Conversion of Palm Kernel Shell into Improved Solid Fuel through Torrefaction Process

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ABSTRACT

Oil Palm fruits (*Eleasis guineensis*) processing yields considerable quantity of palm kernel shell (PKS) which otherwise would have been regarded as a waste. However, this has been predominantly used in rural area as fuel through direct combustion which is inefficient, has poor properties, polluting and is considered a low grade fuel. Better grade fuel could be derived through torrefaction process. The aim of this study was to investigate the potential of torrefaction process to improve the properties of palm kernel shell (PKS) as a solid fuel. The torrefaction process was carried out under temperature ranges between 200ºC to 350ºC, and residence time of 20, 30 and 40 minutes respectively. The torrefied PKS was characterized in terms of the mass yield, energy yield, calorific value, moisture and volatile matter contents, ash content and fixed carbon contents. The torrefied product yields were determined by weighing and proximate analysis using the association of official analytical chemist (AOAC) method. The higher heating value was determined using an oxygen bomb calorimeter. Percentage torrefied product, energy yield, moisture and volatile matter content decrease as the torrefaction temperature and residence time increase, while the ash content and fixed carbon content substantially increased which led to a remarkable increase in higher heating value from 18.31 MJ/Kg to 28.63 MJ/Kg. The results of the experiment; proximate and physical analyses have shown that torrefaction process has significantly improved the fuel properties of PKS, and the process could be used to upgrade it as traditional solid fuel.

Keywords: calorimeter, combustion, higher heating value, palm kernel shell, proximate analysis solid fuel, torrefaction,

1.   INTRODUCTION

Energy demand is increasing continuously due to rapid development in population and industrialization, and the development of energy sources is not keeping pace with the spiraling consumption. Developed countries are also finding it difficult to even-up energy demand and supply due to growth pressure even after increasing the energy production multifold. World's oil reserves are estimated to get depleted by 2050. The major energy demand is compensated from energy sources such as coal, oil, natural gas etc. (Saxena *et al*., 2009).

The United States of America analyzed the rate of depletion done to the ozone layer as a result of fossil fuel which serves as the bulk of energy in use and discovered that the rate of depletion has greatly increased. This was due to the harmful elements released after the burning of petroleum fuels (Mark *et al*., 2005). It is well known that SO_2 emission produced by burning fossil fuels is the major cause of acidic rain. Globally, increase in emissions rates of greenhouse gases particularly CO_2 present a threat to the world climate. As an estimate in the year 2000, over 20 million metric tons of CO_2 were expected to be released into the atmosphere every year (Putun *et al*., 2001 and Bridgewater *et al*, 2003). If this trend continues, some extreme natural calamities are expected such as excessive rainfall and consequent floods, droughts and local imbalance.

These harmful gases released to the atmosphere which causes changes in atmospheric condition and human health deterioration serves as point of challenges to consider alternative sources of energy, which biomass provides.

Biomass energy is a form of renewable energy source and it is derived from domestic wastes, agricultural residues, animal wastes etc.(Jianghong, 2007). Biomass is seen as a more environmental friendly and longer lasting than fossil fuels. Biomass has another advantage over fossil fuels in that plants suitable for producing biomass can be grown almost anywhere in the world. Fossil fuels like petrol are only produced in certain areas of the world. Different sources of biomass have one or more effects on the living organism, human, and the living environment. Some of the effects include deforestation, competition with food materials and other industrial usage which results in more demand for such product, hence, the research into a less competitive product in terms of the environment and inhibiting organism (Demirbas, 2009). And this prompted the selection of the Palm kernel shells (PKS) for this research.

The conversion of biomass into useful energy can produce heat and electricity. The conversion methods include; thermo-chemical, bio-chemical and mechanical conversion. Mechanical conversion method involves compressing the materials together which is known as briquetting. Biochemical method of conversion entails biological activities such as fermentation, aerobic activities on the material and introduction of micro-organism on the material. Thermo-chemical conversion method involves the use of heat, which includes; direct combustion, gasification, pyrolysis and torrefaction.

