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DETERMINATION OF PHYSICAL PROPERTIES AND COMBUSTION CHARACTERISTICS OF WATER HYACINTH (*EICHHORNIACRASSIPES*) BRIQUETTES

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ABSTRACT

Water hyacinth causes practical problems for marine transportation, fishing, hydro power, irrigation schemes, chokes other aquatic lives, favours mosquitoes breeding, fosters water borne diseases and it is a serious threat to biodiversity. A study was undertaken to determine the properties of water hyacinth, physical and combustion properties of briquettes made from water hyacinth (WH) of different binder ratio of plantain peels (PP) at different pressures and particle sizes. There was comparison of the combustion properties of water hyacinth briquette with bituminous-charcoal, red mangrove and Anthonothamacrophylla firewood. Three particle sizes of 0.5 mm (D_1), 1.6 mm (D_2) and 4.0 mm (D_3), four pressure levels of 3MPa (P_1),5MPa (P_2), 7 MPa (P_3), and 9 MPa (P_4), and five binder ratios of 10% (B)$_1$,20% (B_2,), 30% (B_3), 40% (,B_4) and 50% (B_5) by residue weight were used as variables. Comparison of combustion characteristics of water hyacinth briquettes with these energy sources was determined following American Society for Testing and Materials (ASTM) method. Results showed variation in the percentage bulk density with respect to particle size; 349.71% for 0.5 mm, 193% for 1.6 mm and 139% for 4 mm of water hyacinth. PP improved the calorific value of WH from 3190 kcal/kg to 4533.56± 22.44 kcal/kg (briquettes). The burning rate of the briquettes varied from 0.92 + 0.03 g/min to 2.66 ±0.05 g/min. Thermal fuel efficiency and water boiling time of fuel sources were: 28.17±0.88% and 9.25± 0.42 min (briquettes), 31.29±0.19% and 8.99± 0.22 min (bituminous-charcoal), 23.55 ± 0.56% and 11.43 ± 0.43 min (red mangrove wood) and 21.31 ±0.28% and 14.94 ± 0.22 min (Anthonothamacrophylla firewood). The optimum briquettes WH-PP production is at particle size of 0.5 mm, binder ratio of 40% and compaction ratio of 9 MPa.

Keywords: *Physical properties, combustion characteristics, water hyacinth, briquettes, plantain peels.*

INTRODUCTION

Water hyacinth (*Eichhorniacrassipes*) is found globally in the tropics and subtropics and is considered as one of the worst weeds in the world- aquatic or terrestrial (Tawari, 2006). The plant is also a breeding ground for many insects and mollusks (which are vectors of diseases) such as bilharzia, river blindness and malaria (Philp, 1981). A briquette is a block of compressed coal, biomass or charcoal dust that is used as fuel (Chin and Siddique, 2000). In some briquetting techniques, the materials are compressed without addition of adhesive (binderless briquette) while in some others, adhesive materials are added to assist in binding the particles of the materials together.

The recent changes in global environmental conditions and the increase in atmospheric concentration of carbon and sulphur compounds are stimulating studies geared to finding alternatives to the use of fossil fuels. It is understood that fossil fuels have a limited potential and detrimental consequences on the environment. Climate experts are therefore warning against excessive use of fossil energy due to pollution induced by greenhouse gases (Jean *at al*., 2010). For this reason, a transition to a sustainable energy system is urgently needed in the developing countries such as Nigeria (Olorunnisola, 2007). As the finite nature of the fuel wood resources becomes more apparent, focus must be shifted to other forms of renewable energy source in Nigeria.

Many researchers have studied agricultural residues and their energy potentials such as apple pomace (Jewell and Cummings, 1984), rice husk (Singh *et al*., 1990), coffee residue (Antolin *et al*., 1996), charcoal (Fapetu, 2000),orange pomace (Enweremadu *et al*., 2004), soybean and cowpea (Enweremadu *et al*., 2004). Rademaker (2006) reported that the combination of water hyacinth with brakenfern and water lettuce as a means of enhancing the production of biogas, a medium grade fuel. There has been very little information on production and evaluation of briquettes (hollow and solid) made of water hyacinth using binder (Koser *et al*., 1982). The objectives of this study are to determine the physical properties and combustion characteristics of water hyacinth briquettes.

METHODOLOGY

Residue Selection and Process Variables

Water hyacinth and plantain peels were selected because of their abundance as agricultural residues for the purpose of this experiment. Plantain peels were used as binder for production of water hyacinth briquettes at binder ratio (10, 20, 30, 40 and 50% by residue weight), compression pressure (3, 5, 7 and 9MPa) and particle size (0.5, 1.6, and 4.0 mm).The range of compaction pressure chosen falls within the acceptable range of manually produced briquettes using hand press (Chin and Siddique, 2000, and Bamigboye and Bolufawi, 2008). They reported binder inclusion at different levels of 10% to 50% by residue weight for the production of briquettes for guinea corn residue and cassava starch as binder while Olorunnisola, (2007) recommended particle size range of from 0.5 to 4.7 mm for the production of durable briquettes.

