CARITAS UNIVERSITY AMORJI-NIKE, EMENE, ENUGU STATE

Caritas Journal of Engineering Technology

CJET, Volume 4, Issue 1 (2025)

Article History: ***Received: 2nd January, 2025; Revised: 20th February, 2025; Accepted: 25th February, 2025***

Performance Characteristics of Palm Kernel Shell-based Biomass Fuel

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Abstract

The transition toward sustainable and renewable energy sources has become imperative in addressing climate change and reducing greenhouse gas emissions. Biomass, particularly in the form of agricultural waste, presents a viable alternative to traditional fossil fuels. This study investigates the potential of palm kernel shells (PKS), an abundant yet underutilized by-product of palm oil processing in Nigeria as a clean and efficient biofuel through the process of briquetting. Two PKS samples, sourced from local and improved palm varieties, were subjected to pyrolysis to enhance their fuel characteristics. The charred PKS was then combined with varying proportions of cassava starch (25%, 30%, and 35%) as a binder and compressed into cylindrical briquettes. Proximate and ultimate analyses, along with calorific value determination and combustion performance tests, were conducted to assess the energy efficiency and environmental suitability of the briquettes. Results indicate that a 25% starch binder ratio produced the most efficient briquettes, characterized by high fixed carbon content, lower ash and moisture levels, and superior calorific value. Additionally, combustion tests revealed favorable ignition times, burning rates, and fuel consumption efficiency. The findings demonstrate the viability of PKS briquettes as a sustainable alternative to fuelwood and charcoal, offering both environmental and economic benefits. This study contributes to the development of renewable energy solutions in developing regions and underscores the value of waste-to-energy innovations in enhancing energy security and reducing ecological degradation.

Keywords: ***Biomass, Palm kernel shell, Briquettes, Energy, Combustion efficiency***

1. Introduction

The increasing urgency to reduce greenhouse gas emissions and mitigate climate change has intensified global interest in renewable energy sources. Among these, biomass has garnered substantial research attention due to its potential role in decarbonizing the energy sector and contributing to sustainability across the energy supply chain [1]. Biomass currently accounts for over 6% of the global primary energy supply and represents approximately 55% of all renewable energy consumption. Notably, in many developing countries, around 95% of the population still depends on traditional biomass sources such as firewood and charcoal for cooking and heating [2].

However, this heavy reliance on fuelwood has raised serious concerns regarding deforestation and the depletion of forest resources, prompting a search for alternative biomass sources [3]. Research has shown that utilizing biomass derived from combustible waste materials can be a sustainable solution. Such use not only curtails deforestation but also poses minimal environmental and health risks [4, 5].

Despite its potential, raw biomass presents several limitations that hinder its use in modern energy systems. These include low energy density and calorific value, inefficient combustion, high moisture content, and unfavorable size and shape, all of which contribute to high transportation and storage costs [6]. Additionally, burning raw biomass can release harmful pollutants due to its high organic content, leading to adverse environmental and health effects [7]. Briquetting—compressing biomass into solid fuel blocks—is one of the most effective methods currently being explored to overcome these limitations [8]. This process improves the physical and chemical properties of biomass, resulting in a denser, cleaner-burning, and more efficient solid biofuel that can replace traditional fuelwood and charcoal in stoves, boilers, and furnaces [9].

Palm Kernel Shells (PKS), a by-product of palm oil processing, are one such biomass material with high potential for energy generation. Among the materials investigated by Abdullah and Yusup [10], PKS demonstrated the highest promise as a renewable energy source. Additionally, Chen et al. [11] reported enhanced syngas production when PKS was combined with sewage sludge. Despite this potential, in rural regions of Nigeria and other developing countries where palm oil production is concentrated, PKS is often treated as waste. Large quantities are discarded or openly burned near palm oil mills, contributing to environmental degradation and posing health risks [12].

