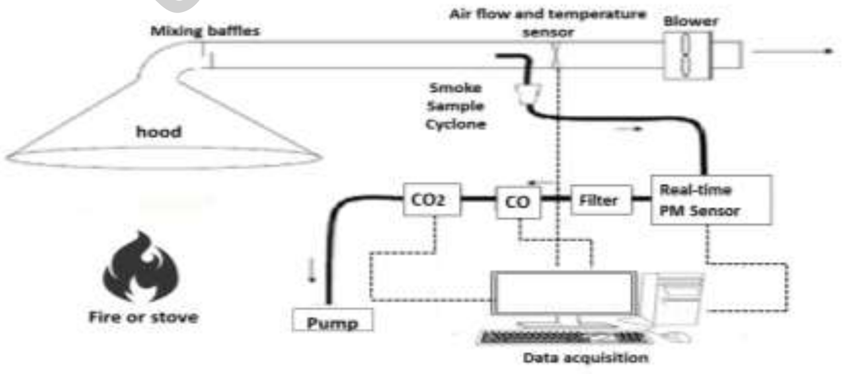

Fig. 2 Experimental Set up of the Laboratory Emissions Monitoring System (Clean Cooking Alliance 2014)

To estimate the fuel characteristics, the dry weight of a clean stainless-steel pot was recorded. 5 kg (5 l) of room temperature water was measured into the pot. A predetermined mass of biochar was weighed to be used for the test. The weight of the stove together with the biochar was also recorded. The pot was placed on the heat source with gradual temperature elevation until the water reached boiling point (Fig. 2). The time for water to reach boiling point was recorded. The pot was then removed from the heat source and the remaining fuel was weighed as well as the residual ash. The test was repeated three times to ensure accuracy and thermometer consistency.

The Laboratory Emissions System (LEMS) included hardware, documentation, and software that allowed the collection of real- time emissions data (CO, CO_2 and $PM_{2.5}$) directly on a PC and processing of data to determine the emission factor in g/kg of fuel (Clean Cooking Alliance 2014). All the wood-based fuels were tested using the same protocol as the biochar.

Uncontrolled Cooking Test

Uncontrolled cooking test (UCT) was used to measure carbon savings and emission characteristics in using the biochar as a source of heating fuel (Robinson, Ibraimo and Pemberton-Pigott 2011). The UCT was used because it provides a basis for comparing the biochar with other baseline fuels such as charcoal from wood sources which is sold in the open market. A cook was asked to prepare a local staple of boiled cowpeas stewed in palm oil with fried ripe plantains using charcoal and biochar as fuel on the same cookstove. 2.0 kg each of both charcoal and biochar were weighed to be used for the test. The cookstove that was used for the cooking was also weighed. The quantity and weight of all the ingredients comprising cowpeas (1.0 kg), ripe plantain (0.7 kg), palm oil (0.5 kg), soyabean oil (0.45 kg) and water (3.5 kg) as well as the stainless-steel cooking pot (1.02 kg) were recorded. Same measures of the ingredients for were used for replicates and both the charcoal and biochar studies. Kitchen ambient conditions of temperature ($32 \pm 1\ ^{o}C$), relative humidity (67 ± 3%) and wind speed (≤0.2 m/s) are noted using the Indoor Air Pollution (IAP) monitor. Kerosene (0.02 kg) was used as a fire starter. The time for the fuel to ignite and the start time for the cooking i.e. when the pot was placed on the cookstove was recorded. The cook was left to prepare the meal with the IAP mounted on her back and the nozzle positioned close to the nostril. The time for preparing the meal and the weight of the cooked food was noted. The cookstove and fire were weighed first, then the fire poured out and any burning fuel was extinguished. The ash was placed in a heat proof container and weighed. Any remaining fuel (unburnt) was also weighed. Emissions data from the IAP were also studied.

Calorific value

The calorific value was determined by a bomb calorimetry method using benzoic acid sample as a standard (ISO 18125 2017).

3 RESULTS AND DISCUSSIONS

3.1 Packed bed carbonization process

The carbonization process causes the decomposition of sewage sludge into char, moisture and volatile organic compounds (Haridan, et al. 2020) through the breakdown of the chemical bonds in an organic material.