Torrefaction is a thermo-chemical conversion method of biomass into improves energy products in the low temperature range of 200-300°C (Van *et al*, 2011). Torrefaction may be called mild-pyrolysis. Different reaction conditions (temperature, inert gas, reaction time) and biomass resources lead to the differences in solid, liquid and gaseous products (Nimlos

et al, 2003). During torrefaction, approximately 25-30% of mass reduction occurs and most of which is accounted for by the vaporization of oxygen-containing molecules (Chin *et al*, 2013). The energy loss associated with the mass loss for optimum product is approximately 10% of total energy content in the feedstock (Pirraglia et al., 2012). Finally, the resulting product appears as energy densified deep brown to black solid which is highly hygroscopic in nature. The product is quite easy to handle, transport and most importantly, it is suitable to burn in existing coal-fired power plant. Because of the advantages of torrefied biomass (bio-coal) to be used as co-firing with coal or full replacement of coal in the existing coal fired power plant and a potentially huge market for electricity generation, the process of torrefaction has received potential interest over the last years (Pirraglia *et al*., 2012 and Malhotra, 2011). In this study, torrefaction of palm kernel shell produced as bio-residues during oil palm processing was carried out to upgrade the material to a value-added fuel.

2   MATERIALS AND METHODS

2.1 Sample Acquisition and Preparation

For the experiment, 10 kg of palm kernel shell (PKS) were collected from Ajaawa, Ogo Oluwa local government, Oyo state, Nigeria. Samples were pre–treated by removing foreign materials like sand, stone, and other plant residue from the samples, then the samples were sundried to reduce the moisture content as shown in Plate 1. Samples were analyzed chemically according to the official methods of analysis by the association of official analytical chemist (A.O.A.C) and all analysis carried out in duplicate.

Plate 1: Palm Kernel Shell during sun drying

2.2 Torrefaction procedure

Torrefaction was carried out in the Crop Processing Laboratory of the Department of Agricultural Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria. The experiment was carried out using a laboratory batch-type torrefaction system which consists of Reactor (round bottom flask), Gallenkamp muffle heating furnace ($1100^{o}C$ capacity), Gallenkamp weighing balance, and digital stopwatch.

A 250 ml round bottom flask (reactor) was placed inside the preheated furnace chamber. It was ensured that the furnace door was securely locked so as to prevent the flow of oxygen.
The muffle furnace was turned on and allowed to heat up to the desired temperature. For each experimental run, a predetermined mass (20 g) of the prepared sample is loaded into the reactor and placed inside the heating furnace. The torrefaction flow line was completed by quickly closing the furnace door. The stopwatch was started after completing the flow line. As the reactor in the furnace was subjected to elevated temperature, torrefaction reaction commences. The heat supplied decomposes the sample inside leading to production of solid remnant (biochar) shown in Plate 2.

At the end of the set time, the furnace was switched off. The furnace was allowed to cool for two minutes before unloading the reactor. The reactor containing the biochar was removed from the furnace and allowed to cool in the desiccators before weighing the content. The solid product yield from the experiment was evaluated using the relation in equation 1

$$Y_{BC}\,(\%) = \frac{Weight\ of\ Biochar}{Weight\ of\ raw\ palm\ kernel\ shell}\,x100 \quad (1)$$

Where;

Y_{BC} = the solid yield of the bio-char expressed as a percentage.