Furthermore, many palm oil producers view PKS as a nuisance rather than a resource, incurring costs for clearing land previously used as PKS dumping sites [13]. This wasteful disposal highlights the need for strategies to improve the utilization of PKS, such as briquetting, to enhance its fuel properties and encourage its adoption as a renewable energy source.

Studies by Azman and Pa [14] have shown that PKS briquettes perform better than traditional wood charcoal, offering greater energy efficiency and cleaner combustion. Additionally, converting PKS into briquettes can create economic opportunities for palm oil producers through the sale of value-added biofuels [15].

Despite the recognized potential of PKS, it remains underutilized in Nigeria. Limited awareness and technological adoption have resulted in continued wastage and environmental harm. This study addresses this gap by investigating the suitability of converting PKS into clean, affordable, and efficient briquettes. Specifically, the research evaluates the energy efficiency of PKS briquettes produced using varying proportions of starch as a binding agent. The study involves proximate and ultimate analyses, calorific value determination, and combustion testing to assess fuel performance. By achieving these objectives, the research aims to promote the adoption of PKS briquettes as a sustainable energy solution and support broader efforts toward environmental protection and energy security.

2. Materials and Methods

In this study, two distinct samples of Palm Kernel Shells (PKS) were used: Sample A, obtained from locally grown palm fruits, and Sample B, sourced from improved variety palm fruits. Both samples were collected from a palm oil mill located in the vicinity of Otuoke, Bayelsa State, Nigeria. Cassava starch, used as a binder in the briquetting process, was procured from a local market.

The briquette production process involved several stages. First, the PKS underwent pyrolysis treatment using a locally fabricated metallic container serving as a kiln. This process was conducted to reduce moisture content and improve combustion characteristics. Following pyrolysis, the treated PKS was mixed with varying proportions of cassava starch binder (25%, 30%, and 35%) by weight to form briquette mixtures.

A manually operated briquetting machine was used to compress the mixtures into solid briquettes under uniform pressure. This method allowed for consistent briquette shapes and densities across all samples.

The sequence of converting raw PKS into briquettes is presented in Figure 1.

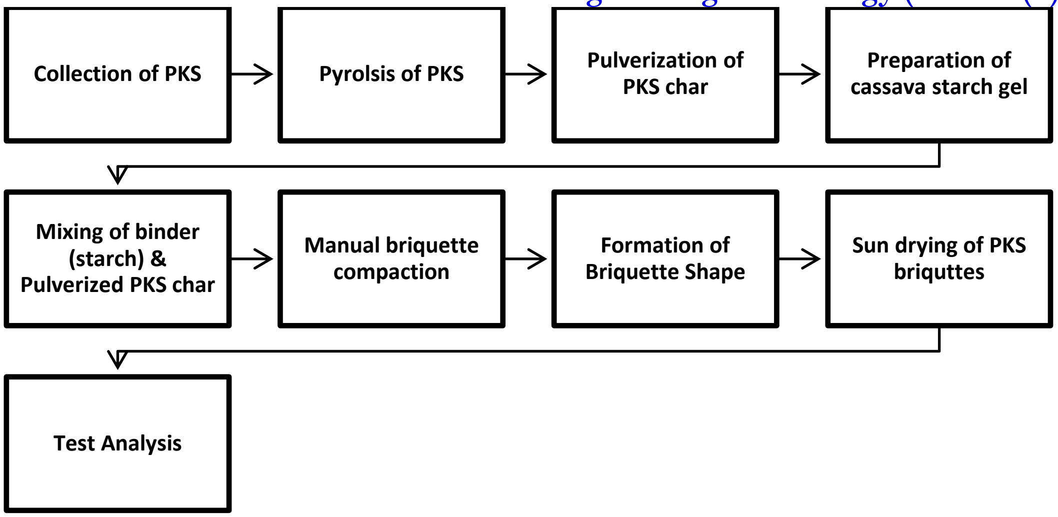

Figure 1: Briquetting process flowchart of PKS sample.