The inorganic materials component of the sludge i.e. sand and heavy metals, therefore, cannot be removed from the char during the carbonization process. Thus, though the concentration of carbon in the materials is realized due to the decreasing volume of samples during carbonization, a high concentration of ash is also obtained. Optimizing the heat and air flow during carbonization is therefore key in realizing the optimum energy density (high fixed carbon content) of the solid fuel. The variation of temperature with time conversion of sludge to biochar during the carbonization process is presented in Fig 3.

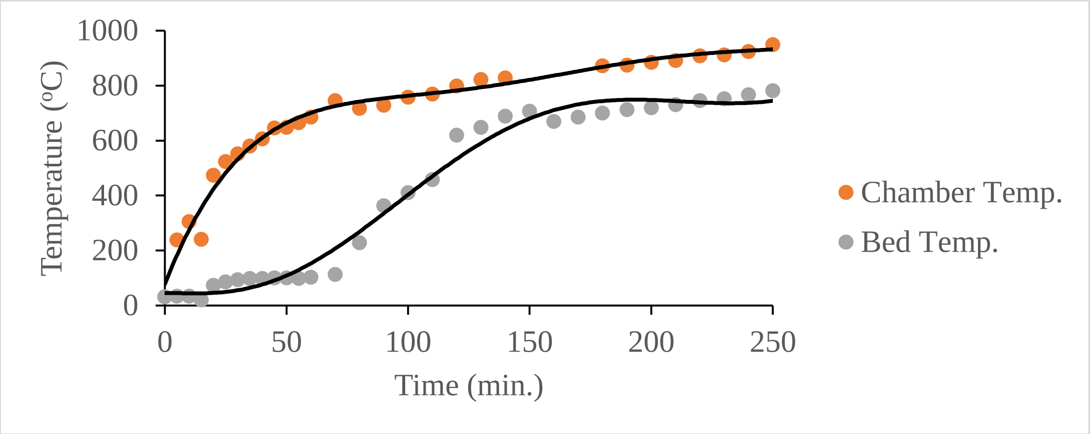

Fig. 3 **Temperature time variation in the carbonization process showing different phases in the materials state of the sewage sludge bed.**

The variation in the area under the temperature time curves (Fig. 3) represented by the area between the two curves, shows the cumulative heat difference between the heating chamber and the biomass bed. Four phases of the carbonization process were observed (Fig. 3). The drying phase (27 ^{o}C to 100 ^{o}C) shows latent heat which represents a loss of moisture over a period of 60 mins. This is followed by the steady ascent in the biomass bed temperature, from 70 mins to 150 mins, showing the carbonization phase (with temperature rising from 103 ^{o}C to 707 ^{o}C). This is indicative of the exothermic phase of spontaneous carbonization process. The third phase shows a second latent heat curve which represents a change in state of the biomass (lignocellulosic matter) to biochar (carbon). This phase is noticed from 150 mins to 210 mins. The final phase is the very gradual rise in the temperature after 210 mins. It is indicative of a transition from char to ash (not desirable). The lag between the bed temperature and the chamber temperature shows heat transfer issues from the heating chamber to the core of the bed. This suggests poor thermal conductivity of the biomass bed. Thus, a more porous packing density may be desirable in achieving better carbonization with minimum energy. This also infers that the carbonization processes using the packed bed method may not be the most efficient in terms of energy usage. A continuous material flow method using a screw conveyor could be more ideal as the thin material layer will allow better heat flow and faster carbonization. To make the process more energy efficient in a packed bed batch reactor system, slower heating rate (around 2 ^{o}C/min) may be most ideal in the first phase (drying of the material) then ramping the heating rate to 10 ^{o}C/min to attain 600 ^{o}C before and maintaining the carbonization at 600 ^{o}C for 120 mins.

