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Development And Performance Evaluation of a Torrefaction Machine for the Production of Combustible Energy Source

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Abstract
The demand for sustainable energy has intensified research into biomass torrefaction as an alternative to fossil fuels. This study focuses on the design, development and performance evaluation of a torrefaction machine optimized for processing low density polyethylene (LDPE) biomass composites at 250°C and 300°C for 60 minutes. Key design parameters, including shaft speed, conveyor mechanisms and heat distribution were optimized to enhance efficiency. The effects of torrefaction on the thermal, mechanical and flammability properties of four rice husk to polymer formulations in percentage [A(80/20), B(60/40), C(40/60) and D(20/80)] respectively were analyzed. Physico-thermal properties such as moisture content (MC), volatile matter content (VMC), fixed carbon content (FCC), ash content, calorific value (CV) and flammability characteristics were evaluated. The mechanical properties that were assessed are hardness, tensile strength, impact resistance and compression yield strength (CYST). Results indicate that increasing polymer content enhances FCC, CV (8,539.45 Kcal/kg), burn duration (330s), hardness and CYST (6.5872), while reducing MC and VMC. Sample D containing 20% rice husk & 80% polymer which exhibited the highest energy density and structural integrity is ideal for high-energy and load-bearing applications. Whereas Sample A containing 80% rice husk & 20% polymer is suitable for quick combustion applications because of its rapid ignition of 3s at 300°C. The results from polymer-rich LDPE-biomass composites will be useful for industrial, metallurgical and energy applications.

Keywords: T**orrefaction**, **Temperature, Energy, Nuggets, LDPE biomass**

1.0 INTRODUCTION

1.1 Background of study

The extensive use of fossil fuels for energy has become a major cause of global warming due to increasing emission of carbon dioxide into the atmosphere.There are several sources of energy ranging from fossil fuels to renewable source(Garba et al., 2018). Most of this world energy needs are derived from fossil fuel such as coal, oil and natural gas. Fossil fuels are non-renewable and demand for this energy is projected to increase, creating concern for sustainability.

The importance of energy and fuel cannot be over-emphasized, hence for effective economic growth and development of a country, the energy has to be adequate and affordable. However, to find a balance between growing economy, environmental protection and improved quality of life in the nearest future, there is need for renewable energy source. The demand for biomass as a better fuel is high, though raw biomass has a relatively low density, energy and contains too much moisture which cannot during storage and is also difficult to comminute in small particles.

In Nigeria, the major source of energy in the rural community is fuel wood and with the uncontrolled level of cutting of wood for fire wood and charcoal for combustion and for other domestic and industrial uses, fuel wood source is becoming a serious problem in the country. This has led to environmental degradation, deforestation and misuse of soil forests and water resources.

Bio-energy is among the highly promising energy resources that is renewable which hold not just the key to the present fuel problem but also a future solution (Omemu et al., 2018). Biomass is an organic material derived from plants or animals, excluding materials that take millions of years to produce such as coal or petroleum (Basu, 2010). The energy produced from biomass does not contribute acid rain gases due to the negligible sulphur and nitrogen contents of biomass (Demirbas, 2008).Biomass energy is a renewable energy source that can be used in three forms namely solid as briquette, Nuggets, Char, liquid as ethanol, biodiesel and gaseous as producer gas, biogas (Koh & Hoi, 2003).

As an energy source, biomass can either be used directly through combustion to produce heat or indirectly after converting it to various forms of bio-fuel which thermal (briquetting, torrefaction, pyrolysis and gasification), chemical and biochemical methods are part of those processes.

Biomass is generally characterized by its high moisture content and volatility. Also, itslow higher heating value and energy density level compared to fossil fuels (Pondel 2015).

The potential for the use of biomass as energy source in Nigeria is very high because about 80% of Nigerians are rural and semi-urban dwellers and they solely depend on biomass for their energy needs (Onuegbu & Igwe, 2011).

A technology that meets all these challenges mentioned above and also improves the quality of biomass as fuel is torrefaction. Torrefaction and briquetting of biomass process improves the handling characteristics of the biomass, enhances its volumetric calorific value and reduces transportation cost (Sandip et al., 2014). This technology among so many advantages is eco-friendly with rice husk and straw mostly available in Nigeria in a large quantity

Torrefaction is a mild form of thermal degradation at temperatures ranging between 200^0c and 300^0c in an inert and enclosed environment. During torrefaction process, common biomass reaction includes devolatilization, depolymerisation and carbonization of hemicelluloses, lignin and cellulose.The torrefaction process produces a brown to black uniform solid product as well as condensable (water, organics and lipids) and non-condensable gases (CO_2, CO and CH_4).

Torrefied biomass is a new green fuel source resulting from a mild degradation applied to feedstock on conditions between drying and carbonization process.

Torrefaction makes the material undergo maillard reactions. Torrefied biomass can be used as an energy carrier or as a feedstock in the production of bio-based fuels and chemicals.To create efficient biomass-to-energy chains, torrefaction of biomass combined with densification (pelletization or briquetting) is a promising step towards overcoming the logistical challenges in developing large-scale sustainable energy solutions, by making it easier to transport and store. Nuggets or briquettes have higher density, contain less moisture and are more stable in storage than the biomass they are derived from.

The torrefaction process (machine) enhances the effectiveness of biomass as solid fuel which leads to improvement of combustion properties such as increased calorific value, adiabatic flame temperatures and reduced volatility (Muhammad et al., 2014). The torrefaction machine also helps to achieve increased hydrophobicity, better grinding and decrease in biological degradation activity. The degree to which the biomass properties are altered depends on the supposed severity of torrefaction, which relates to the residence time and temperature used in the process(Yash et al., 2014).

1.2 Objectives of the study

The general objective of this research is to contribute in the improvement of the technology used in designing and development of the torrefaction machine for the production of stored combustible energy source.

The following specific objectives will be carried out in this research

i) To design and develop the torrefaction machine
ii) To produce a high combustible energy source on calorific value, heating value, ash content and fixed carbon value using the torrefaction machine
iii) To characterize a combustible energy source using a polymeric composite of biomass through torrefaction process.