2.1 Sample Collection

The Palm Kernel Shell (PKS) samples used in this study were collected from two different palm oil processing facilities located near Otuoke, Bayelsa State, Nigeria, where PKS is generated as a by-product of palm oil extraction. Sample A was sourced from local palm oil mills in the Emeya area, while Sample B was obtained from the Bayelsa State Government-owned palm plantation. A representative image of raw PKS is shown in Figure 2(a).

2.2 Pyrolysis Treatment

The pyrolysis method adopted in this study followed the procedure described by Bonsu et al. [16]. Initially, the raw PKS samples were sun-dried for seven days to reduce their moisture content. A total of 1800 g of the dried PKS was weighed and divided into three portions of 600 g each. These portions were placed into three metallic containers, which functioned as kilns for biochar production.

To ensure even heat distribution during pyrolysis, holes were drilled at the base of each container using a nail. Additionally, a 15 cm diameter hole was cut into the lid of each container. A cylindrical metal pipe, 20 cm in length and 14.9 mm in diameter, was inserted through the opening to act as a chimney, enabling the escape of combustion gases.

Ignition was initiated by lighting a small quantity of dry biomass (primarily dried leaves) placed inside the container with the PKS. After initial smoke emissions subsided, sand was packed around the container's edges to seal it and contain the combustion process. Once sealed, the lid and chimney were secured on top, completing the setup for pyrolysis (figure 2(b)).

The PKS was pyrolyzed for two hours to produce biochar. Upon completion, the chimney was removed, and the biochar was allowed to cool for approximately 40 minutes. This procedure was repeated twice to process the remaining 1200 g of PKS.

2.3 Briquette Preparation

The resulting PKS biochar was pulverized using a mortar and pestle and sieved through a 2 mm mesh to obtain uniform particle sizes. Cassava starch, used as a binder, was prepared by dissolving 20 g of starch in 40 ml of cold water and mixing thoroughly to form a paste. Subsequently, 100 ml of boiling water was added and stirred to create a thick starch gel (figure 2 (c)).

Approximately 150 g of the pulverized biochar was gradually mixed with varying proportions of the starch gel (25%, 30%, and 35% by weight) using a stirring stick, resulting in a dense black paste suitable for briquetting.

The prepared mixtures were manually compressed into cylindrical molds. After compaction, the molded briquettes were ejected and sun-dried for seven days to reduce residual moisture and enhance structural integrity. A central hole was introduced into each briquette to promote uniform combustion. Samples of the finished briquettes are presented in figure 2 (d).

Following the drying period, the briquettes were subjected to a series of analyses—proximate, ultimate, and combustion tests—to evaluate their fuel properties, including moisture content, calorific value, ash content, and combustion efficiency.

2.4 Proximate Analysis

Proximate analysis was conducted to determine key fuel parameters such as moisture content, volatile matter, ash content, and fixed carbon. These properties were assessed in accordance with ASTM D3173 standards.

(a) (b)

(c) (d)

Figure 2: Briquetting materials: (a) Raw PKS, (b) Kiln for pyrolysis treatment, (c) Starch for binding and (d) PKS briquettes.

2.5 Ultimate Analysis

Ultimate analysis was performed to quantify the elemental composition of the briquettes, including carbon, hydrogen, oxygen, nitrogen, and sulfur content. This analysis was carried out using specialized analytical equipment at O.K. Research Laboratory, Rivers State, Nigeria.

2.6 Calorific Value

The calorific (heating) value, which represents the energy content of the briquettes, was determined using a bomb calorimeter. This test was also conducted at O.K. Research Laboratory, Rivers State, Nigeria.