3.2 Proximate analysis and calorific value of sludge biochar with variations with carbon enrichment

The general trend observed was that the temperature in the carbonization process reduces both moisture and the volatile matter of the biochar whilst increasing the fixed carbon content which is ideal for solid fuels. High moisture and volatile matter content in solid fuels leads to the emission of smoke (particulate matter < 2.5 µm) during combustion (Price-Allison, et al. 2023) (Chomanee, et al. 2009) thus, posing health risks in the use of the fuel. The ash content also increases with processing temperature which is a result of the concentration of the inert content of the sludge during carbonization. The high ash content is inimical in the use of solid fuels as it reduces the concentration of fixed carbon available for combustion to release energy as well as producing slag. The calorific value of the raw sludge (13.85 MJ/kg) used in this study, though low, possesses burning characteristics to provide some heating properties. Though carbonization improves the fuel quality of the biomass with respect to all the proximate parameters except the ash content (Table 2), briquette from carbonized sludge alone will need some modification to improve its fuel performance to match existing wood charcoal sources in the market. Studies have shown that the combination of diverse biomass materials can increase the quality and economic viability of the compacted briquettes (Bot, et al. 2022). The fixed carbon content of the biochar from sewage sludge was thus improved by adding carbon from carbonized wood shavings. This significantly improved all the proximate parameters of the composite biochar as shown in Table 2. Adding wood shavings to the sludge to produce biochar briquettes significantly improves the fuel value of the biochar as indicated in Table 2 with about three-fold improvement in the fixed carbon compared to the dried sewage sludge (from 6.36 % to 19.03 %).

Table 2 Effect of carbonization temperature and carbon enrichment on proximate parameters of biochar

Sample	Mean ± Standard Deviation			Fixed carbon (%)	NCV (MJ/kg)
	Moisture Content (%)	Volatile Matter (%)	Ash Content (%)		
Dried sludge	8.21 ± 0.48^{a}	59.56 ± 3.16^{g}	31.65 ± 1.21^{p}	0.58	13.84

Carbonized sludge 400 °C	3.61 ± 0.29^{d}	38.94 ± 2.31^{h}	55.31 ± 2.13^{m}	2.14	11.41
Carbonized sludge 600 °C	1.55 ± 0.14^{f}	27.21 ± 4.80^{k}	64.88 ± 2.94^{l}	6.36	11.13
Carbonized sludge 800 °C	1.42 ± 0.22^{f}	19.66 ± 4.80^{k}	71.36 ± 4.80^{l}	7.56	11.13
CSD:CS 1:2 at 600 °C	4.88 ± 0.05^{b}	30.48 ± 0.12^{j}	51.90 ± 0.20^{n}	12.74	11.24
CSD:CS (1:1) at 600 °C	2.38 ± 0.33^{e}	37.20 ± 0.57^{h}	45.24 ± 0.38^{o}	15.18	10.50
CSD:CS (3:2) at 600 °C	4.23 ± 0.07^{c}	33.51 ± 0.12^{i}	43.23 ± 0.22^{o}	19.03	10.31

NB. Numbers followed by different letters are statistically different p= 0.05

3.3 Elemental analysis of the biochar

Faecal sludge has been known to have high levels of heavy metals because humans are high on the food chain and tend to bioaccumulate these elements (Ali, Ezzat and Ikram 2019) (Hejna, et al. 2018). Heavy metals pose significant health and safety risk in solid fuels as they concentrate in the ash content representing environmental danger because of poor disposal of the ash. Also, metals like iron can occasion pyrotechnic effects at higher concentrations during high temperature burning, increasing the fire hazard with the use of the fuel. Hence, the designing of a high quality and safe solid fuel must be considered with careful monitoring of the levels of heavy metals. The high sulphur content in the raw sludge and in biochar high composition of CS (Table 3) results in the release of fetid odour from burning of fuels. The fetid odour, however, subsides as the CS is diluted with CSD. The high ash content in the fuel (Table 2) can be attributed to the high SiO_2 and Al_2O_3 concentration. The presence high quantities of ash in sewage sludge has been reported in most sewage treatment plants (Ahmad, Ahmad and Alam 2017), (Merino, Arevalo and Romero 2005) and it is attributable to sand, silt and clay that infiltrate the sewerage systems.

The major mineral component of the biochar is silica and alumina. Silica alumina concentrations increased from 50.21% wt/wt. in the dry sludge to 63.8% wt./wt. when carbonized at 600 °C. Carbonized wood shavings however, had silica alumina content of about 27%. Therefore, mixing CS with CSD can achieve a silica and alumina content of between 57% and 59% thereby enriching the fixed carbon content.