1.3 Significance of the study

The performance evaluation of the torrefaction machine and characterization of its product is of great importance as

1. It could serve as a source of credible information for industrialist to evaluate the advantages of using a torrefaction machine to other methods in the production of stored combustible energy source
2. It would also enable users to know the optimum pre-determined parameters of the torrefaction machine.
3. It will help to produce a stored combustible energy source for usage in the metallurgy industry.

2.0 DESIGN ANALYSIS AND SPECIFICATIONS OF THE TORREFACTION MACHINE FOR THE PRODUCTION OF COMBUSTIBLE ENERGY SOURCE

2.1 Design Concepts and Considerations

The machine was designed to torrefy LDPE-biomass composite materials in a manner to remove the moisture and other volatile constituents and enhance the production of high calorific value and dense nuggets to be used as alternative energy source

From the onset, it was our intention to make the design incorporate already available components instead of requiring the production of part which will add to the cost of the machine.

The specification process was rather iterative in nature. From the literature we had to set a target temperature value for the heating chamber and then employ engineering equations to work backwards to obtain the other parameters and specifications of the components. The determination of the minimum force needed to drive the machine and hence the specification for the electric motor followed the same process. The following was determined; machine production capacity, efficiency of the machine, speed of drive, power consumption, energy requirements/specific mechanical energy consumption and diameter of shaft conveyor.

The following machine specifications were considered for the design

2.2Determination of the Speed of the Drive (Shaft Speed)

Below is a relationship used to determine the transmitted speed according to Khurmi and Gupta 2012 (Khurmi& Gupta, 2012).

$$\frac{N1}{N2} = \frac{D2}{D1} \qquad \text{(i)}$$

Where N_1 = speed of rotation of driving pulley in rpm

N_2 = speed of rotation of driven pulley in rpm

D_1 = diameter of the driving pulley

D_2 = diameter of the driven pulley

2.3 Shaft design analysis/consideration

The shaft is cylindrical with circular cross section and a coupling mounted on end linked to the shaft of a geared motor for low-speed drive. The shaft will be subjected to fluctuating torque and bending moments, and therefore combined shock and fatigue factors are taken into account. Bending moment and shear force bending can occur as a result of the applied loads on the shaft.

i) Shaft subjected to twisting moment only

Torsion equation

$$\frac{F_t}{r} = \frac{T}{J} = \frac{C\theta}{t} \qquad \text{(ii)}$$

Where, F_t = tensional shear stress

R = distance from neutral axis to outermost

J = twisting moment (or torque)

C = modulus of rigidity of shaft material
L = length of shaft
θ = angle of twist in radius on a length l
(ASME 1995)
Polar moment of sound solid shaft
$J = \frac{\pi}{32} x\ d^4$

$\frac{T}{\frac{\pi}{32} Xd4} = \frac{f_t}{\frac{d}{2}}$,

where $r = \frac{d}{2}$

$T = f_t \ x\ \frac{\pi}{32}\ x\ d^4\ x\ \frac{2}{d}$

$T = f_t \ x\ \frac{\pi}{16}\ x\ d^3$

Twisting moment, T can be obtained from $P = \frac{2\pi NT}{60}$

ii) Shaft subjected to bending moment only

Bending equation is given by

$\frac{M}{I} = \frac{f_b}{y}$ (iii)

Where, M = bending moment

I= moment of merits of cross-sectional area of the shaft about axis of rotation

f_b = bending stress

y = distance from neutral axis to outer most fibre#

But, $I = \frac{\pi}{64}\ x\ d^4$

Then $M = \frac{f_b}{y}\ x\ I$

$M = \frac{f_b}{y}\ x\ \frac{\pi}{64}\ x\ d^3$

But $y = \frac{d}{2}$

$M = \frac{\pi f_b}{32}\ x\ d^3$

Also bending moment equation is given by M = w x L

2.4 Determination of shaft diameter

The diameter, *d* of the poly film dehumidification machine transmission shafts was determined from the maximum stress relations given by Khurmi and Gupta (2012) as:

$$d = \left[\frac{16}{\pi \tau} \sqrt{(k_b m_b)^2 + (k_t m_t)^2} \right]^{1/3} \qquad \text{(iv)}$$

But equivalent maximum twisting moment is given as

$$T_e = \frac{\pi}{16} \text{ x } \tau \text{ x } d^3 = \sqrt{M^2 + T^2} \quad \text{(v)}$$

2.5 Selection of electric motor for the operation of the torrefaction machine

The power required to drive the torrefaction machine is determined as

$$P = T\omega \qquad \text{(vi)}$$

Where p = power, T= torque and ω = angular velocity

But $\omega = \frac{2\pi N}{60}$

where, N= speed of machine.

$$P = \frac{2T\pi N}{60}$$

2.6 Determination of heat source/ quantity of heat

The degrading temperature of torrefaction process is between 200^0C – 300^0C. We choose 200^0 C target temperature of the barrel. The materials must be raised from room temperature of 25^0 C to 200^0C and above. Assuming a comingled plastic and biomass of mass 200g as torrefied and bagged, so the quantity of heat needed to raise this temperature from 25^0C to 200^0C can be calculated thus;

Q = heat needed to raise the material to its drying point

$$Q = mC_p\theta \qquad \text{(vii)}$$

Where; m = mass of material and measured at 200g

C_p = specific heat capacity of material and has been determined from standard table as 2.004KJ/KgK

θ = temperature change = 200 - 25 = 175^0C.

The heat source must be able to generate this amount of heat and the amount of heat that will be lost to the surroundings.

3.0 DEVELOPMENTAL PROCEDURE/DESCRIPTION OF THE TORREFACTION MACHINE FOR THE PRODUCTION OF COMBUSTIBLE ENERGY SOURCE

The major components of the deveopled torrefaction machine include barrel, screw, variable speed motor, die, heating element, temperature controller, thermocouple, buzzer. The detailed production drawing for the fabrication of this machine are shown below.

