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Physical and Emission Properties of Blended Bio-Coal Briquettes Derived from Agro-Wastes in Nigeria

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A B S T R A C T

Nigeria has one of the highest deforestation rates in the world, due mainly to felling of trees for fuelwood and charcoal production. This challenge could be managed if agricultural waste briquettes are used to augment the fuelwood demand for cooking energy provisioning. Energy density of biomass fuels can be raised by blending with coal, but particulate matter emissions are also increased in the process. Therefore, some physical and fuel properties of briquettes produced from blends of corn cob and palm mesocarp fibre (PMF) with Sub-bituminous coal from Onyeama mine, using cassava starch binder were studied. Blending ratios were varied from 0% to 100% biomass. After briquetting in a hydraulic press, drying and characterization, Water Boiling Test (WBT) of the briquette samples was performed using Laboratory Emissions Measuring System (LEMS). Results showed that average High-Power Thermal Efficiency was 28.8% for corn cob/coal and 26.0% for PMF/coal briquettes, but High-Power CO emissions decreased from 10.8 mg/MJd to 8.9 mg/MJd (8.31-6.90 ppm) as the composition of corn cob increased from 0% to 100%. Corn cob/coal briquettes produced lower PM emissions than pmf/coal, although both were above the WHO recommended limits.

1. Introduction

Millions of households in Nigeria rely on the traditional use of firewood for their daily cooking needs. This practice has persisted in spite of the fact that smoke from cooking fire causes over 95,000 deaths in Nigeria annually [1]. It is the third biggest killer after malaria and HIV/AIDS in Nigeria [2]. Majority of poor families using three-stone fire spend much of their food budgets on wood and charcoal; others spend hours collecting wood. Inefficiency in the combustion of wood in open three-stone fires raises the cost of cooking for the poor and contributes to high level of deforestation. Nigeria lost about 2.3% of her forest reserves between 1990 and 2010 [3].

The use of bio-coal briquettes as cooking fuels, especially in improved cookstoves, could provide a solution to the afore-mentioned health and deforestation problems [4] and help cut down on the consumption of fossil fuel [5]. Research has shown that blending coal with biomass to produce briquettes helps to ameliorate the emission problems thus result in anenvironmentally friendly briquette with better combustion and physical characteristics [6].

Nigeria has a large deposit of coals, which are mostly sub-bituminous and lignitic formations. With the exception of the

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Lafia coal, which is partially coking [7], these coals are non-coking and are not very useful in the metallurgical industry. Nigeria produces about 10.8 MMT of corn annually and about 20.9 million tonnes of Mesocarp Fibre annually [8]. The disposal of these agro-wastes poses a serious challenge for municipal authorities. Blending biomass with coal helps to reduce the emission of particulate matter from coal, while increasing the energy density of the biomass. The overall effect is a reduction in deforestation and enhanced management of agro-wastes.

Bio-coal briquettes are prepared by blending coal, biomass and binders; a sulphur fixation agent may, sometimes be incorporated. A briquette is a compressed block of coal dust or other combustiblebiomass material such as charcoal, sawdust, wood chips, peat, or paper used for fuel and kindling to start a fire[9]. Biomass briquettes, mostly made of green waste and other organic materials, are commonly used for electricity generation, heating, and cooking. These compressed compounds contain various organic materials, including rice husk, bagasse, ground nut shells, municipal solid waste, and agricultural waste. The use of organic briquettes (biomass briquettes) started more recently compared to coal briquettes, which dates back to eighteenth century [10]. Corn cobs and palm waste, such as mesocarp fibre are not only in abundant supply, but constitute all-year-round environmental waste in Nigeria. Industrial starch produced mainly from cassava is a common energy resource in Nigeria, since the country produces over 62.0 MMT of cassava annually, out of which about 53.0 MMT is demanded as food [11]. Starch is usually produced from cassava wastes, especially the peels.

The present work reports the production of bio-coal briquettes, composed of sub-bituminous coal and palm mesocarp fibre or corn cob and the characterization of their physical and fuel properties as cooking fuel using the Laboratory Emissions Measuring System (LEMS).