Table 3 Elemental Analysis of sludge and biochar

Conc.	**Element**	**S**	**CS**	**CSD**	**CSD:CS (1:2)**	**CSD:CS (1:1)**
Major (%wt./wt.)	Al_2O_3	0.74	1.21	0.71	2.19	0.16
	SiO_2	9.40	13.66	1.86	20.24	2.34

	Fe_2O_3	1.29	2.45	0.55	3.68	3.22
	S	1.66	0.69	0.17	0.38	0.48
	P_2O_5	0.26	0.27	0.13	0.28	0.15
	Cl	5.04	6.46	9.23	13.34	4.63
	K_2O	5.03	7.76	10.93	9.38	6.30
	CaO	3.83	5.90	11.26	8.69	5.65
Minor (ppm)	Ti	3178.00	3259.00	2887.00	2975.00	3112.00
	Mn	147.00	572.00	bdl	901.00	693.00
	Cu	213.90	219.00	138.60	215.40	219.00
	Zn	773.50	708.00	206.90	625.60	625.20
	Ga	1284.10	1019.80	333.90	800.00	777.10
	As	44.00	32.30	48.40	bdl	14.10
	Pb	20.00	30.00	20.00	30.00	30.00
	Bi	56.30	44.60	76.40	33.60	36.50
	Th	13.00	19.30	17.20	22.30	21.20

The concentrations of potentially hazardous heavy metals like As and Pb were relatively lower, averaging 31.60 ± 17.16 ppm and 26.00 ± 5.50 ppm respectively.

3.4 Effect of Co-carbonization process

Burning characteristics of a fuel play a key role in user acceptability and safety. Some key features of a good quality solid fuel include moderate burning rate, high firepower (calories), low specific fuel consumption and low emissions in terms of CO and smoke (particulate matter). Typical biomass sources used as fuel in Ghana has notable burning rate that averages around 12 g/min and firepower that averages around 3500 W, as depicted in Fig. 4 and Fig. 5. Factors such as density of the biomass account for higher burning rates, as is typical of the less dense straw-like fuels (sugar cane bagasse, millet stalk and corn straw) as compared to the denser fuels (woody and charcoal from woody plants). Hence, it is projected that for the biochar to receive wider user acceptability, based on common cookstove devices on the market, the targeted burning rate and firepower of the fuel should be in the range of 5-20 g/min and 2 -5 kW respectively.

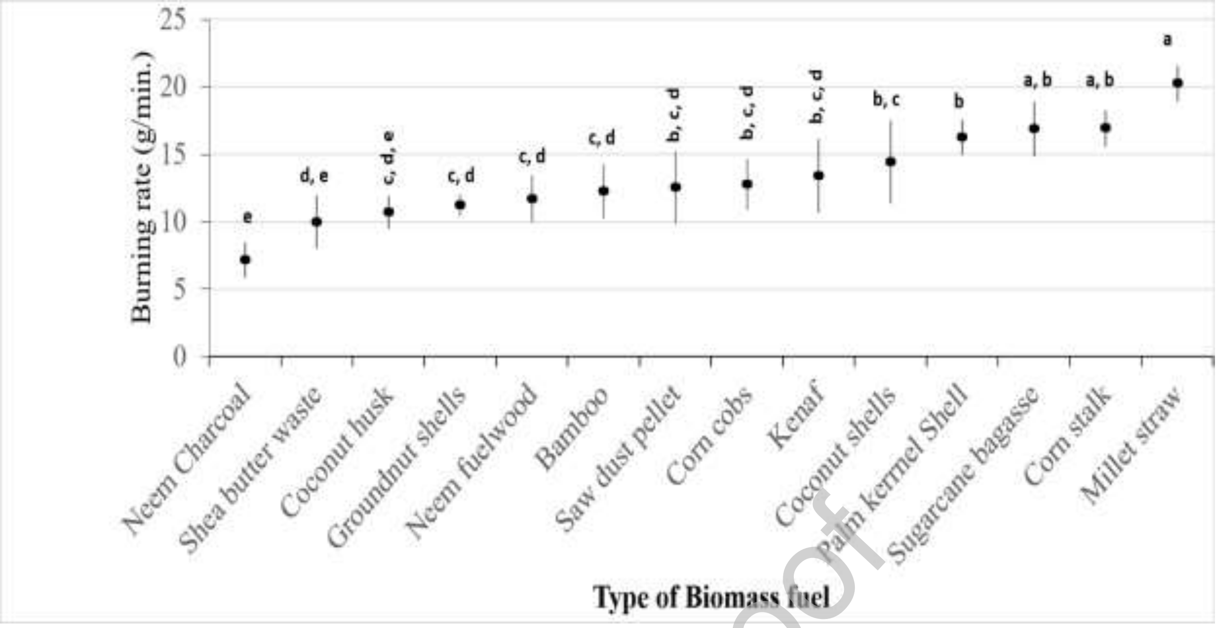

Fig. 4 **The mean ± SD burning rate (g/min) of typical biomass fuels in Ghana with significant difference (p=0.05) indicated by different alphabets**