2.3 Determination of Ash Content (AC)

Finely ground oven dried sample was placed in a porcelain crucible and weighed, W_1, before it was transferred into a preheated muffle furnace set at temperature of 900°C. The furnace was left on for about an hour after which the crucible with the content was transferred to the desiccators and allowed to cool. The crucible with its content was re-weighed, W_2, and the weight of the empty crucible was Wc, the ash content (% dry basis), was given as;

$$Ash\,(\%) = \frac{(W_2 - W_c)}{(W_1 - W_c)}\,x\,100 \quad (2)$$

2.4 Moisture Content (MC) Determination

The apparatus used in the determination of the moisture content were oven, crucibles, desiccators and weighing balance. The moisture content of the torrefied char was determined in accordance with the certified method. A known weight of the samples, Wo, was oven dried at a temperature of 103±2°C until a constant weight, Wf was reached. The loss in the weight of each sample expressed as a percentage of Wf

will give the moisture content on dry basis, MC (db), as;

$$MC\,(\%) = \frac{W_0 - W_f}{W_f}\,x\,100 \quad (3)$$

2.5 Determination of Fixed Carbon (FC)

The fixed carbon content was determined by computing the difference between 100 and the sum of the moisture(MC), volatile matter (VC) and Ash contents (AC) of the samples and it is given as;

$$FC = 100 - (MC + VC + AC) \quad (4)$$

2.6 Determination of Volatile Content (VC)

The air–dried samples of the palm kernel shell W1 was heated at about 900°C for seven minutes in a partially enclosed porcelain crucible, placed in a furnace, in accordance with BSI standard. The crucible was retrieved and left to cool in the desiccators. The weight of the refuse left content (VC) was determined with the equation 5.

$$VC\,(\%) = \frac{W_1 - W_f}{W_f}\,x\,100 \quad (5)$$

Where;

Wf = the oven-dried weight of samples

2.7 Determination of Higher Heating Value and Energy yield

The calorific value (HHV) of raw and torrefied palm kernel shell was measured using bomb calorimeter. The value was used to determine energy yield for each sample using the equation 6:

$$Y_E\,(\%) = \frac{HHV\ of\ torrefied\ palm\ kernel\ shell}{HHV\ of\ raw\ palm\ kernel\ shell}\,x$$
$$solid\ yield\,(\%) \quad (6)$$

Where;

Y_E = the energy yield expressed as a percentage.

3 RESULTS AND DISCUSSIONS

3.1 Analysis of physiochemical properties of the raw palm kernel shell

Table 1: Physiochemical properties of raw

Properties	Value	Value from Amin and Murni (2011)
Moisture	4.01%	2.88%
Ash content	1.80%	4.29%
Volatile matter	89.26%	84.86%
Particle size	≤8.5mm	250μm
Fixed carbon	9.10%	10.85%
Higher Heating Value	18.02MJ/kg	18.18 MJ/Kg

The results of analysis of physiochemical properties of raw palm kernel shell as determined are shown in Table 1. The results were compared with previous study using similar procedure, it was discovered that some of the properties tested were similar to the value obtained by Amin and Murni (2011) in terms of volatile matter, fixed carbon content and higher heating value. The observed dissimilarities could possibly be as a result of difference in location of study, and the particle sizes. The high moisture content accounted for the smaller percentage of ash content.

3.2 Biochar (mass) yield from Torrefied Palm Kernel Shell

Biochar is the material remains after the torrefaction process. At different temperature and residence time, the percentage biochar yield (mass) is presented in Table 2. It was observed that as the torrefaction temperature increases the material (PKS) break down under high temperature to produce smaller percentage of biochar. The least biochar produced was 50% at 350 °C and 40 min. torrefaction temperature and residence time respectively, while at 200 °C and 20 min the highest biochar yield (mass) was produced. Thus, for a higher biochar yield, temperature and residence time have to be minimal.

The energy values as presented also in Table 2 show the same trend as the biochar yield, although at a much greater value. The results established the process as suitable to transform the material (PKS) to value-added energy, and this agreed with the findings of Amin and Murni, (2011). The value decreases with increase in torrefaction temperature and residence time. It thus implies that for a value-added energy, the torrefaction process should be within a lower range of temperature.