Preparation of Samples for Physical Properties Experiment

Water hyacinth was harvested from ten different earthen fish ponds, each having length and breadth of 50 m and 50 m, respectively. A total of 1500 kg of fresh water hyacinth was manually harvested using rake to draw it close to pond edge before being packed into bag. It was sorted out from other aquatic weeds entangled with it and cleaned by dipping into clean water inside 200 litres bath to devoid foreign matters (stones and dust) prior to drying. Water hyacinth was sun dried for 7 days in an open field and ground using hammer mill (model: TFS 198) powered by diesel engine. The particle sizes were obtained using Tyler sieves (model: RX-29, S/N 21949) size corresponding to 0.5, 1.6 and 4.0 mm.

A total of 700 kg of ripe plantain peels was collected, cleaned to devoid of foreign materials, and sun dried for 5 days. The dried materials were ground using hammer mills and the particle size was achieved by using Tyler sieves (model: RX-29, S/N 21949). One hundred gramme (100 g) of ground plantain peels was hydrated with 50 ml of boiling water at 100^0C to form colloidal solution of the binder. The solution was kept on fire, and constantly stirred until smooth paste was formed. The consistency of the binder was maintained at a fixed level with its concentration in the sample mixture varied at 10, 20, 30, 40 and 50% level of the residue by weight (Bamigboye and Bolufawi, 2008).

Preparation of Samples Briquettes

The particle size analysis test was conducted using particle size analysis equipment consisting of sieve shaker and Tyler sieves (model: RX-29, S/N 21949) of different size openings. Sieves of 0.5 mm, 1.6 mm and 4.0 mm that correspond to fine, medium and coarse aggregate, respectively were used. Each of the particle size was subdivided into three parts, while binder (ground plantain peels) in the ratio of 10, 20, 30, 40 and 50% by weight of the residue was added to each of the subdivided residue. The agitating process was done in a mixer to enhance proper blending prior to compaction. The blends were briquetted in a manually - operated hydraulic press machine (model: TT-LM/LS) having capacity of 20 tonnes. Compaction tests on the blend samples were carried out using hydraulic press machine. A steel cylindrical die of dimension 14.3mm height and 4.7 mm diameter was used. The die was filled with each sample mixture and positioned in the hydraulic press machine (model: TT-LM/LS) for compression into briquettes. The piston was actuated through hydraulic pump at the speed of 39 mm/min of piston movement to compress the sample. Compressed pressure range of 3 to 9 MPa was applied at a time to the material in the die and allowed to stay for 45 seconds (dwell time) before released. The briquette formed was then extruded and labelled. Stop watch was used for timing. Prior to the release of applied pressure, the maximum depth of piston movement was measured for the purpose of calculating the volume displacement by the briquette. Densities and combustion characteristics of the water hyacinth were determined.

Determination of Physical Properties of Briquette

Compressive density of briquette

A steel cylindrical die of length 14.3 mm and width of 4.7 mm filled with a known weight of each sample mixture. A known pressure of 3 to 9 MPa was applied at a time to the material in the die and allowed for 45secs (dwell time) before released (Chin and Siddique, 2000). The pressure was read from dial gauge and the briquette density was measured directly after pressing. The briquette density was then calculated by dividing the average mass of the briquette by its volume.

Compressive strength

The axial compressive strength of the briquette was measured by using Universal Testing Machine (model: UTN-10) with accuracy of ± 0.5% and maximum capacity of 100 kN. The briquette was positioned directly under the plunger to be pressed. The machine was operated until failure occurred on the briquette. The compressive strength was calculated using Equation 1 (Chin and Siddique, 2000):

$$\text{Compressive strength (Nmm}^{-2}\text{)} = F/A \qquad (1)$$

where;

F = Breaking force (N)

A = Area of briquette (mm^2)

Compression ratio

Compression ratio (CR) is described as the ratio of the density (kg/m^3) of the in-die briquettes (Y_i) to initial density (kg/m^3) of residue (Y_d). The compression ratio was determined from equation 2 (ASABE, 2003):

$$\text{Compression ratio (CR)} = Y_d/Y_i. \qquad (2)$$

Compaction energy

The area under the pressure versus compaction ratio curve was used to determine compaction energy in accordance with Faborode and O' Callagham (1987).

Bulk density

The bulk density of ground and unground water hyacinth plant was measured using the method described in ASABE (2003). A cuboid of 0.5 m by 0.5 m made of particle of predetermined weight (W_1) was determined. The box was filled with the materials and weighed (W_2). The weight of water hyacinth (W_3) was calculated as W_2-W_1. The volume of the material was measured and bulk density calculated by dividing the average mass of the material by the volume of the container (ASABE, 2003).

The wet bulk density of the sample was calculated from Equation 3 as:

$$\rho_b = \frac{(W_2 - W_1)}{V} \qquad (3)$$

where;

ρ_b= bulk density of the sample (kg/m^3)

W_2 = weight of the container and sample (kg)

W_1= weight of the container (kg),

V = volume of the container (m^3).