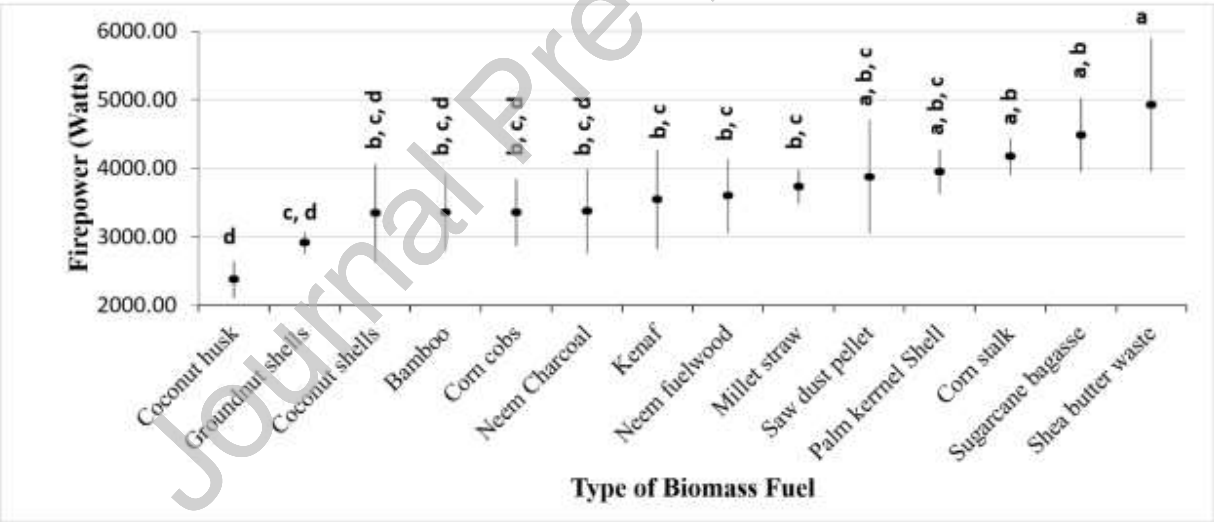

Fig. 5 **The mean ± SD Firepower (W) of typical biomass fuels in Ghana with significant difference (p=0.05) indicated by different alphabets**

The energy and burning characteristics of the fuels are presented in Table 4. The sludge alone was observed to have a lower burning rate. A similar observation was reported by (Hafford, et al. 2018) Biochar briquette with equal ratio of carbonized sludge and wood shavings presents superior quality solid fuel in terms of the burning characteristic (burning rate, specific fuel consumption, firepower) and emission levels (CO and $PM_{2.5}$).

Table 4 Burning characteristics of the sewage sludge-wood shavings composite biochar in a controlled environment

Burning characteristics	**Charcoal**	**CS**	**CS:CSD**	
			1:1	2:1
Burning rate (g/min)	4.84	6.74 ± 0.01	10.51 ± 1.62	8.50 ± 1.37
Specific Fuel Consumption (g/l)	36.76	199.9 ± 11.36	107.13 ± 9.29	142.98 ± 46.51
Firepower (kW)	2.277	1.88 ± 0.01	3.80 ± 0.59	3.45 ± 0.56
CO (g/kg of fuel)	176.6	196.45 ± 28.50	59.64 ± 12.45	215.48 ± 42.17
CO_2 (g/kg of fuel)	2186.6	1837.5 ± 0.01	1739.67 ± 19.63	1495.00 ± 66.36
$PM_{2.5}$ (g/kg of fuel)	2.71	23.02 ± 9.75	4.76 ± 0.50	22.95 ± 1.93
Density (g/cm^3)	0.6	1.33± 0.03	0.73 ± 0.03	0.810 ± 0.02
Hardness (MJ/m^2)	10.58	15.89± 2.03	6.902 ± 2.45	10.33 ± 4.54