Furthermore in Table 2, the calorific value (HHV) of the torrefied PKS is presented. The results indicated that as the temperature and residence time of the torrefaction process increase, the calorific value was also increasing. The increase in calorific value of torrefied product ranges between 1.61- 58.88%. The high increase in the upper range (58.88%) of calorific value occurred as a result of high temperature beyond recommended value of 300°C of torrefaction process, which confirmed the findings of Bergman as reported in Jaya *et al*, (2011), that increasing the temperature to >300°C results in extensive

devolatization and carbonization of the polymers. The value of HHV (19-24 MJ/Kg) in this study compare with findings of other researchers Amin and Murni, (2011) (19 – 22 MJ/Kg) and Jaya *et al* (2011) (20 – 24 MJ/Kg) within the same limit of temperature ranges (200 – 300 ºC).

3.3 The Physical and Proximate analysis of the Torrified PKS

The results of physical and proximate analysis of the torrefied PKS which include; the moisture content, volatile matter, ash content and fixed carbon content respectively are shown in Table 3. The fixed carbon and ash content of the torrefed PKS increased with the increase in torrefaction temperature and residence time. The increase in temperature with longer residence time resulted in decomposition and devolatization reactions which otherwise could be regarded as destructive drying process. This thereby leads to extensive carbonization and ash production. The range of increase in ash content was between 144 – 317%, while fixed carbon increase ranges between approximately 1 – 249%. In the torrefaction process, the two determinant factors which are; temperature and residence time, largely have impact on the torrefed PKS.

Moisture and volatile matter declined with increase in temperature and residence time. The moisture content of the torrefed PKS decreases in the range of 42 – 76 % due to the gradual increase in torrefaction temperature with commensurate increase in residence time of the process. Moisture loss, which is one of the components in condensable products, makes a major contribution to the total mass reduction. Volatile matter, like the moisture content also reduces with increase in torrefaction conditions (temperature and residence time). It was observed that the reduction in the volatile matter was between

approximately 6 – 33% from the initial torrefaction temperature of 200 ºC and 20 min. residence time and the highest conditions of 350 ºC and 40 min. The torrefaction process drives away the volatile matter as well as fixed carbon from the biomass due to the decomposition and the devolatization reactions. The decrease in the volatiles along with the chemical transformation of the remaining polymeric components produces brittle, black coloured carbonaceous coal-like solid torrefed products as shown in Plate 2. The increase in residence time and temperature reduces the volatile content of the biomass. The results agreed with similar studies (Amin and Murni, 2011) although with little degree of variation.
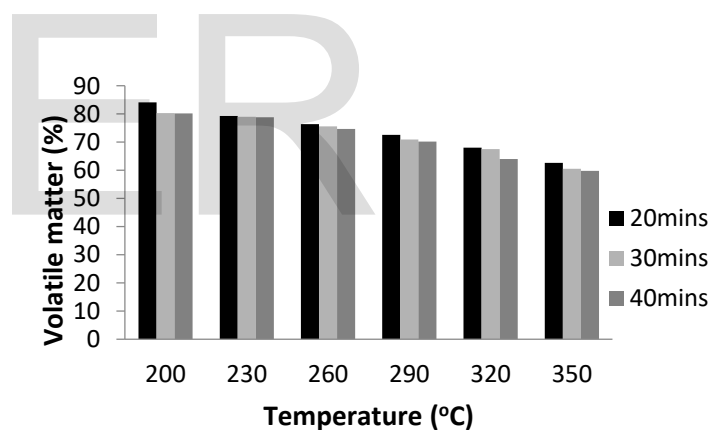

Fig. 1: Effect of torrefaction temperature and residence time on Volatile Matter content