The height and diameter of briquette samples were measured consistently until it was constant. The stabled height and diameter were used to determine the volume and density of the briquette (Chin and Siddique, 2000; Olorunnisola, 2004).

Tap density

Tap density of ground and unground water hyacinth was determined using agraduated cylindrical container of 30 mm diameter and 306 mm high. It was filled with the sample and the container was dropped five times from the height of 150 mm on to surface to allow for settling with observed little change in volume. The tap density was determined using Equation 4 (Singh and Singh, 1982):

$$T_d = M_a / V_c \tag{4}$$

where:

T_d = Tap density (Kg/m^3)

M_a = Mass of material (Kg)

V_c = Volume of the material (m^3)

Relative change in height and diameter

The briquette samples were placed in a beaker and the initial height on graduated scale was measure. The beaker was filled with water, enough to submerge the briquettes completely. The briquettes absorbed moisture and the corresponding height with time was taken. The percentage relative change in height with time was computed in Equation 5 (Olorunnisola, 2007):

H_e = (H_l-H_o)/H_o x 100%. (5)

where;

H_e = relative change in height (%)

H_o = initial height of briquettes before immersion (cm)

H_i= height of the briquettes after immersion (cm).

The percentage relative change in diameter was computed in Equation 6as:

D_e = (D_f-D_i)/D_i x 100% (6)

where:

D_e =percentage relative change in diameter (%)

D_i = initial diameter of the briquettes under compression (cm)

D_f= final diameter of the briquettes after compression (cm)

Shattering index

Briquettes shattering index (durability index) was measured according to D440-86 of drop shatter developed for coal by Lindley and Vossough (1989). Briquettes shattering index was determined according to equation 7 (Kaliyan and Morey, 2006):

Ø = W_i/W_f (7)

where;

Ø = shattering index,

W_i = weight of briquettes before dropping (g), and

W_f = weight of briquettes retained on the screen after dropping (g).

Combustion Characteristics of the Briquettes

Calorific value

The calorific value of the sample was determined using Gallenkamp Ballistic Bomb Calorimeter according to ASTM (E711-87) (2004). The heating value of the test sample was calculated according to Equation 8 (ASTM E711-87, 2004):

$$\text{Gross calorific value (KJ/Kg)}=\frac{\left(M_1+M_2C_W\right)x(T_1-T_2)}{M_S} \tag{8}$$

where;

M_1 = heat capacity of calorimeter obtained from standard experiment, kJ/ ^{o}C.

M_2 = Mass of water in copper calorimeter (kg),

T_1 = Initial temperature of water (^{0}C),

T_2 = Final temperature of water (^{0}C),

M_s = Mass of fuel sample taken (kg)

C_w = specific heat capacity of water (kJ/kg ^{0}C)

Water boiling time

The volume of a pot was measured and filled to 2/3 of its volume with water. The pot was kept on a biomass stove and covered with propped lid to minimize the losses. The thermometer was fixed in the central part of the pot. Two (2) kg of briquettes was measured and made into four parts for testing. The ambient temperature and initial temperature of water in the pot were measured. After boiling, the pot was cooled for 2 hours and volume of water was measured. This was carried out to compare the cooking efficiency of the briquettes. It measures the time taken for each set of the briquettes to boil an equal volume of water under similar conditions.

Thermal fuel efficiency

The thermal efficiency indicates how well energy in fuel will be converted to heat. The thermal fuel efficiency of briquette sample was determined by carrying out water boiling test as described by Sengar *et al.* (2012). The thermal fuel efficiency of the briquettes, red mangrove wood, firewood and bituminous charcoal were calculated from Equation9 (Sengar, *et al.*, 2012):

$$\text{TFE=}\frac{M_wC_p(T_b-T_0)+M_cL\,x100\%}{M_tE_t} \tag{9}$$

And power output was obtained from Equation 10 as:

$P = M_tE_t / T$ (10)

where;

TFE = Thermal fuel efficiency of the energy (%)

P = Power output

M_w = Mass of water in the pot (kg)

Cp = Specific heat of water (kJ/kgK)

T_o = Initial temperature of the water (K)

T_b = Boiling temperature of the water (K)

M_c = Mass of water evaporated (kg)

L = Latent heat of evaporation (kJ)

M_t = Mass of fuel burnt (kg)

E_t = Calorific value of the fuel (kJ/kg)

T = Time taken to burn fuel (secs).

Burning rate

The burning rate (B_R) determines the rate at which a certain mass of fuel is combusted in air and it was calculated using Equation 11 (Ndirika, 2002):

B_R =Q_1-Q_2 / T (11)

where;

Q_1 = Initial weight of fuel prior to cooking (g)

Q_2 = Final weight of fuel after cooking (g)

T = Total smoking time (min)

Ignition time

Each briquette was placed in the centre of a steel wire mesh grid resting on two supporting fire rectangular bricks. There was free flow of air around the briquette. A bursen burner was placed directly beneath the platform and flame was not allowed to spread in the transverse directions. The burner was left in until the briquette was well ignited and had entered into its stead state burn phase and the time taken was recorded.