3.5 Ecological Risk assessment of biochar as a source of fuel.

The UCT provided a basis for comparing the biochar with charcoal from wood sources which is sold in the open market (Robinson, Ibraimo and Pemberton-Pigott 2011). Though the total fuel consumed using biochar was about three times higher than wood charcoal (**Table 5**) the carbon from charcoal in cooking the meal could be considered saved when cooking is done with the biochar as it comes from a regenerative source. The emission levels are also comparable to wood charcoal which makes it safe to use in a well-ventilated cooking environment. The classification of Air Quality Index (AQI) in the United States considers levels between $0 \leq AQI \leq 50$ as good, $51 \leq AQI \leq 100$ as moderate, $101 \leq AQI \leq 150$ as unhealthy for sensitive groups, $151 \leq AQI \leq 200$ as unhealthy, $201 \leq AQI \leq 300$ as very unhealthy and $301 \leq AQI \leq 500$ as hazardous (U.S. Environmental Protection Agency 2018). Thus, an average AQI value of 35.32 compares favourably with wood-based charcoal (AQI 30.82) and could be classified as good and therefore not have adverse effects on users when used within a well-ventilated kitchen environment.

Table 5 **Uncontrolled Cooking Test of combustion and emission characteristics of biochar from sewage sludge and wood shavings compared with wood charcoal (neem)**

Fuel characteristics	Biochar CS:CSD (1:1)	Wood Charcoal	Standard (*WHO and **USEPA)
Total weight of ingredients cooked (kg)	6.15	6.15	
Weight of stainless-steel cooking pot (kg)	1.02	1.02	
Total Fuel Consumed (g)	2500	810	
Ash Content (%)	34.06	2.0	
Total Carbon (g)	1690	790	
Time to cook (min.)	190.8	128.4	
Burning rate (g/min.)	6.01	4.29	
Emission rate CO (mg/m^3)	13.9	17.3	35.0 mg/m^3 *
Emission rate AQI	35.23	30.82	50.0 **
Density (kg/m^3)	242.83	180.0	

NB **WHO for 1 hr continuous exposure* (WHO 2010)

*** US EPA is from the United States Environmental Protection Agency air quality scale* (U.S. Environmental Protection Agency 2018).

Table 6 Mineral and elemental composition of residual Ash from the biochar

Conc.	Element	Ash (C_n)	Max levels in polluted soils (WHO, 1996)	EU limit in soil (F_n)	$C_f = C_n/F_n$	T_f	$E_i = T_f . C_f$	PER
Major (%wt./wt.)	Al_2O_3	4.42 ± 0.10						
	SiO_2	27.78 ± 3.92						
	Fe_2O_3	3.09 ± 0.08						
	S	1.66 ±0.02						
	P_2O_5	0.27 ± 0.01						
	Cl	7.14 ± 0.94						
	K_2O	12.15 ± 1.49						
	CaO	13.79 ± 0.43						
Minor (mg/kg)	Cr	619.00 ± 62.52	100 [a]	170	3.64	2	7.28	Low
	Mn	77.54 ± 2.02	740 [a]	1800	0.04	1	0.04	Low
	Cu	219.8 ± 0.3	100 [a]	50	21.98	5	109.9	Considerable
	Zn	636.6 ± 41.3	300 [a]	350	1.82	1	1.82	Low
	As	0.8 ± 0.3	20 [a]	15	0.03	10	0.3	Low
	Pb	40.0 ± 0.0	100 [a]	200	0.44	5	2.2	Low
PER							121.54	

[a] Is the WHO maximum allowable limits of heavy metals in polluted soils (WHO 1996).

In the assessment of the risk in using the biochar as a fuel source, another hazard identified is the disposal of the residual ash after the use of the biochar in heating. Typically, ash from combustion of biomass will be disposed of together with other municipal solid waste which may end up in recycling plants to produce compost or in landfills. The choices of disposal methods influence the ecology, which has to be investigated to advise the biochar lifecycle evaluation.