Also, in Fig. 2, there is a gradual decrease in the biochar yield with increase in torrefaction conditions. Thus, the highest biochar yield was recorded at the lowest temperature regime of 200 ºC and residence time of 20 minutes which was about 92%.
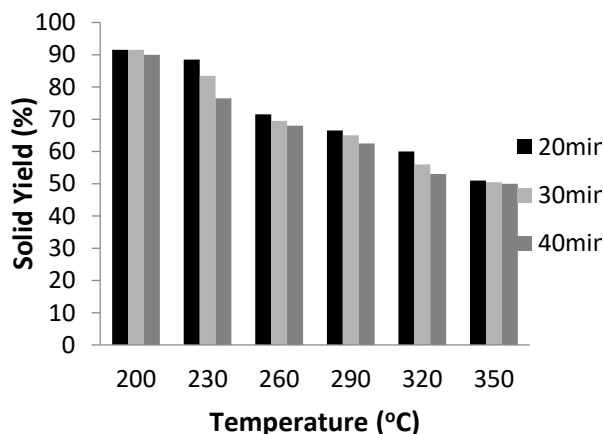
Fig. 2: Effect of temperature and residence time on solid yield (biochar)

CONCLUSION

Palm kernel shell was torrefied at a temperature of 200ºC to 350ºC at a step of 30ºC with a residence time of 20mins, 30mins and 40mins respectively.

The experimental and physio-chemical analyses results show that the solid and energy yields of torrefied palm kernel shell decreased with the increase of the torrefaction temperature and residence time. The HHV of torrefied palm kernel shell increased with the increase of the torrefaction temperature and residence time. The fixed carbon and ash contents of torrefied palm kernel shell increased, while the moisture and volatile matter contents decreased with the increase in torrefaction temperature and residence time.

Comparing the results of determined properties of the raw palm kernel shell and torrefied palm kernel shell has shown that torrefaction process has significantly improved the properties of palm kernel shell as a solid fuel.

Conflict of Interest: The authors hereby declare that they have no conflict of interest.

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Plate 2: Sample of Solid by-product (bio-char) after torrefaction process

Table 2: Calorific Value of Torrefied product at different temperature and residence time

Sample	Temperature (ºC)	Residence Time (mins)	Biochar (mass) Yield (%)	Calorific value HHV (MJ/Kg)	Energy value (%)
1.	200	20	91.5	18.31	93.02
		30	91.5	18.56	93.78
		40	90.0	19.02	95.01
2.	230	20	88.5	19.81	97.20
		30	83.5	19.87	91.79
		40	76.5	20.01	84.99
3.	260	20	71.5	20.33	80.59
		30	69.5	20.81	80.26
		40	68.0	21.22	80.04
4.	290	20	66.5	21.71	80.12
		30	65.0	22.89	81.02
		40	62.5	23.91	82.94
5.	320	20	60.0	24.82	82.60
		30	56.0	25.62	79.65
		40	53.0	26.17	76.83
6.	350	20	51.0	27.84	78.72
		30	50.5	28.39	79.31
		40	50.0	28.63	79.40

Table 3: The result of proximate analysis of torrefied palm kernel shell at different process conditions.

Sample		Proximate Analysis				
Temp(ºC)	Time (mins)	Moisture (%)	Ash content (%)	Volatile matter (%)	Fixed Carbon (%)	Particle size (mm)
200	20	2.34	4.4	84.1	9.16	≤8.5
	30	2.27	4.4	80.3	13.03	≤8.5
	40	2.11	4.7	80.2	12.99	≤8.5
230	20	2.07	4.7	79.3	13.93	≤8.5
	30	2.01	4.9	79.0	14.09	≤8.5
	40	1.98	5.2	78.8	14.02	≤8.5
260	20	1.91	5.2	76.4	16.49	≤8.5
	30	1.91	5.8	75.6	16.69	≤8.5
	40	1.84	5.9	74.7	17.56	≤8.5
290	20	1.85	6.4	72.6	19.15	≤8.5
	30	1.77	6.6	70.9	20.73	≤8.5
	40	1.77	6.9	70.2	21.13	≤8.5
320	20	1.70	6.9	68.0	23.40	≤8.5
	30	1.63	7.0	67.5	23.80	≤8.5
	40	1.54	7.2	64.0	27.26	≤8.5
350	20	1.31	7.2	62.6	28.89	≤8.5
	30	1.01	7.4	60.5	31.09	≤8.5
	40	0.98	7.5	59.8	31.72	≤8.5