Statistical Analysis of Data

The obtained data were statistically analysed with Statistical Analysis System (SAS) (2007) and Analysis of Variance (ANOVA). To further analysis the significant level of the variables, Duncan Multiple Range Tests (DMRT) was used.

RESULTS AND DISCUSSION

Physical Parameters of Unground and Ground Water Hyacinth

The unground sample of water hyacinth showed the lowest bulk density of 34.69 kg /m^3. When the water hyacinth was milled, the bulk density increased to 155.56 kg/m^3, 106.69 kg/m^3 and 82.55 kg/m^3, for 0.5 mm, 1.6 mm and 4 mm particle sizes, respectively (Table 1). It showed that briquettes with smaller particle sizes have higher bulk density. For the purpose of packaging and transporting; briquettes with good bulk density should be produced. The increased percentage in bulk density of ground with respect to particle sizes showed 139%, 193% and 349.71%, for4, 1.6 and 0.5 mm particle sizes, respectively. The bulk density of ground water hyacinth (processed) increased with decrease in particle size of the sample. This finding is in agreement with Manickam and Suresh (2011) who reported that bulk density increased with decrease in the particle size.

Tap Density

The tap density ranged between 36.64 kg/m^3 (unground water hyacinth) and 161.82 kg/m^3 (ground water hyacinth of particle size of 0.5 mm). The percentage increment with respect to tap densities ranged between 153.92% for particle size of 4 mm and 369.57% for particle size of 0.5mm. Increase in binder ratio resulted to relative increase in bulk density of water hyacinth briquette. The trend is in agreement with the report of Omojogberun (2016) who concluded that briquettes with smaller particle sizes and higher starch content have better bulk density than others due to better compaction of these briquettes. The bulk density was significantly affected by binder ratio at P < 0.001 (Table 2).

Table 1: Physical properties of water hyacinth

Whole water hyacinth	**Particle size (mm)**	**Geometric mean diameter (mm)**	**Particle density (kg/m3)**	**Bulk density (kg/m3)**	**Increment wrt bulk density (%)**	**Tap density (kg/m3)**	**Increment wrt tap density (%)**
Unground	-	-	-	34.69	-	36.64	5.76
Ground	0.5	0.25	1453	155.56	349.71	161.82	369.57
Ground	1.6	0.47	1372	106.69	193.54	108.87	222.36
Ground	4.0	0.96	1189	82.55	139.63	88.41	153.92

Note: wrt = with respect to

Table 2: ANOVA of the effect of binder ratio, particle size and pressure on the measured properties of water hyacinth briquettes

Properties	**Source**	**DF**	**Sum of squares**	**Mean square**	**F- value**	**Pr>1**
Initial Density (kg/m^3)	Binder	4	9410.304	2352.576	169.790	< 0.001
	Pressure	3	0.000	-	-	-
	Size	2	-	-	-	-
	Binder x Pressure	12	0.000	-	-	-
	Size x Binder	8	246.680	30.835	2.230	0.054
	Size x Pressure	6	0.000	-	-	-
	Sizex Binderx Pressure			-	-	-
	Error					
	Corrected Total	24	0.00	13.856	-	-
		120	415.665	-	-	-
		179	30633.869			
Compressive Density	Binder	4	1371139.701	342784.925	248.020	< 0.001
	Pressure	3	1439479.641	479826.547	347.180	< 0.001
	Size	2	3051104.158	1525552.079	1103.800	< 0.001
	Binder x Pressure	12	28726.340	2393.862	1.730	<0.068
	Size x Binder	8	911016.992	113677.124	82.400	< 0.001
	Size x Pressure	6	46764.738	7794.124	5.640	< 0.001
	Size x Binder x Pressure	24	154551.545	6239.648	4.660	< 0.001
	Error					
	Corrected Total	120	165850.279	-	-	-
		179	7168633.394	-	-	-
Relaxed density	Binder	4	162503.778	40625.944	87.430	< 0.001
	Pressure	3	606334.914	20211.638	43.490	< 0.001