2. Materials and Methodology

2.1. Materials

The materials used in the work were: Sub-bituminous coal from Onyeama mine, Enugu state Nigeria, palm mesocarp fibre (PMF) obtained from a local oil mill in Nsukka, corn cob obtained from various farms in Nsukka, Enugu state, bowl and water.

The equipment used were locally made attrition mill, which was used to crush the coal, electronic weighing balance (Citizen Instruments Inc.), hydraulic press briquetting machine (locally made), improved briquette stove (locally made) and iKA bomb calorimeter. Hydraulic press briquetting machine was used to compound the materials into blocks. It is a manually operated briquetting machine, designed and fabricated at the National Center for Energy Research and Development (NCERD), University of Nigeria Nsukka. It uses vertically mounted 200 kN capacity hydraulic press to its maximum compaction pressure of 160 N/m^2 and has 12 cavities of 70 mm/100 mm cross-sectional area, each where the biomass, coal and binder are loaded for compaction. The press was designed to handle a maximum load of 7.0 kg of biomass. At full capacity, it can produce about 2.80 tons of briquettes per day.

2.2. Methodology

The coal was first reduced to fine particles of less than 0.5 mm diameter using the attrition mill. The mesocarp fibre is a fluffy material. It was reduced to particles of about 2-3 mm, while the corn cobs were milled into small particles of about 0.5-1.0 mm size. The coal, biomass (i.e. palm mesocarp fibre or corn cob) and starch were weighed using the weighing balance into pre-determined proportions, and tied in nylon bags. The samples were then put into a bowl according to a pre-determined ratio for mixing. Binder (starch) content was varied between 10% and 30% at 10% intervals, giving a total of three treatment levels. Each mixed sample was put in a cavity in the hydraulic press briquetting machine and manually pressed into briquettes. The briquettes were then left to dry for about three days in a cabinet solar dryer. After solar- drying the briquettes, the heating (calorific) values were determined using the bomb calorimeter. The HHV of the blended briquettes were then calculated using Equation. 1 as follows:

$$HHV = \frac{\sum_{1}^{n} C_i hv_i}{100} \quad (1)$$

where,
C_i = Mass composition of ith component (coal, biomass or starch, %);hv_i = Heating value of ith component.

The percentage compositions of the bio-coal briquettes, from where their mass compositions were worked out using a typical briquette final mass of approximately 115 g ranged between 0 and 100 % (mass) for the biomass, coal and starch. The hydraulic press loaded with bio-coal blend for briquetting is shown in Figure 1. Appendix 1 is the photograph of the briquetting machine used for the research.

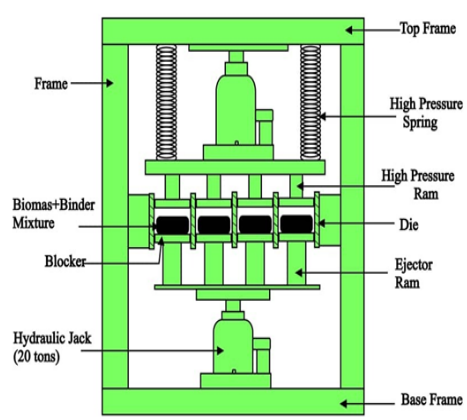

Figure 1: Schematic of the Hydraulic Press Briquetting Machine

The Laboratory Emissions Measuring System (LEMS)™ was used for characterization of the thermal efficiency and emissions released from the briquettes during the WBT. It is equipped with sensors for CO, CO_2 and Particulate Matter (PM) emissions. The CO sensor is an electrochemical cell [12], which takes advantage of the fact that conductivity between two electrodes in the cell is proportional to the concentration of CO present. This cell has a reference terminal as well and requires a potentiostatic controller. The CO_2 sensor uses non-dispersive infrared (NDIR) to measure CO_2 concentration and outputs voltage. It is self- calibrating, with pure Nitrogen gas used for zero reference. The LEMS has two PM sensors, namely the regular photometer sensor and the gravimetric system. The scattering photometer has both a laser and a light receiver. When smoke enters the sensing chamber, particles of smoke scatter the laser light into the receiver. The amount of scattered light is calibrated with a laboratory-standard nephelometer. The gravimetric system gives a direct measurement of total PM via filter-based sampling. A vacuum pump pulls the exhaust gases through the sample line and the critical orifice, which holds the flow at a steady 16.7 L/min [12]. A cyclone particle separator is used so that all $PM_{2.5}$ (particulate matter of aerodynamic diameter equal to or less than 2.5 μm) is collected on a glass fibre filter while the pump is on. The filter was pre- and post-weighed to calculate the total mass of $PM_{2.5}$ deposited on it.