An assay of the elemental composition of the ash identifies some heavy metals. Though Cu (219.8 mg/kg) and Zn (636.6 mg/kg) may be essential as plant nutrients, higher concentrations may pose toxicity risk. Other toxic heavy metals components detected in the ash include As (0.8 mg/kg), Cr (619 mg/kg), Mn (77.54 mg/kg) and Pb (40 ppm) as shown in Table 6. The Potential Ecological Risk (PER) of the ash of the biochar was determined using the equation 6 below to be 121.54.

$$PER = \sum_{i=1}^{n}(E_i) \qquad \text{Equation 6}$$

E_i is (Ecological risk factor of each metal).

$$E_i = T_f \times C_f \qquad \text{Equation 7}$$

T_f is metal toxic response factor and C_f is the single metal pollution index. (Hakanson 1980)

$$C_f = {}^{C_n}/_{F_n} \qquad \text{Equation 8}$$

F_n is the background concentration in the soil which was adopted as the European Union maximum tolerable limits in soils for agriculture. The contamination factor, C_n is the concentration of metal in the ash.

Ei < 40 low, 40 ≤ Ei ≤ 80 moderate, 80 ≤ E_i ≤160 considerable, 160 ≤ E_i <320 high and E_i ≥ 320 very high ecological risk assessment (Jahandari 2020), (Hakanson 1980) and (Hua, et al. 2018).

Though the PER of Copper was considerable in this study, previous studies have shown that liming soils can have ameliorative effect in heavy metals uptake by plants or the mobility of the metals in the soil (Tlustos, et al. 2006) (Fang and Wong 1999). The ash itself has a pH of 7.5 and thus will reduce its availability in the soil for adsorption by plants.

The potential ecological risk for *PER* is divided into four classes: low potential ecological risk (PER ≤ 150), moderate potential ecological risk (150 < PER ≤ 300), considerable potential ecological risk (300 < PER ≤ 600), high potential ecological risk (PER > 600) (Yesilkanat, Mert and Kobya 2021).This shows the ash poses low potential ecological risk when disposed of in the soil.

3.6 Estimation of net energy derived

The net energy derived from the biochar was computed as a difference between the energy output (E_o) and energy input (E_i)

$$Net\ Energy = E_o - E_i \qquad \text{Equation 8}$$

Energy used for drying 10 kg of dried sewage sludge and 10 kg of wood shavings at 105± 20 °C for 2 hours was 0.1 kg of LPG estimated as 5.5 MJ. 2.5 kg of LPG was used to carbonize 10 kg of sewage sludge and 10 kg of wood shavings was equivalent to 137.5 MJ. The mixing of the carbonized biomass and the binder was done with a mechanical stirrer with a 0.746 kW motor operating for 10 minutes. The hydraulic press is equipped with a 1.86 kW motor operated for 20 minutes. The net calorific value of briquettes CSD:CS (1:1) produced was 10.5 MJ/kg. Hence, as shown in Table 7, the net energy derived from processing the sewage sludge and wood shavings was estimated to be 2.35 MJ/kg of biochar briquette.

Table 7 Energy balance for the conversion of sewage sludge and wood shavings to fuel briquettes

Energy requirements	Energy input (E_i)	Energy Output (E_o)
Energy for drying biomass (MJ/kg)	0.28	
Energy for carbonization (MJ/kg)	7.7	
Energy for stirring for 10 minutes (MJ/kg)	0.022	
Energy requirement for hydraulic press machine for moulding (MJ/kg)	0.112	
Energy for preparing 200 g of binder (MJ)	0.036	
Net calorific value of briquette (MJ/kg)		10.50
Total Energy (MJ/kg)	8.15	10.50
Net Energy (E_o-E_i) (MJ/kg)		2.35

4 CONCLUSIONS

Biochar briquette with equal ratio of carbonized sludge and wood shavings grants a solid fuel with good quality in terms of the burning rate (10.51 g/min.), specific fuel consumption (107.13 g/l) and emission levels of CO (59.64 g/kg of fuel) and $PM_{2.5}$ (4.76 g/kg of fuel). This fuel compared favourably with other biomass fuels in use. The net energy derived from processing the sewage sludge and wood shavings to produce biochar briquette with a net calorific value of 10.5 MJ/kg was estimated to be 2.35 MJ/kg. The positive energy balance is indicative the potential carbon savings. Also, no adverse impact on the environment and human health was observed in the use of the biochar with the low air quality index (35.23) recorded when the fuel is used in a well-ventilated cooking environment as well as showed low potential ecological risk (121.54) in terms of the heavy metals in the residual ash when disposed of in the soil.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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