	Size	2	404434.121	202217.060	435.160	< 0.001
	Binder x Pressure	12	18839.919	1569.993	3.380	0.0003
	Size x Binder	8	40267.669	5033.4587	10.830	< 0.001
	Size x Pressure	6	5899.514	983.252	2.12	0.056
	Size x Binder x Pressure	24	15017.306	625.721	1.350	0.149
	Error					
	Corrected Total	120	55763.333	464.694	-	-
		179	763360.551	-	-	-
Compaction ratio	Binder	4	3.183	0.795	8.600	0.001
	Pressure	3	68.447	22.816	246.560	0.001
	Size	2	591.693	295.846	3197.120	0.001
	Binder x Pressure	12	2.589	0.216	2.330	0.002
	Size x Binder	8	87.454	10.932	118.140	0.001
	Size x Pressure	6	6.876	1.146	12.380	0.001
	Size x Binder x Pressure	24	10.399	0.433	4.680	0.001
	Error					
	Corrected Total	120	11.104	0.093	-	-
		179	781.744	-	-	-
Relative change height	Binder	4	26893.887	6723.472	7.720	0.001
	Pressure	3	18549.254	6183.085	10.480	0.001
	Size	2	35551.201	17775.600	12.730	0.001
	Binder x Pressure	12	100362.991	8363.583	6.320	0.001
	Size x Binder	8	59664.921	7458.115	2.550	0.009
	Size x Pressure	6	42927.020	7154.503	13.020	0.0004
	Size x Binder x Pressure	24	201839.681	8409.987	34.470	0.001
	Error					
	Corrected Total	120	975309.147	8127.576	-	-
		179	1461098.102	-	-	-
Relative change diameter	Binder	4	1.659	0.415	9.76	0.001
	Pressure	3	17.629	5.876	137.72	0.001
	Size	2	8.633	4.317	101.17	0.001
	Binder x Pressure	12	7.436	0.620	14.52	0.001
	Size x Binder	8	15.658	1.957	45.87	0.001
	Size x Pressure	6	29.385	4.898	114.79	0.001
	Size x Binder x Pressure	24	22.201	0.925	21.68	0.001
	Error					
	Corrected Total	120	5.120	0.043	-	-
		179	107.722	-	-	-
Shattering index	Binder	4	1.478	0.370	297.360	< .0001
	Pressure	3	0.231	0.077	62.080	< .0001
	Size	2	1.262	0.631	507.800	< .0001
	Binder x Pressure	12	0.041	0.003	2.750	0.0025
	Size x Binder	8	0.083	0.010	8.310	< .0001
	Size x Pressure	6	0.035	0.006	4.680	0.0003
	Size x Binder x Pressure	24	0.059	0.002	1.970	0.0093
	Error					
	Corrected Total	120	0.149	0.001	-	-
		179	3.338	-	-	-
Compressive strength	Binder	4	1.337	0.359	12.430	0.0005
	Pressure	3	5.140	1.713	28.770	0.001
	Size	2	3.595	0.180	20.410	< 0.001
	Binder x Pressure	12	28.954	2.413	32.270	< 0.001
	Size x Binder	8	9.315	1.164	8.790	< 0.001
	Size x Pressure	6	1.524	0.254	21.030	< 0.001
	Size x Binder x Pressure	24	58.860	1.240	18.270	< 0.001
	Error					
	Corrected Total	120	51.670	0.431	-	-
		179	1361.791	-	-	-
Compressive energy	Binder	4	410.078	102.519	173.770	< 0.001
	Pressure	3	2351.732	783.911	1328.760	0.001
	Size	2	1583.434	791.717	341.990	0.001
	Binder x Pressure	12	153.775	12.815	21.720	0.001
	Size x Binder	8	2442.142	305.268	517.440	0.001

	Size x Pressure	6	339.367	56.561	95.870	0.001
	Size x Binder x Pressure	24	437.149	18.215	30.870	0.001
	Error	120	70.795	0.590	-	-
	Corrected Total	179	7788.472	-	-	-

The particle size 0.5 mm recorded the highest value of bulk density 155.56 kg/m^3, followed by particle size 1. 6 mm with bulk density of 106.69 kg/m^3 and the lowest particle size was 4.0 mm with bulk density of 82.55 kg/m^3.The bulk density was significantly influenced by the particle size at $P < 0.05$. The bulk density increased with decrease in particle size of the water hyacinth.

Compressive Density

There was increase in increased compressive density (727.80 ± 44.61 (B_I) to 957.89 ± 19.02 kg/m^3 (B_5)) with increase in binder (10 to 50%) as shown in Table 3. The result of analysis of variance (ANOVA) indicated that the mean values of compressive density at different binder proportions showed significant difference at $P< 0.001$. This study showed that compressive density is directly proportional to binder proportions which are in agreement with the values reported by Olorunnisola (2007) for production of fuel briquettes from waste paper and coconut husk admixture which ranged from 8.1 to 11.2 kg/m^3 at different binder levels. The values of compressive density ranged from 551.16 kg/m^3 (B_ID_I) to 1048.92 kg/m^3 (B_2B_3). The analysis of variance indicated significant difference for the compressive density at the different binder ratio and particle sizes ($P< 0.001$). The difference among the compressive density values of the briquettes at the different compaction pressure levels and binder ratio and particle size were significantly different ($P< 0.001$).