Flow rate was measured by an orifice meter pressure transducer which outputs a signal based on the pressure drop measured across the flow grid. The temperature of the exhaust gas was measured using a K-type thermocouple sensor in real-time. These data were required to calculate the density of exhaust air in order to determine the mass flow rate of emissions. A thermocouple (TC) temperature sensor was used to record the temperature of the water in the pot. The LEMS sensor box outputs data through an RS-232 serial port of a connected computer.

2.2.1. Water Boiling Test using LEMS

Water Boiling Test (WBT) was conducted using an improved briquette stove and the LEMS equipment in the National Stove Eligibility laboratory, NCERD, University of Nigeria, Nsukka. The stove used for the WBT, the LEMS accessories and the whole experimental set-up are shown in Figure 2 (See appendix 2). The LEMS is suitable for real-time logging of total emissions data emanating from biomass-fired stoves during WBT. It is equipped with sensors for CO_2, CO and Particulate matter (PM), as well as a gravimetric system for more accurate determination of PM emissions. The LEMS sensor box and other accessories were run for at least 1 minute with the blower off in order to capture a zero flow reading. The Magnehelic™ flow meter was adjusted using a small screw to ensure it was reading zero. The blower was turned on and the background period was observed starting from 4 minutes after the LEMS began logging to allow time for the sensors to warm up. The room temperature and other necessary inputs were recorded, while other test materials such as fuel and water were weighed and loaded.

Each WBT test comprised of a Hot start phase (during which 3L of water was brought to boiling point with heat generated from the briquette sample), and Simmer phase (during which the boiling water was kept at a temperature not less than 97°C for 45 minutes), following IWA Protocol and NIS 1000:2018 Part 1, Standard for Clean Cookstoves - Solid Biomass [13]. At the end of the test, the stove and briquettes were removed from under the hood and the system was allowed to run for another 10 minutes to clear out the gases in the sensors. The logged data was then processed using the LEMS software to obtain the thermal efficiency, specific fuel consumption, average CO, CO_2 and PM emissions etc, which are reported according to the ISO International Working Agreement (IWA) format.

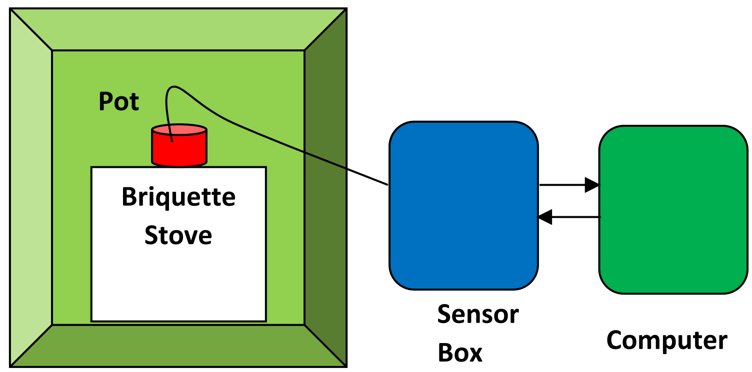

Figure 2: Experimental Set-up for the WBT using LEMS

2.3. Experimental Uncertainty

Uncertainties in experimental studies occur often owing to improper instrument selection, environmental conditions, instrument inaccuracy, readability and human errors [14]. It is very necessary for the investigator to estimate the maximum possible uncertainties in the independent variables (in this case, water temperature, mass of charcoal, mass of water, and exit speed of flue gases) as well as the calculated parameters ($PM_{2.5}$ emissions, CO emissions, CO_2 emissions, thermal efficiency, specific fuel consumption, etc). The uncertainties of the variables are temperature measurement (w_T) ± 0.1°C, relative humidity (w_{RH}) ± 3%, weight of charcoal and water (wm) ± 0.0001kg. The result R is a given function in terms of the independent variables x1, x2, x3, ….., x_n. Let wR be the uncertainty in the result and w1, w2,……,wn be the uncertainties in the independent variables. Therefore, the fractional uncertainty in the thermal efficiency (TE) can be calculated using eqn. 2 as follows:

$$\frac{\partial TE_{eff}}{TE_{eff}} = \sqrt{\left(\frac{\partial \dot{E}_{out}}{\dot{E}_{out}}\right)^2 + \left(\frac{\partial \dot{E}_{in}}{\dot{E}_{in}}\right)^2} \quad (2)$$

Since.,

$$TE = \frac{M_w C_{pw} \Delta T}{M_{ch} HV_{ch}} \quad (3)$$

It follows that,

$$\frac{\partial TE_{eff}}{TE_{eff}} = \sqrt{\left(\frac{\partial M_w}{M_w}\right)^2 + \left(\frac{\partial M_{ch}}{M_{ch}}\right)^2} \quad (4)$$

where;

C_{Pw} = Specific heat capacity of water (4,190 kJ/kg);

HV_{ch} = Heating value of charcoal (29,400 kJ/kg);
$E_{in(out)}$ = Energy Input (output) from the stove, kJ;
Mw = Mass of water, kg;
Mch = Mass of charcoal, kg;
ΔT = Temperature difference, K.

Solving eqn. 4 leads to fractional efficiency of 2.71% for the system.

2.3. Practical application

In practical terms, this work could help enviro-preneurs wishing to venture into the production of biocoal briquettes as alternative to firewood for domestic and cottage industrial application (e.g. in bakeries etc).

3. Results and Discussion

3.1 Results of bio-coal briquetting

The produced pure sample (coal, corn cob and palm mesocarp fibre) briquettes are shown in Figure 3, while some blended briquettes are shown in Figure 4.

Figure. 3: Pure briquettes of coal, palm mesocarp fibre (pmf) and corn cob.

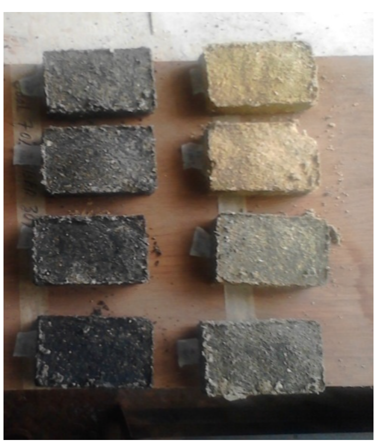

Figure 4: Some bio-coal briquettes.

3.2. Results of briquettes characterization

Table 1 shows the mass, volume, bulk density and HHVs of the coal/corn cob briquettes produced in accordance with their compositions, while the characteristics of the coal/pmf briquettes are presented in Table 2.

Table. 1: Mass, Volume, Bulk Densities and HHV of the Coal/Corn Cob Briquettes.

S/N	Coal %	Corn cob %	Starch %	Mass (g)	Volume (cm^3)	Bulk Density (g/cm^3)	HHV (kJ/kg)
1	100	0	0	119.2	156.24	0.7629	24525
2	90	0	10	115.6	148.59	0.7779	23732.5
3	80	10	10	108.2	164.43	0.6580	22780
4	70	20	10	102.7	160.16	0.6412	21827.5
5	60	30	10	97.2	180.22	0.5393	20875
6	50	40	10	92.7	200.45	0.4625	19922.5
7	40	50	10	82.8	194.18	0.4264	18970
8	30	60	10	81.7	188.79	0.4328	18017.5
9	20	70	10	75.2	204.97	0.3669	17065
10	10	80	10	71.6	218.24	0.3281	16112.5
11	0	90	10	65.9	229.15	0.2876	15160
12	0	100	0	75.9	290.16	0.2616	15000
13	80	0	20	105.1	122.55	0.7629	22940
14	70	10	20	98.0	137.95	0.7779	21987.5
15	60	20	20	92.9	149.69	0.6580	21035
16	50	30	20	89.9	153.79	0.6412	20082.5
17	40	40	20	83.7	175.50	0.5393	19130
18	30	50	20	78.2	187.20	0.4625	18177.5
19	20	60	20	70.1	207.90	0.4264	17225
20	10	70	20	64.3	191.36	0.4328	16272.5
21	0	80	20	59.2	239.20	0.3669	15320
22	70	0	30	98.9	143.00	0.3281	22147.5
23	60	10	30	92.9	154.44	0.2876	21195
24	50	20	30	85.7	154.44	0.2616	20242.5
25	40	30	30	81.1	168.96	0.4799	19290
26	30	40	30	77.0	166.32	0.4629	18337.5