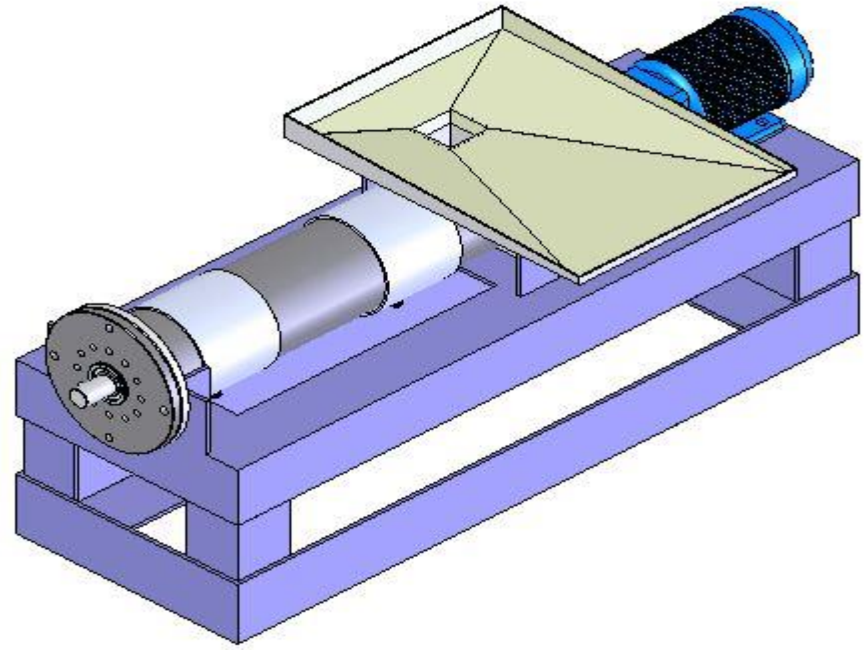

Fig. 1 The Isometric View of the Developed Torrefaction Machine

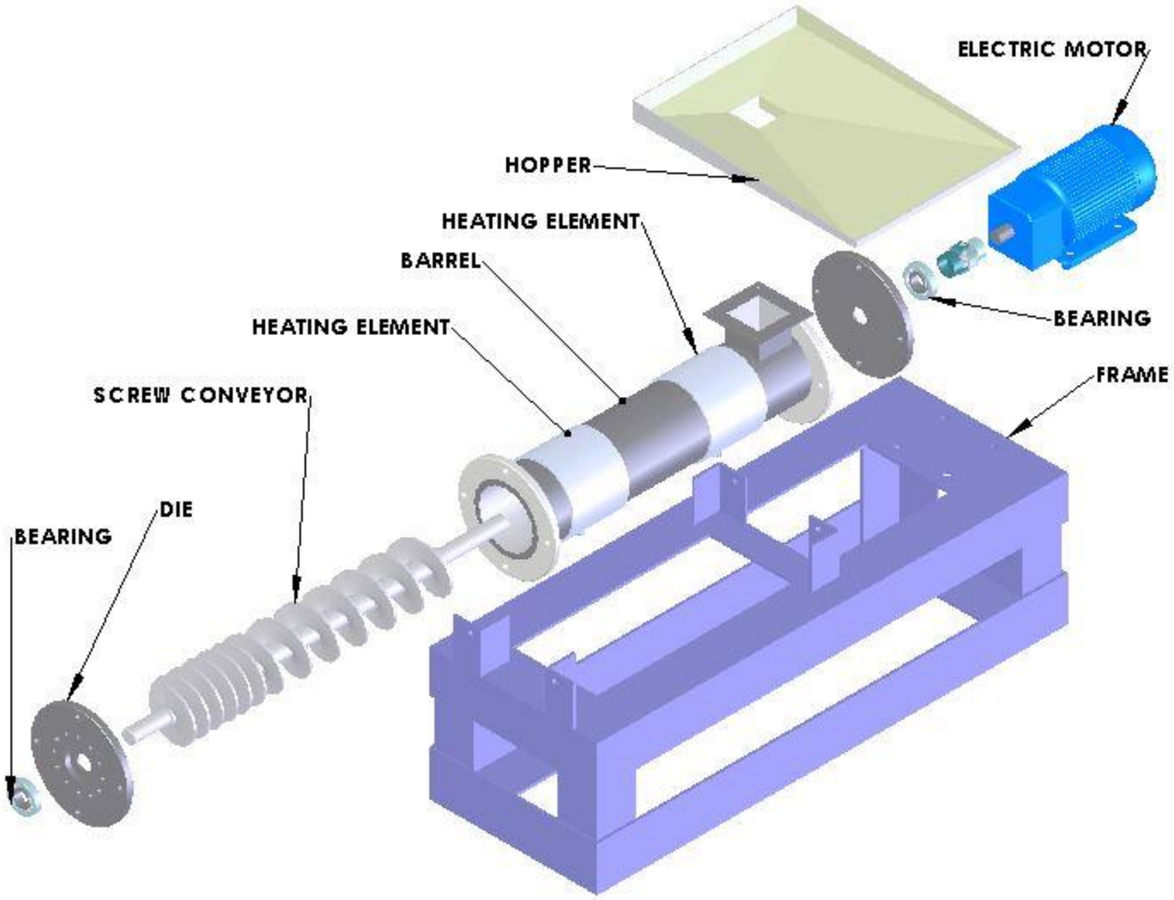

Fig. 2 Exploded View of the Developed Torrefaction Machine

However, the design of the torrefaction included the determination of the power and speed of drive of the motor, determination of the internal diameter of the barrel, configuration of the screw, power of the heating elements and also the selection of a convenient material for the fabrication of the individual units. The bulk of the parts of the equipment were fabricated using mild steel pipe, angle iron and mild steel sheet, this is because it is easiest to be joined among all other metals. It is a very versatile material necessitating its use by many industries for fabrication of process unit equipment. It is also readily available and affordable.

The machine was fabricated with 50x50x2mm angle bar to give rigidity and stability that will withstand load and vibration. The heating compartment is where heat required for the thermal operation is generated from and transferred into the barrel by means of the principles of conduction and convection. The machine is powered by a geared motor via a cable connected to the electrical components that energizes the equipment.

3.1 Performance Testing Procedure

Rice husk and dehumidified LDPE-waste sourced from Ebonyi and Enugu state respectively was used for the evaluation of this machine. Evaluations of the machine were carried out at temperatures of 250^0c and 300^0c at 60minutes duration for different LDPE-rice husk composite compositions [A(80/20), B(60/40), C(40/60) and D(20/80)] in percentage.