Table 3: Effect of binder ratio, particle size, and compaction pressure on the measured physical properties

Properties	**binder Ratio**	**particle size (mm) 0.5**	**1.6**	**4**	**Mean**	**Compaction pressure (MPa) 3**	**5**	**7**	**9**	**mean**
Compressive density	10	551.16	591.52	1040.73	727.80	617.64	678.15	770.12	845.29	727.80
	20	627.48	738.57	1048.92	804.99	695.02	738.33	836.05	950.56	804.99
	30	722.01	844.99	1017.88	861.63	760.73	819.32	883.78	982.67	861.63
	40	814.34	984.31	1045.70	949.45	826.62	880.24	1002.22	1088.71	949.45
	50	863.77	1010.31	999.58	957.89	879.04	900.10	990.55	1081.83	957.88
	Mean	715.75	833.94	1031.35	860.35	755.81	803.23	892.54	989.81	864.35
Relaxed density	10	455.58	420.26	388.02	421.39	383.77	401.46	454.10	446.21	421.39
	20	487.26	435.63	402.21	441.70	420.51	415.46	448.78	482.36	441.70
	30	557.97	477.39	410.37	481.91	452.48	472.71	500.28	502.17	481.91
	40	578.76	478.52	430.80	492.90	473.99	489.93	499.99	507.67	492.90
	50	569.37	466.67	445.60	497.00	491.04	490.71	499.21	506.07	497.01
	Mean	529.84	455.69	415.40	466.98	444.36	454.05	480.47	488.84	466.98
Compaction ratio	10	3.53	4.29	9.09	5.64	4.98	5.50	6.26	6.92	5.91
	20	3.87	5.07	9.02	5.99	5.18	5.50	6.22	7.07	5.99
	30	4.00	5.44	8.17	5.87	5.22	5.59	6.01	6.67	5.87
	40	4.43	6.01	7.65	6.03	5.33	5.61	6.24	6.96	6.04
	50	4.24	5.74	7.97	5.05	5.21	5.31	5.73	6.37	5.65
	Mean	4.01	5.31	8.18	5.84	5.18	5.50	6.09	6.80	5.90
Shattering index	10	0.77	0.58	0.51	0.62	0.55	0.60	0.62	0.70	0.62
	20	0.83	0.68	0.61	0.71	0.62	0.69	0.72	0.77	0.70
	30	0.90	0.78	0.66	0.78	0.72	0.79	0.79	0.81	0.78
	40	0.95	0.83	0.78	0.85	0.80	0.84	0.87	0.88	0.85
	50	0.92	0.85	0.79	0.85	0.82	0.85	0.88	0.88	0.86
	Mean	0.87	0.74	0.67	0.76	0.70	0.75	0.78	0.81	0.76
Compressive strength	10	0.95	0.86	0.71	0.84	0.62	0.77	0.80	1.17	0.84
	20	1.09	0.82	0.72	0.88	0.69	0.72	0.92	1.17	0.88
	30	1.24	0.93	0.78	0.98	0.16	0.92	1.06	1.39	2.88
	40	1.42	1.03	0.08	1.18	0.93	1.10	1.18	1.49	1.18
	50	1.43	1.13	1.04	1.20	0.99	1.06	1.21	1.52	1.20
	Mean	1.23	0.95	0.67	1.02	0.68	0.91	1.03	1.35	1.39

Compaction energy	10	3.00	7.64	21.21	10.75	5.73	5.97	11.98	17.32	10.25
	20	8.81	7.72	14.95	10.49	5.77	8.33	10.62	17.14	10.52
	30	7.14	7.47	19.42	11.34	7.26	8.62	11.42	18.05	11.34
	40	8.20	10.02	4.03	7.42	3.97	8.74	8.67	11.31	8.17
	50	5.42	10.88	8.80	8.37	6.69	8.86	7.33	12.98	8.97
	Mean	6.95	8.75	13.68	9.67	5.88	8.10	10.00	15.36	9.85
Relative Change in height	10	8.07	14.00	24.79	15.62	25.41	13.50	12.19	11.38	15.62
	20	7.09	12.39	15.36	10.61	13.27	12.37	10.71	10.12	11.61
	30	5.96	8.63	14.21	9.60	11.35	10.01	9.16	7.89	9.60
	40	4.93	8.41	11.31	8.22	10.23	9.15	8.59	14.06	10.50
	50	4.71	7.43	21.36	11.17	9.59	20.97	7.25	6.86	11.17
	Mean	6.15	10.17	17.41	11.24	13.97	13.20	9.58	10.06	11.70
Relative change in diameter	10	2.29	3.10	3.57	3.02	1.66	1.73	1.77	1.88	1.76
	20	2.02	2.83	3.45	2.77	1.66	1.83	1.91	2.04	1.86
	30	3.15	2.73	3.08	2.99	1.69	1.79	1.83	2.02	1.83
	40	9.92	2.83	2.93	2.86	1.80	1.83	2.05	2.22	1.98
	50	2.82	2.81	2.83	2.82	1.89	1.86	1.98	2.18	1.98
	Mean	2.64	2.86	3.17	2.89	1.74	1.81	1.91	2.07	1.88

Relaxed Density

The interaction between binder ratio and compaction pressure on relaxed density of the briquettes were significant (P< 0.001), be inferred that the optimum amount of binder required for densification was 40% (B_4) above this level depicted economic loss (Davies, 2013). Increased relaxed density was observed with increased compaction pressure. The result of analysis of variance showed that there was significant difference among all the values obtained for compaction ratio at the various binder levels.