27	20	50	30	73.8	172.80	0.4271	17385
28	10	60	30	66.3	175.50	0.3778	16432.5
29	0	70	30	65.1	187.20	0.3478	15480
30	80	20	0	113.0	167.04	0.6765	22620
31	90	10	0	119.7	160.16	0.7474	23572.5
32	70	30	0	104.9	175.50	0.5977	21667.5

Table. 2: Mass, Volume, Bulk Densities and HHV of the Coal/PMF Briquettes

S/N	Coal %	PMF %	Starch %	Mass (g)	Volume (cm^3)	Bulk Density (g/cm^3)	HHV (kJ/kg)
1	100	0	0	111.1	138.591	0.801639	24525
2	90	0	10	118.8	138.288	0.859077	23732.5
3	80	10	10	114.5	161.04	0.711003	23130
4	70	20	10	116.2	165.088	0.703867	22527.5
5	60	30	10	106.9	168.299	0.635179	21925
6	50	40	10	99.1	187.968	0.527217	21322.5
7	40	50	10	98.9	179.18	0.551959	20720
8	30	60	10	88.7	197.64	0.448796	20117.5
9	20	70	10	78.8	248.31	0.317345	19515
10	10	80	10	77.4	249.744	0.309917	18912.5
11	0	90	10	74.7	246.906	0.302544	18310
12	0	100	0	80	321.9	0.248524	18500
13	80	0	20	102.9	133.5	0.770787	22940
14	70	10	20	102.6	140.94	0.727969	22337.5
15	60	20	20	97.5	133.056	0.732774	21735
16	50	30	20	92.6	146.432	0.632375	21132.5
17	40	40	20	91.1	150.15	0.606727	20530
18	30	50	20	85.6	132.526	0.645911	19927.5
19	20	60	20	73.2	194.568	0.376218	19325
20	10	70	20	71	190.08	0.373527	18722.5
21	0	80	20	72.5	216.448	0.334953	18120
22	70	0	30	89.6	133.055	0.673406	22147.5
23	60	10	30	89.7	133.584	0.671488	21545
24	50	20	30	86.8	137.28	0.632284	20942.5
25	40	30	30	79.7	161.001	0.495028	20340
26	30	40	30	79.1	135.168	0.585198	19737.5
27	20	50	30	74.2	170.346	0.435584	19135
28	10	60	30	64.8	165.184	0.39229	18532.5
29	0	70	30	65.9	170.716	0.386021	17930
30	80	20	0	113.2	148.096	0.764369	23320
31	90	10	0	106.2	144.625	0.734313	23922.5
32	70	30	0	101.2	161.28	0.62748	22717.5

Although PMF is a fluffy material, the bulk densities of the coal/corn cob briquettes were generally lower, due to the smaller aggregate size of the crushed corn cobs when compared with the palm mesocarp fibre.

HHVs of the pure samples were 24,525 kJ/kg for Coal, 16,600 kJ/kg for cassava starch, 15,000 kJ/kg for Corn Cob, and 18,500 kJ/kg for palm mesocarp fibre, respectively. Results of HHV determination indicate that the higher the percentage composition of coal in the coal/corn cob briquettes, the greater the higher heating value, whereas the reverse is the case for coal/pmf briquettes. This is easily explained from the values of the HHV of the pure components used in the study.