The LDPE-rice husk mixture was fed into the machine and allowed to be torrefied for the time frame stated above. The experimentations were done for about four different times to obtain the average performance of the machine for the two different temperature readings.

3.2 Development of Mathematical Model Procedures for Performance Evaluation of the Machine

The effects of screw speed, temperature, power and torque parameters on system responses: drying efficiency and throughput were investigated. The temperature attained by the effect of heat generated through the heating element at the time of drying was read by a thermocouple well embedded on the barrel. The objective was to understand the effect of screw speed and drying system variables (power, speed, temperature and torque) on the performance of the machine.

The following independent factors or variables were considered; electric motor power, screw diameter, amount of heat generated, screw speed, torque etc. The dependent variables/responses of the machine are moisture content, ash content caloric value, heating value fixed carbon content, drying efficiency (DE), drying rate (throughput TP).

Amount of moisture removed M_w, (kg)

The amount of moisture to be removed from a given quantity poly film waste to bring the moisture content to a safe usable/processing level in a specified time is calculated from the equation below according Khurmi and Gupta (2012);

$$M_r = M_o \frac{M_i - M_f}{100 - M_f} \quad \text{(viii)}$$

where;

M_o = initial mass of the poly film waste to be dried

M_i = initial moisture content, % wet basis

M_f = final moisture content, % wet basis

Moisture content (M_c)

The moisture content was determined by the gravimetric method according to the official methods of analysis employed by Association of Official Analytical Chemist (AOAC) 2009.

$$M_c = \frac{M_i - M_f}{M_i} \text{ x } 100 \quad \text{(ix)}$$

where;

M_i = mass of poly film waste before drying

M_f = mass of poly film waste after drying

Percentage Moisture content of the wet basis

$$\% \text{ wet basis} = \frac{moisture\ retained}{sample\ weight} \text{ x } 100 \quad \text{(x)}$$

Percentage Moisture content of the dry basis

$$\% \text{ dry basis} = \frac{moisture\ retained}{weight\ of\ sample - moisture\ retained} \text{ x } 100 \quad \text{(xi)}$$

Hence

Average drying rate, M_{dr} (kg/hr)

Average drying rate, M_{dr} was determined from the mass of moisture to be removed by heat generated through frictional force and drying time by the equation below;

$$M_{dr} = \frac{M_w}{T_d} \quad \text{(xii)}$$

Where,

M_{dr} = drying rate

M_w = moisture to be removed

T_d = time taken for drying to occur

Drying Efficiency DE,

$$DE = \frac{wet\ basis}{dry\ basis} \times 100 \qquad (xiii)$$

$$DE = \frac{output\ weight\ of\ dried\ polyfilms}{input\ weight\ of\ wet\ polyfilms} \times \text{Throughput} \qquad (xiv)$$

$$DE = \frac{output\ weight\ of\ dried\ polyfilms}{time\ taken\ for\ drying} \qquad (xv)$$

3.3 Physico-Thermal Analysis

Prior to torrefaction, the samples of the rice straw, rice husk and polymer prepared was subjected to physico-chemical analysis with the following physical and thermal parameters measured.

The mechanical parameters measured were:

Moisture Content- The samples were dried in an oven (Uclear England Model number: DHG-9053A) at 105^0C until the samples arrived at a constant weight according to BS EN 14774-1 standard. The values taken were measured in triplicates and the average value recorded for each briquette sample. Moisture content was calculated using equation

$$\text{Moisture content} = \frac{Wb-Wa}{Wb} \times 100 \qquad (xvi)$$

whereW_b is the weight of sample before oven drying

W_a is the weight of sample after oven drying on a dry basis

Hardness Test -It used for determining the hardness of briquette when dropped on concrete floor from a height of one meter. The weight and size of the disintegrated briquette was recorded. The percentage loss of the material was calculated by using the equation

$$\text{Percentage of weight loss} = \frac{w2-w1}{w1} \qquad (xvii)$$

where W_1 = Weight of briquette before shattering (g)

W_2 = Weight of briquette after shattering (g)

Tensile Test -This is a measure of the maximum stress a material can withstand without breaking of failing when stretched or pulled. It is used in various applications where they may be subjected to tensile forces.

Tensile strength is typically measured in units of force per unit area (e.g.; MPa, Psi) and is calculated by dividing the maximum force applied to the material by its original cross-sectional area.

Test procedure:

- Sample preparation: Cutting the composite material into a standard shape and size (e.g., ASTM D638 Type 1).
- Clamping the sample: Securing the sample between the grips of the testing machine applying force.
- Applying force: Gradually increasing the tensile force until the sample breaks of fails.
- Measuring strength: Recording the maximum force (stress) at which the sample fails.

Tensile strength is typically reported in units of stress (e.g., MPa or psi).

Impact Test -This is also known as impact resistance or toughness test.It is a measure of a material's ability to absorb energy and plastically deform without breaking or shattering when subjected to a sudden impact or shock. It is an important property for materials that may be exposed to drops, collisions, or other types of impact loading. In the context of LDPE-sawdust composites, impact strength is an important property to consider as it determines the material's ability to withstand impacts and drops without cracking or breaking.

Impact test is typically reported in units of energy such as Joules (J), Foot-pounds (ft-lb) or Newton-meter (N-m). This testing property can be done using a standard method of American Society for Testing Materials (Izod impact test ASTM D790, Charpy impact test ASTM D6110 or Drop weight impact test ASTM D4226).

Test procedure:

The tests involve striking a sample with a controlled amount of energy and measuring the resultant damage or breakage.

Compression Yield StrengthTest – This refers to the stress at which the specimen begins to deform plastically (yield point). This test evaluates the compressive properties of torrefied LDPE-rice husk waste composite. It is determined by ASTM D695: Standard Test Method for Compressive Properties of Rigid Plastics or ISO 604: Plastics - Determination of compressive properties.

Test procedure:

1. Conditioning: The test specimen is conditioned at a controlled temperature (23^0c ± 20^0c) and humidity (50%± 10%) for at least24 hours before testing.
2. Compression testing: The conditioned specimen is placed between the compression platens of universal testing machine (UTM).
3. Loading: A compressive load is applied to the specimen at a constant rate (typically 1-5mm/min) until the specimen yields or fails.
4. Data collection: The compressive load and displacement are recorded during the test.