Relative Change in Height and Diameter

The relative change in height of briquettes ranged from 8.22 ± 0.24 mm (B_5) to 15.62 ± 3.07 mm (B_l) and the variation was significant (P<0.05).The relative change in diameter of briquettes immersed in water varied between 2.77 ± 0.12 mm (P_l) and 3.02 ± 0.11 mm (P_l) and was significant at P< 0.00l. The mean shattering index ranged between 0.62 ± 0.02 (B_l) and 0.85 ± 0.01 (B_5) and variation of the values were significant at P< 0.00l. The mean values of shattering index for binder (10%) and particle size 4.0 mm (D_1) showed minimum shattering index. The compressive strength of the briquettes ranged from 0.84 ± 0.05 Nmm^{-2} (B_l) to 1.20 ± 0.05 Nmm^{-2} (B_5) at different binder proportions at P< 0.05. The compressive strength of briquettes increased with increased binder proportions. Compaction energy of the briquette increased with increased compaction pressure and particle sizes. The variations were significant at P< 0.00l.

Combustive Characteristics of Water Hyacinth

The obtained values of thermal fuel efficiency of water hyacinth briquettes showed that increased binder subsequently increased the fuel efficiency from 16.78 ± 0.24% (B_l) to 28.73 ± 0.48% (B_5) as shown in Table 4.Binder (B_4) could be regarded as the optimum binder level required to produce briquettes of acceptable thermal fuel efficiency and low smoke. The thermal fuel efficiency values at the four compaction pressure levels ranged from 16.80 ± 0.22% (P_l) to36.94 ± 0.47% (P_3) as shown in Table 5. With increase in applied pressure, briquettes become more compact. Combustion rate is reduced due to high density with decrease in voids. Similar result was reported by Mallika *et al*. (2015). The applied pressure clearly influenced the thermal fuel efficiency, calorific value, ignition time, and water boiling time. Burning rate increased with the increase of applied pressure.

Table 4: Combustion Characteristics of water hyacinth briquettes and binder proportions

Combustion parameters	**Bi (10%) Mean ± SEM**	**B2 (20%) Mean ± SEM**	**B3 (30%) Mean ± SEM**	**B4 (40%) Mean ± SEM**	**B5 (50%) Mean ± SEM**
Thermal fuel efficiency %	16.78 ± 024d	17.64 ± 03.31c	19.54 ± 0.50b	78.00 ± 0.58a	28.73 ± 0.48a.
Ignition time (min)	66.61 ± 3.88e	78.56 ± 2.91d	89.47 ± 2.51c	101.25 ± 3.09b	107.92 ± 2.92a
Calorific value (J/g)	3443.03 ± 59.42c	3605.92 ± 53.09d	4185.75 ± 77.0c	4444.0 ± 40.43b	4533.56 ±22.44a
Specific fuel consumption (g/l)	290.69 ± 7.78a	281.08 ± 7.64b	271.22 ± 7.46c	256.31 ± 6.51d	252.50 ± 6.86c
Burning rate (g/min)	2.30 ± 0.15a	2.01 ± 0.13b	1.89 ± 0.14c	1.71 ± 0.12d	1.57 ± 0.11c
Burning time (min)	14.09 ± 0.32d	14.16 ± o.26c	15.58 ± 0.29b	16.03 ± 0.20b	17.04 ± 0.21a

Means with the same letter along the column are not significantly different (P > 0.05); SEM = Standard error of mean

Table 5: Combustion characteristics of water hyacinth briquettes and compaction pressure levels

Combustion Parameters	**Pl (3 MPa) Mean ± SEM**	**P2 (5 MPa) Mean ± SEM**	**P3 (7 MPa) Mean ± SEM**	**P4 (9 MPa) Mean ± SEM**
Thermal fuel efficiency (%)	16.80 ± 0.22d	18.44 ± 0.31c	36.94 ± 0.47b	28.17 ± 5.8a
Ignition time (mm)	74.64 ± 3.54d	86.98 ± 3.27c	93.96 ± 3.26b	98.47 ± 3.19a
Calorific value	3437 ± 82.80a	3432 ±81.94a	3445 ± 79.79a	3430 ± 73.62a
Specific fuel consumption (g/l)	287.07 ± 7.24a	273.89 ± 7.00b	264.87 ± 625c	255.62 ± 5.86d
Burning rate (g/min)	2.13 ± 0.13a	1.94 ± 0.12b	1.84 ± 0.11c	1.68 ± 011d
Water boiling time (min)	14.51 ± 0.26c	15.10 ± 0.31b	15.13 ± 0.27b	15.58 ± 0.26a

Means with same letter along the column are not significantly different (P > 0.05); SEM = standard error of mean

Comparison of Combustion Characteristics of Water Hyacinth and Other Energy Sources

The thermal fuel efficiency of the fuel sources were water hyacinth briquettes (28.17 ± 0.88%), bituminous–charcoal (31.29 ± 0.19), red mangrove wood (23.55 ± 0.56%) and firewood (*Anthonothamacrophylla*) (21.31 ± 0.28%) (Table 6). The thermal fuel efficiency values differed significantly (P < 0.001) (Table 7). The fuel efficiency of charcoal (31.29 ± 0.19%) was the highest followed by water hyacinth briquette (B_4 P_4 D_1) (28.17 ± 0.88%).The calorific values of the energy sources ranged from 447 ± 16.82 kcal/kg (fire wood) to 6552.00 ± 4.73 kcal/kg (bituminous-charcoal) (Table 6).