3.3. *Results of emissions from WBT using LEMS*

The major indicators (metrics) determined were High Power Thermal Efficiency (%), Low Power Specific Consumption (MJ/min/L), High Power CO (g/MJd), Low Power CO (g/min/L), High Power PM (mg/MJd), Low Power PM (mg/min/L), Indoor Emissions CO (g/min), Indoor Emissions PM (mg/min).These parameters were analyzed by categorizing the results into five Tiers as described in appendix 3.

The thermal efficiency of a stove varies from about 10% for traditional open fires (regarded as Tier 0 stoves) to above 55% for the most efficient gasifier stoves (Tier 5). It is a very useful indicator that shows how efficiently heat from the fuel is converted to useful energy by the stove, and depends on the stove-fuel configuration. As such, when using the same stove, TE can vary between fuels, but when using the same fuel, it can also vary from stove to stove. The HP Thermal efficiency recorded in the present work ranged between 27.6% and 29.3% (typically Tier 2), averaging around 28.8% for all the briquettes.

The Low power specific consumption varied between 0.030 and 0.036 MJ/min/L for all the briquettes, which corresponds to Tier 2 performance. Briquettes with coal composition above 60% produced High Power CO in the range of 12.0 g/MJd (9.2 ppm, Tier 1), while for the briquettes with lower coal content, HPCO hovered around 10.5g/MJd (8.1 ppm, Tier 2). Low Power CO varied between 0.6 and 0.7 g/minL (See Fig. 5 and 6).

HPPM emissions were in the range of 302 – 365 mg/MJd (241.3-290.2 μg/m^3), but were generally higher for briquettes with PMF content above 50%, probably due to their oil content. LPPM emissions varied between 1.7 and 2.8 mg/min/L (8.23-9.09 μg/m^3,Tier 3). The High-Power figures are higher than the WHO recommended value of 35 μg/m^3. Indoor emissions of CO were within Tier 2 as they hovered around 0.56g/min, whereas indoor emissions of PM were in the range of 14 mg/min, equivalent to Tier 2. In all, CO emissions were generally higher than the WHO recommended standard of 10 ppm [15], but the HPPM emissions were far higher than the WHO recommended limits.

Many newer biomass cookstoves with chimneys are able tomeet the WHO Targets of 7mg/min. for $PM_{2.5}$ and 1.45 g/min. for CO when tested in the laboratory. WHO permissible exposure to CO emissions for ambient air is 10 ppm. The WHO vented stove Emission Rate Targets are based on 75% of the smoke and gases being removed up the chimney and out of the house. In their review of field studies, an average of 25% of the smoke and gas remained in the kitchen. Almost none of the residential biomass heating stoves in the United States meet the WHO Targets for $PM_{2.5}$ but the chimney transports the smoke outside where it is diluted by clean outdoor air to safe levels of concentration [16]. For a five-minutes sampling period the permissible CO emission level is 200 ppm [17]. The highest CO emissions recorded in this study was 9.2 ppm. This is within permissible limits even for a five-minutes sampling period.

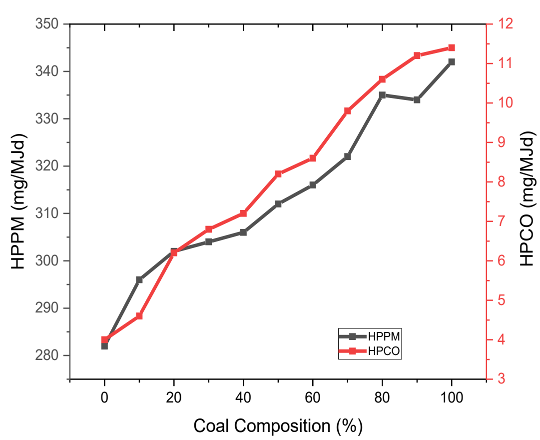

Figure 5: Graph of HPPM and HPCO versus Coal Composition for PMF Briquettes/Coal

The emissions values were generally lower than those obtained from pure coal. In [18], they reported that switching to semi-coke briquettes for household cooking can reduce average emission factors of primary $PM_{2.5}$, elemental carbon, organic carbon, and carbon monoxide by about 92%, 98%, 91%, and 34%, respectively. Although conventional coal devolatilization was not carried out in this study but from the studyon the emissions produced from the combustion of eco-fuel briquettes for domestic applications, blending coal with biomass was found to drastically reduce PM and CO emissions[19]. The CO and $PM_{2.5}$ emissions of the blended bio-coal briquettes are presented in Figures 5 and 6.