The thermal properties measured were:

Ash Content – Two grams of each briquette sample was measured then placed in a crucible of known mass and oven dried to constant mass. These samples are later heated in the furnace (Vecstar Ltd, Model No/Serial No: LF3/F4244) of 555^0C for 4hours according to ASTM E-1755-01 standard (47) and weighed after cooling. the ash content was then estimated from the percentage loss in mass of the sample using equation xix.

$$\text{Ash Content} = \frac{D}{B} \times 100 \qquad \text{(xviii)}$$

where D is weight of ash (Furnace dried) (g)

B is the weight of the oven dried sample (g)

Volatile Matter Content –Two grams of each briquette sample was measured and placed in a crucible of known mass and oven dried to constant mass. a heating furnace (Vecstar Ltd, Model No/Serial No: LF3/F4244) was used at a temperature of 555^0C for 10minutes according to CEN/TS 15148 standard method also used by Onukak et al and Ogwu et al. (Ogwu et al., 2022; Onukak et al., 2017). The volatile matter (Vm) was then evaluated as the percentage loss in mass of the sample using equation

$$\text{Vm} = \frac{B-C}{B} \times 100 \qquad \text{(xix)}$$

where B is the weight of sample before oven drying

C is the weight of the sample after oven drying

Fixed Carbon Content - To determine the percentage fixed carbon of each sample of briquette, equation was utilized as stated by Sengar et al and Adelek et al (Adeleke et al., 2021; Sengar1 et al., 2012).

$$F_c\ (\text{wt\%}) = 100 - (V_m + M_c + A_c) \qquad \text{(xx)}$$

whereV_m is Volatile matter

M_c is Moisture content

A_c is Ash content

F_c is Fixed carbon content of the briquette sample

Calorific value:The calorific value is the total energy released as heat when a substance undergoes complete combustion with oxygen under standard conditions. The chemical reaction is typically a hydrocarbon or other organic molecule reacting with oxygen to form carbon dioxide and water and release heat. It may be expressed with the quantities:

- energy/mole of fuel
- energy/mass of fuel
- energy/volume of the fuel

Flammability test:The combustibility tests for torrefied LDPE-rice husk waste composite evaluate its burning behaviour and potential fire hazards.A vertical burn test (ASTM D641) was used for this research work. It is a test on biomass nuggets to evaluate their tendency to ignite, spread flames, and sustain combustion. The prepared sample was vertically mounted in a metal frame. An ignition source (bunsen burner) was placed 19mm below the sample's bottom edge, and flame was applied to it for 10 seconds. As the flame was removed, the following burning behaviour was observed.

a) Ignition time (sec)
b) Time to self–extinguish (sec)
c) Glow time (sec)
d) Ignition of cotton indicator.
e) Burning rate

A standard Test Method (ASTM D7140-18) was used for test. The measured samples were ignited using a controlled ignition, and each was calculated using the formula below:

$$\text{Burning Rate} = \frac{\text{Change in mass}}{\text{Change in time}} \qquad \text{(xxi)}$$

Its unit is in mass per unit time (g/s).

3.4 Characterization

A composition of 100% rice husk and polymer mixture in different ratios was torrefied. Samples of the torrefied material (nuggets) were packaged for further analysis at 250^0c and 300^0c for 60 minutes respectively.

Four (4) sets of each composition sample mixture were labelled A, B, C and D respectively such that;
Mixture of 80% rice husk and 20% polymer is considered as A

Mixture of 60% rice husk and 40% polymer is considered as B
Mixture of 40% rice husk and 60% polymer is considered as C
Mixture of 20% rice husk and 80% polymer is considered as D

All the sample mixtures were kept at the same atmospheric temperature and pressure condition before analyses. Aseptically, a nugget was collected from each sample mixture for mechanical and thermal parameters. The values obtained in the 250^0C and 300^0C temperatures were compared with respect to the parameters evaluated. Hence the values were used to determine the efficiency of the machines.

4.0 RESULTS AND DISCUSSION

4.1 Results Obtained Prior to Torrefaction and Post Torrefaction

Table 4.1:Physico-thermal analysis of torrefied LDPE-biomass waste mixture for temperature of 250^0C at 60 minutes

Sample code	Parameters										
	Thermal properties				Flammability properties			Mechanical properties			
Sample	AC	VMC	FCC	CV	IG-T	EX-T	GL-T	MC	H	IT	CYST
A	10.970	1.46	84.09	7,631.45	-	-	-	2.71	-	-	-
B	9.482	1.37	85.94	7,567.67	-	-	-	4.51	-	-	-
C	7.718	1.31	88.57	7,888.38	-	-	-	3.52	-	-	-
D	7.718	0.65	94.27	8,539.45	2	402	2	1.49	54.0	0.0655	3.0573

Table 4.1 shows various samples of different compositions of LDPE-Rice husk composite at torrefaction temperature of 250^0C. The volatile matter content (VMC) decreased as the percentage of the rice husk reduced in the composition with the extinguishing time (flammability test) increasing.