The variation in the calorific values of the fuel types was significantly different (P < 0. 001). The calorific value of the water hyacinth briquette was higher than the calorific values of *Anthonothamacrophyla* firewood and red mangrove wood but lower than charcoal. This is an indication that more heat during combustion was generated from briquette than firewood and mangrove but lesser than charcoal. The recorded water boiling time values were 11.43 ± 0.43 min (briquette), 14.94 ± 0.22 mm bituminous–charcoal). 9.25 ± 0.42 min (*Anthonothamacrophylla* firewood) and 8.99 ± 0.22 min (red mangrove firewood). Ranking of the mean values of combustion properties of briquettes showed no significant different (P< 0.005), except for burning rate and specific fuel consumption. Similar result was obtained for bituminous charcoal. Also, thermal fuel efficiency, calorific value, and ignition time showed no significant different (P< 0.005). The obtained values of the water boiling time for different energy sources were significantly different at P <0.001as shown in Table 7. The burning rate values of the energy sources ranged between 0.97 ± 0.01 g/min (bituminous-charcoal) and 2.49 ± 0.01 g/min (*Anthonothamacrophylla* firewood).

Table 6: Combustion properties of the various energy sources

Combustion Propitiates	**Energy Sources**			
	Briquettes mean ± SEM	**Bituminous charcoal Mean ± SEM**	**Fire wood *(AntonothaMacrophylla) Mean ± SEM***	**Red mangrove wood Mean ± SEM**
Thermal fuel efficiency (%)	28.17 ± 0.88b	31.29 ± 0.19b	21.31 ± 0.28d	23.55 ±0.56c
Calorific value	447 ± 16.82b	6552.00 ± 4.73a	4166.67 ± 4.33d	4398 ± 6.57c
Burning rate (g/min)	1.25 ± 0.016 c	0.97 ±0.016d	2.49 ± 0.016a	2.05 ± 0.016b
Water boiling time (min)	11.43 ± 0.43b	14.94 ± 0.22a	9.25 ± 0.42c	8.99 ± 0.22d
Ignition time (min)	115.00 ± 0.88b	138.00 ± 0.19a	83.34 ± 0.28d	92.67 ± 0.56c
Specific fuel consumption (g/l)	217.00 ± 0.57d	228.00 ± 2.52c	264.00 ± 28a	253.33 ± 1.86b

Means with different letters are significantly different (P < 0.05); SEM = Standard error of mean

Table 7: ANOVA of combustion properties of the various energy sources

Properties	Source	DF	SS	Mean square	F-value	Pr>F
Calorific value	Energy Error Corrected Total	3 8 11	2350900.917 2203.333 2353104.250	783633.639 275.417	2845.27	< 0.001
Water boiling time	Energy Error Corrected Total	3 8 11	57.771 2.778 60.549	19.257 0.347	55.46	< 0.001
Burning rate	Energy Error Corrected Total	3 8 11	8.381 0.001 8.382	2.794 0.0001	27936.00	< 0.001
Specific fuel consumption	Energy Error Corrected Total	3 8 11	8006.250 86.667 8092.917	2668.750 10.833	246.35	< 0.001
Thermal fuel efficiency	Energy Error Corrected Total	3 8 11	182.001 7.161 189.162	60.667 0.895	67.77	<0.001
Ignition time	Energy Error Corrected Total	3 8 11	182.001 7.161 189.162	60.667 0.895	67.77	< 0.001

The variation of the burning rate values of fuel types was significantly different (P < 0. 001). The specific fuel consumption of the four fuel sources were 217.00 ± 0.58 g (briquette), 228.00 ± 2.52 g (charcoal), 264.00 ± 2.08 g (firewood) and 253.33 ±1.86 g (mangrove). The variation of the specific fuel consumption values of the energy sources was significantly different (P < 0.001). The ignition time of the energy sources varied between 83.33 ± 0.28 sec (*Anthonothamacrophylla* firewood) and 138.00 ± 0.19 sec (Bituminous charcoal). There was significant difference in variation of the ignition time of the energy sources. The observed values on ignition time showed that charcoal took a longest time for it to start burning as compared to other energy sources. This could be due to its low volatile matter and high ash content.

CONCLUSIONS

The production of briquettes from water hyacinth using plantain peels as binder is feasible and its physical and combustion characteristics compared favourably with briquettes from other agricultural residues. This study found that particle size, percentage binder ratio and compaction pressure significantly (P<0.001) affected the physical and combustion characteristics of water hyacinth briquettes. The combustion characteristics of water hyacinth briquettes competed favourably with those of firewood, mangrove wood and charcoal. The variables with particle size D_l (0.5 mm), binder ratio B_4 (40%) and compaction pressure P_4 (9MPa) exhibited the most positive attributes than other variables examined in the study.

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