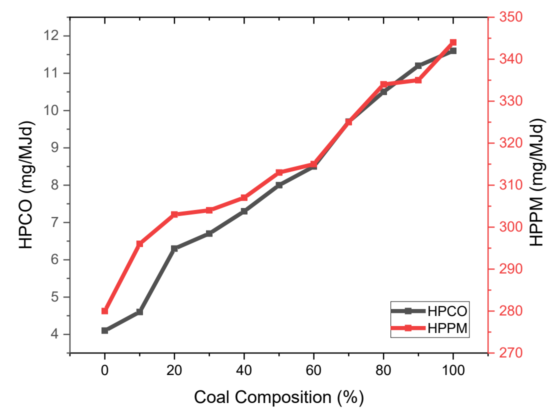

Figure 6: Graph of HPPM and HPCO versus Coal Composition for Corn Cob/Coal Briquettes

4. Findings

The work has shown that although bio-coal briquettes are suitable replacement for firewood as a climate change mitigation measure, the particulate matter (PM2.5) emissions derived from Palm Mesocarp Fibre briquettes are far above the WHO limits probably due to its residual oil content.

5. Conclusion

Bio-coal briquettes were produced from blends of Nigerian sub-bituminous coal and corn cob/palm mesocarp fibre with cassava starch as binding agent, using a purpose-built hydraulic press. Computer-assisted WBT was carried out on the fuel samples using the Laboratory Emissions Measuring System (LEMS). Results of the tests showed that average High Power Thermal Efficiency was 28.8% for Corn cob/coal and 29.2 % for PMF/coal briquettes. High Power CO emissions decreased marginally from 10.8 mg/MJd to 10.5 mg/MJd as the composition of corn cob increased from 0% to 100%. Although the bio-coal briquettes showed improved emissions characteristics over pure coal, their PM emissions were generally above WHO recommended allowable limits.

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References

[1] O, Bede-Ojimadu, O, E Orisakwe "Exposure to Wood Smoke and Associated Health Effects in Sub-Saharan Africa" A Systematic Review. Annals of Global Health. 2020; **86**(1): 32, 1–27. DOI: https://doi.org/10.5334/aogh.2725

[2] GACC "The Truth about Cooking Landscape Analysis" Global Alliance for Clean Cookstoves, October 2016.

[3] Mongabay "Forest Cover, Forest types, Breakdown of forest types, Change in Forest Cover, Primary forests, Forest designation, Disturbances affecting forest land, Value of forests, Production, trade and consumption of forest products" The Food And Agriculture Organization of the United Nations' Global Forest Resources Assessment (2005 & 2010) and the State of the World's Forests (2009, 2007, 2005, 2003, 2001), Accessed from http://rainforests.mongabay.com/deforestation on 23rd February, 2017.

[4] C. N. Ibeto, J. N. Oyedele, and C. N. Anyanwu "Evaluation of Pollution Potentials and Fuel Properties of Nigerian Sub-Bituminous Coal and its blends with Biomass" Journal of Mater. Environ. Sci. **7** (8), 2929-2937, 2016.

[5] Yuan, Ye, Yong, He, Jiaxin, Tan, Yongmeng Wang, Sunel Kumar and Zhihua Wang "Co-combustion characteristics of typical biomass and coal blends by thermogravimetric analysis" Frontiers in Energy research, **9**, 1-11, 2021, doi.org/10.3389/fenrg.2021.753622

[6] L.M Esriaty, D. Fatimah and Widodo "Bio-coal briquettes using low-grade coal" in 2018, IOP Conf. Series: Earth and Environmental Science **118**, 2018, doi:10.1088/1755-1315/118/1/012066

[7] D. Mathias "Effect of Locally Available Bitumen on the Coking Properties of Lafia Coal." Thesis, Ahmadu Bello University, Zaria, 2008.