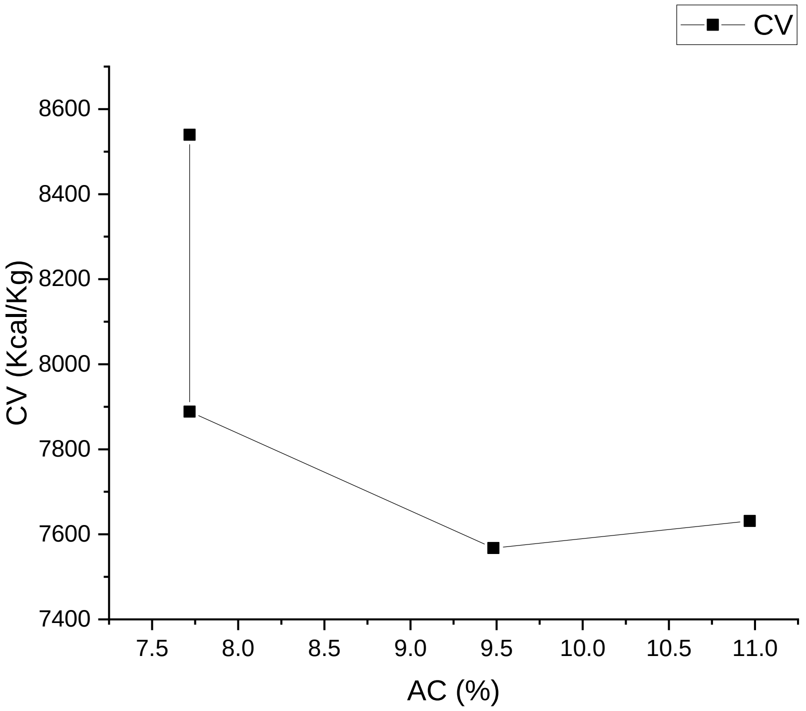

Figure 1 Graph of Calorific Value versus Ash Content

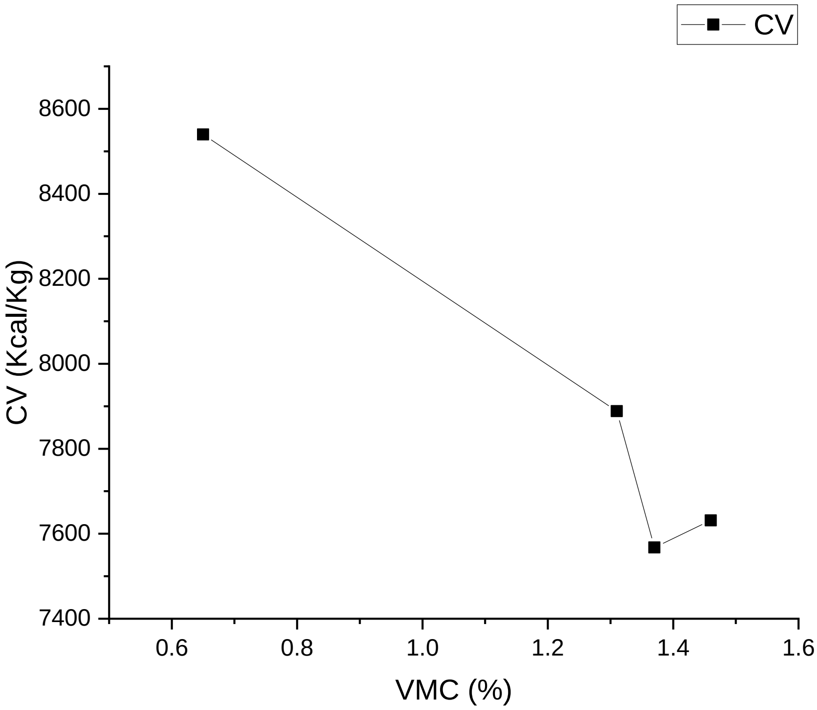

Figure 2 Graph of Calorific Value versus Volatile Matter Content

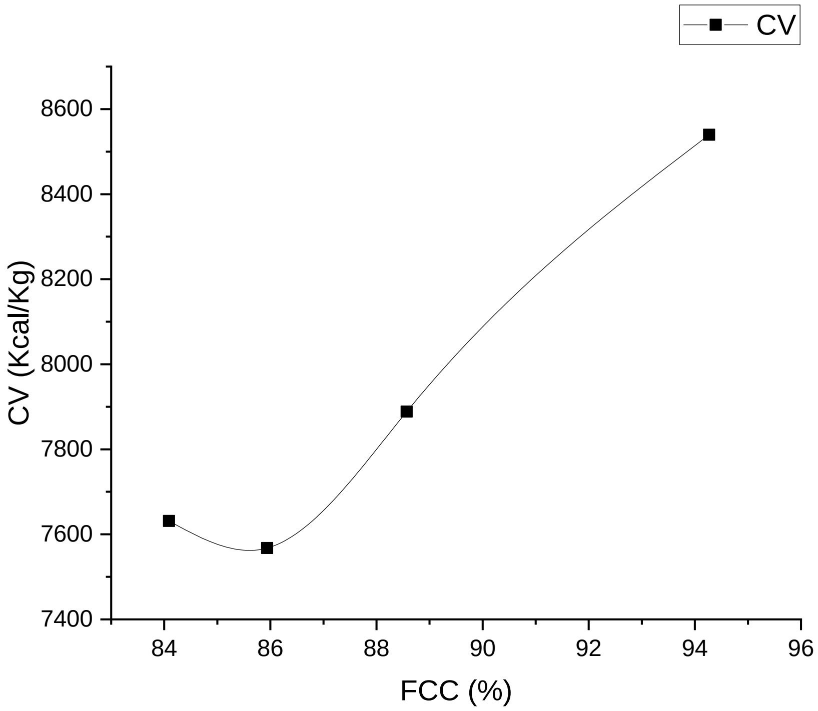

Figure 3 Graph of Calorific Value versus Fixed Carbon Content

Table 4.2: Physico-chemical analysis of torrefied LDPE-biomass waste mixture for temperature of 300^{0}C at 60 minutes

Sample code	Parameters										
	Thermal properties				Flammability properties			Mechanical properties			
	AC	VMC	FCC	CV	IG-T	EX-T	GL-T	MC	H	IT	CYST
A	4.634	0.83	95.70	8,461.84	3	279	5	2.11	58.5	0.0324	5.5732
B	8.673	0.19	90.81	8,224.14	2	290	3	0.56	60.0	0.0352	4.2463
C	8.780	0.04	90.62	8,245.62	2	300	4	0.43	61.0	0.0398	5.4272
D	7.619	0.02	91.12	8,337.35	9	330	17	0.39	60.0	0.0109	6.5872

Table 4.2 shows various samples of different compositions of LDPE-rice husk composite at torrefaction temperature of 300^{0}C.The extinguishing time (flammability test) increased as the percentage content of the polymer increased with the volatile mater content decreasing.

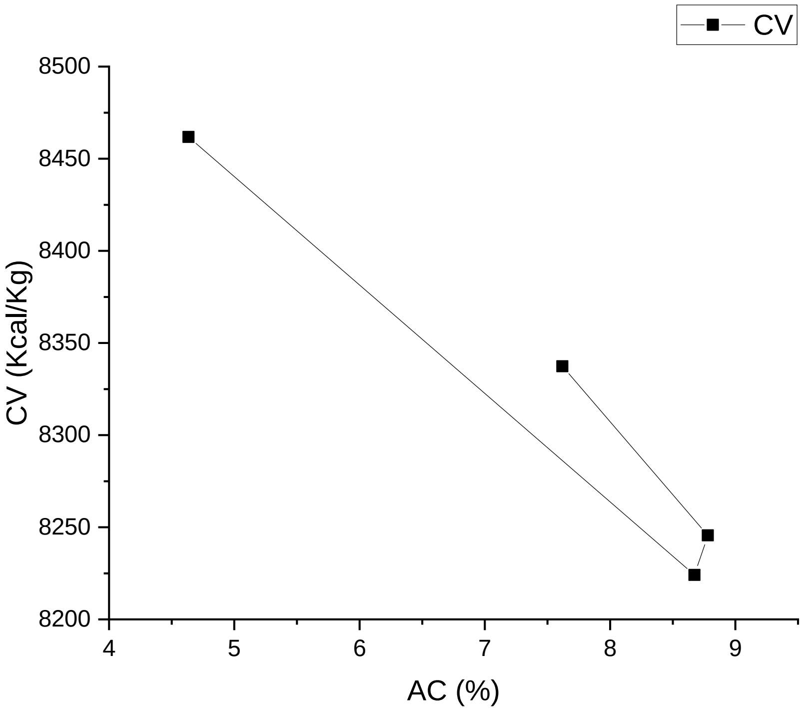

Figure 4 Graph of Calorific value versus Ash content

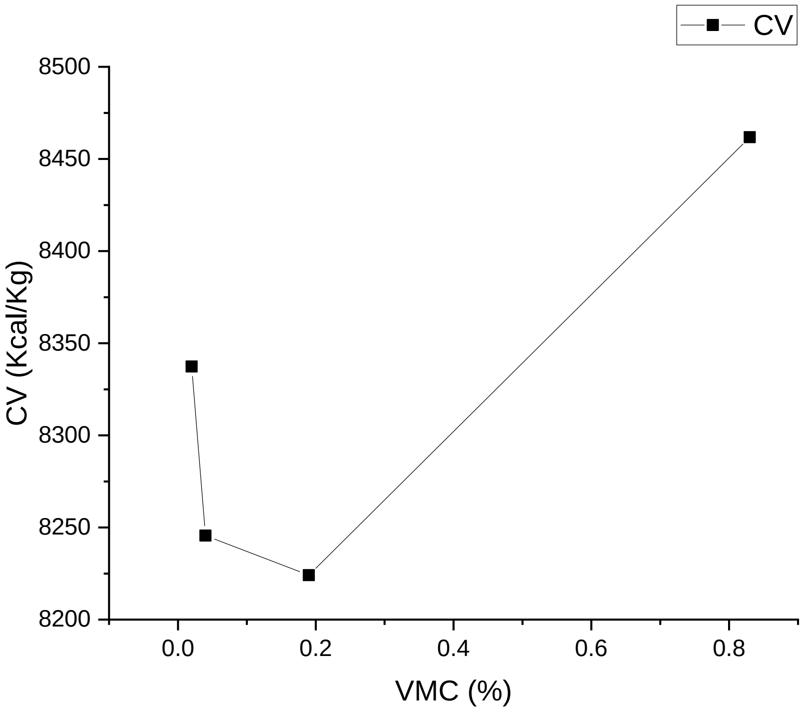

Figure 5 Graph of Calorific value versus Volatile matter content

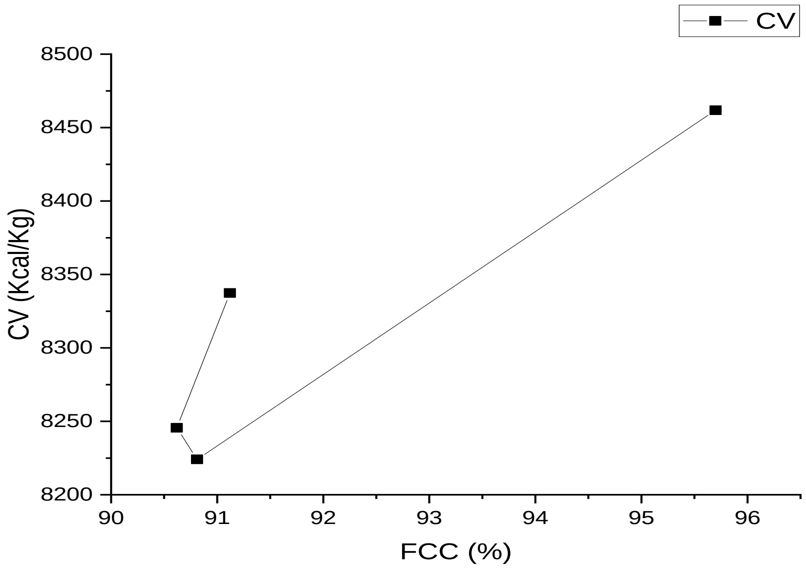

Figure 6 Graph of Calorific value versus Fixed carbon content

Description of terms used in tables 4.1 and 4.2

A = Mixture of 80%rice husk and 20%polymer
B = Mixture of 60%rice husk and 40%polymer.

C = Mixture of 40%rice husk and 60%polymer.

D = Mixture of 20%rice husk and 80%polymer.

AC = Ash content (%)

VMC = Volatile matter content (%)

FCC = Fixed carbon content (%)

CV = Calorific value (Kcal/kg)

IG-T = Ignition time (sec)

EX-T = Extinguishing time (sec)

GL-T = Glow time (sec)

MC = Moisture content (%)

H = Hardness test

IT = Impact test (J/mm^2)

CYST = Compression yield strength test

4.2 Discussion

The data in Table 4.1 presents the physico-thermal, flammability, and mechanical properties of LDPE-biomass composite mixtures torrefied at 250°C for 60 minutes. The composite samples (A, B, C, and D) differ in the ratio of rice husk to polymer content, with Sample A containing the highest biomass percentage (80% rice husk, 20% polymer) and Sample D containing the lowest biomass percentage (20% rice husk, 80% polymer).