[8] K. E. Anyaoha, R. Sakrabani, K. Patchigolla, and A. M. Mouazen "Evaluating oil palm fresh fruit bunch processing in Nigeria" Waste Management & Research, **36**(3) 236–246, 2018.

[9] Anon., 2016 https://en.wikipedia.org/wiki/Biomass_briquettes last modified on 14 March 2016, sourced 3rd December, 2018.

[10] S. Choudhurl "Briquetting of Organic Residue" proceedings from Bio-Energy Society Convention and Symposium, Delhi, **4**(2) 22-28, 1983.

[11] C. N. Anyanwu, C. N. Ibeto, S. L. Ezeoha, and N. J. Ogbuagu, Sustainability of cassava (Manihot esculenta Crantz) as industrial feedstock, energy and food crop in Nigeria**.** Renewable Energy 81:745-752, 2015, DOI:10.1016/j.renene.2015.03.075

[12] ARC "Instructions for use of the Laboratory Emissions Measuring System (LEMS)" Aprovecho, Research Center, Cottage Grove Oregon, USA, 2013

[13] Standards Organisation of Nigeria "Nigerian Industrial Standards NIS 1000:2018 Part 1, Standard for Clean Cookstoves- Solid Biomass", 2018.

[14] S.Vijayan, T.V.Arjunan, and A.Kumar "Exergo-environmental analysis of an indirect forced convection solar dryer for drying bitter gourd slices" Renewable Energy 146, 2210 -2223, 2020.

[15] WHO "World Health Organisation Air Quality guidelines for Particulate Matter", Ozone, Nitrogen dioxide and Sulfur dioxide. Global update 2005, Geneva 2006.

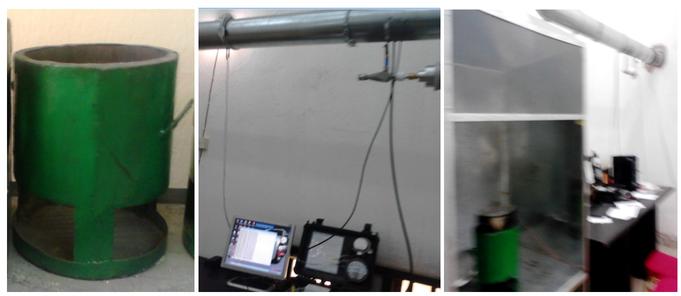
[16] ARC, "Meeting World Health Organization Emission Rate Targets" Newsletter of the Aprovecho Research Center, Cottage Grove Oregon, USA, 2021.

[17] WHO "Carbon Monoxide", Ch. 5 In: Air Quality Guidelines, 2nd Ed. World Health Organisation Regional Office for Europe, Copenhagen, 2010.

[18] Q. Li, X. Li, J. Jiang, L. Duan, S. Ge, Q. Zhang, J. Deng, S. Wang, and J. Hao "Semi-coke briquettes: towards reducing emissions of primary PM2.5, particulate carbon, and carbon monoxide from household coal combustion in China" Scientific Reports **6**, 19306, 2016. DOI: 10.1038/srep19306.

[19] T. J. Pilusa, R. Huberts and E. Muzeda "Emissions Analysis from Combustion of Eco-fuel Briquettes for Domestic Applications". Journal of Energy in Southern Africa, **24**(4), 30-36, 2013.

Appendix 1: Hydraulic Press Briquetting Machine.



Appendix 2: Photo of the Experimental Set-up

		Metric	Value	Unit	Sub-Tier
Efficiency/Fuel Use					
Tier	3	High power Thermal Efficiency		%	3
		Low power Specific Consumption		MJ/min/l	4
Emissions					
Tier	2	High power CO		g/MJ_d	2
		Low power CO		g/min/l	3
		High power PM 2.5		mg/MJ_d	4
		Low power PM 2.5		mg/min/l	3
Indoor emissions					
Tier	3	High power Indoor emissions CO		g/min	3
		Low power Indoor emissions CO		g/min	4
		High power Indoor emissions PM 2.5		Mg/min	3
		Low power Indoor emissions PM 2.5		Mg/min	3
Safety					
Tier	4	Points from 10 weighted safety parameters		points	

Tier 0 → Improving Importance → Tier 4

Appendix 3: Description of Tiers