As the polymer content rises, the ash content (AC) declines, falling from 10.97% in Sample A to 7.718% in Samples C and D.. Furthermore, the volatile matter content (VMC) significantly decreases with higher polymer content, from 1.46% in Sample A to 0.65% in Sample D.

The fixed carbon content (FCC) demonstrates an upward trend with increasing polymer content, rising from 84.09% in Sample A to 94.27% in Sample D. This trend is attributed to a decrease in volatile matter and enhanced carbon retention during the torrefaction process, which improves the thermal stability of the composite(Bridgeman et al., 2008). Additionally, the calorific value (CV) also increases with higher polymer content, ranging from 7,567.67 Kcal/kg in Sample B to 8,539.45 Kcal/kg in Sample D.

In relation to the flammability assessment of sample D, the IG-T value noted at 2 seconds demonstrates a quick ignition response. The extended time required for extinguishment indicates a longer duration of burning, which can be linked to the substantial carbon retention from the polymeric substances (Ogabi et al., 2021). Furthermore, the GL-T recorded at 2 seconds indicates limited smoldering following the extinguishment of the flame, a behaviour that is typical of composites rich in polymers.

Sample D exhibits a relatively low moisture content of 1.49%, which can be attributed to the drying effect of torrefaction, thereby enhancing the composite's stability and its resistance to biodegradation (Medic, 2012). The hardness value of 54.0 suggests that the material has increased strength, likely due to a higher polymer content that enhances structural rigidity (Kabir et al., 2012). Furthermore, a moderate impact toughness of 0.0655 J/mm² indicates a fair level of impact resistance, while a CYST of 3.0573 points to improved mechanical durability, likely resulting from polymer reinforcement (Najafi, 2013).

These results imply that a higher polymer content in LDPE-biomass composites significantly improves the material's thermal, flammability, and mechanical properties. The observed reduction in ash content and volatile matter supports the effectiveness of torrefaction in enhancing carbon retention. Furthermore, the increase in calorific value corresponds with previous research that indicates polymer-rich composites have a higher energy potential(Bridgeman et al., 2008). The flammability tests on Sample D show that a greater polymer content extends the duration of combustion, which could be beneficial for applications requiring controlled burning.

Analyzing the mechanical properties, Sample D demonstrates superior performance characterized by elevated hardness and compression yield strength, rendering it an ideal choice for applications that demand greater structural integrity. Additionally, its lower moisture content suggests enhanced resistance to degradation, a vital factor for prolonged storage and use (Kabir et al., 2012).

The data in Table 4.2 presents the physico-thermal, flammability, and mechanical properties of LDPE-biomass composite mixtures torrefied at 300°C for 60 minutes.The ash content (AC) in Sample A experienced a notable reduction of 4.634%, in contrast to the higher polymer content samples B and C, which recorded AC values of 8.673% and 8.780%, respectively. This observation implies that elevated temperatures facilitate a more thorough combustion of biomass constituents. In Sample D, the volatile matter content (VMC) plummeted to a mere 0.02%, suggesting that increased torrefaction temperatures further diminish volatile substances, thereby enhancing thermal stability (Prins et al., 2006). Conversely, the fixed carbon content (FCC) exhibited a slight increase across all samples, reaching a maximum of 95.70% in Sample A, which indicates that the carbonization process is optimized at 300°C. Additionally, there was a general enhancement in the calorific value (CV) across all samples, with values ranging from 8,224.14 Kcal/kg in Sample B to 8,461.84 Kcal/kg in Sample A, supporting the conclusion that higher polymer content contributes to improved fuel efficiency.

In the flammability assessment, IG-T was observed to increase to 9 seconds in Sample D, indicating that the higher polymer content has resulted in a delay in ignition. Conversely, EX-T showed an upward trend across all samples, reaching a peak of 330 seconds in Sample D, which emphasizes the extended burning times that are beneficial for applications involving sustained combustion. The GL-T values ranged from 3 to 17 seconds, with Sample D exhibiting the longest duration, suggesting a prolonged afterglow potentially due to char formation from the polymeric constituents(Ghomi et al., 2020).

Across all samples, the moisture content (MC) exhibited an upward trend, with Sample D recording the lowest value at 0.39%. This finding indicates an enhancement in stability and resistance to environmental degradation. The hardness of the samples improved marginally, with Sample C achieving the highest measurement of 61.0, which implies a direct correlation between the polymer content and the rigidity of the material. The impact toughness (IT) values remained fairly uniform across the samples, ranging from 0.0109 J/mm² to 0.0398 J/mm², indicating minimal fluctuations in impact resistance at higher torrefaction temperatures. Furthermore, a notable increase in compressive yield strength (CYST) was observed, peaking at 6.5872 in Sample D, reinforcing the conclusion that increased polymer content enhances both structural strength and durability (Najafi, 2013).

These results imply that elevating the polymer content in LDPE-biomass composites significantly improves the material's thermal, flammability, and mechanical properties. The lower levels of ash and volatile matter support the effectiveness of torrefaction in enhancing carbon retention. The increase in calorific value corresponds with previous research that indicates polymer-rich composites have a higher energy potential (Bridgeman et al., 2008). The flammability tests on Sample D show that increased polymer content extends the burning duration, which could be advantageous for applications involving controlled combustion. From a mechanical perspective, Sample D outperforms others, showcasing greater hardness and compression yield strength, making it suitable for applications that require superior structural integrity. Furthermore, the lower moisture content reflects an improved resistance to degradation, which is crucial for long-term storage and application (Kabir et al., 2012).

5.0 CONCLUSION AND RECOMMENDATIONS

The study reveals that elevating the polymer content in LDPE-biomass composites significantly improves their thermal, mechanical, and flammability attributes. The machine torrefies the LDPE-rice husk mixture by decomposing, mixing and extruding the composite in a densified form called nuggets. The observed decrease in volatile matter and the increase in fixed carbon content indicate that torrefaction effectively stabilizes and carbonizes the composites, leading to enhanced thermal efficiency.

The machine demonstrate a high degree of efficiency in carbonization of the composite by products of a durable and energy densed nuggets through the removal of adequate moisture content and volatile matter content.

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