2.7 Ignition Test

The ignition test was conducted to determine the time required for the briquette samples to ignite, defined as the point at which the briquettes began to glow red. Two briquette lumps from each of the A and B samples (prepared with 25% starch binder) were ignited near the base using a lighter. A stopwatch was used to measure the time taken for each sample to reach ignition. The test was performed twice for each briquette type, and the average ignition time was calculated and recorded.

2.8 Combustion Test

The combustion performance of the briquettes was assessed using a standard water boiling test. A measured quantity of each PKS briquette sample was placed in a charcoal stove and ignited with a lighter. Subsequently, 100 ml of water at room temperature was poured into a pot, which was then covered and placed on the stove. The time required for the water to reach boiling point was recorded using a stopwatch. During the test, the mass of the briquettes consumed was measured to evaluate combustion characteristics. From this data, specific fuel consumption (SFC) and burning rate were calculated to assess the fuel efficiency and combustion behavior of each briquette sample.

3. **Results and Discussion**

In this section, the results of the proximate analysis, ultimate analysis, calorific value, and combustion tests of the palm kernel shell (PKS) briquettes are presented and discussed to evaluate their suitability as biofuel. The **proximate analysis** provided insight into the fundamental properties of the briquettes, including moisture content, volatile matter, ash content, and fixed carbon, all of which influence combustion behavior and fuel efficiency. The **ultimate analysis** determined the elemental composition—carbon, hydrogen, oxygen, nitrogen, and sulfur—which impacts the energy content and environmental emissions. The **calorific value** test assessed the energy potential of the briquettes, showing how binder composition affects heat output. Finally, the **combustion test** examined real-use performance through ignition time, burning rate, and specific fuel consumption, helping to identify the most efficient briquette formulation. Together, these results inform the overall fuel quality and practicality of the briquettes for energy applications.

3.1 Proximate Analysis Result

The **proximate analysis results** which includes ash content, moisture content, volatile matter, and fixed carbon for both PKS Sample A and B across three starch binder ratios (25%, 30%, and 35%) are presented in **Table 1.**

3.1.1 Ash content (%)

Ash content is a measue of the inorganic residue left after combustion and indicates the amount of non-combustible material in the briquettes. **Sample A** shows a **decreasing trend** in ash content as the starch percentage increases from **4.51% at 25% starch** content to **4.01% at 35% starch content**. Similarly, **Sample B** follows the same pattern from **4.62%** at 25% starch level to **4.21%** at 35% starch level. The gradual reduction in ash content with increasing starch concentration suggests that starch, being an organic material, contributes less to ash formation. This is favorable for combustion, as lower ash content results in cleaner burning and less residue, reducing maintenance requirements for combustion equipment.

3.1.2 Moisture Content (%)

Moisture content affects the ignition, combustion efficiency, and overall energy yield of briquettes. **Sample A** shows a slight increase from **6.28% at 25% starch content** to **6.58% at 35% starch content**. S**ample B** follows a similar trend, increasing from **6.32%** to **6.67%** as starch concentration rises. The increase in moisture content is likely due to the hygroscopic nature of the starch binder, which tends to retain water. Higher moisture content can negatively impact combustion by requiring additional energy for drying during ignition, thereby lowering the net calorific value. However, all values remain within an acceptable range (typically below 10%), suggesting good drying during briquette preparation.

3.1.3 Volatile Matter (%)

Volatile matter represents the compounds released when the briquette is heated and significantly contributes to flame and ignition behavior. For **Sample A**, the volatile matter increases from **57.46% at 25% starch concentration** to **61.86% at 35% starch concentration**. **Sample B** shows a comparable increase from **57.85%** to **61.56%** across the same starch ratios. Higher starch content appears to enhance the volatile matter, which can be attributed to the decomposition of the organic binder during combustion. Increased volatile content facilitates better ignition and a more vigorous initial flame, which is advantageous for quick startup in cooking applications.

3.1.4 Fixed Carbon (%)

Fixed carbon indicates the solid combustible residue remaining after the volatile matter is released. It is a crucial parameter for determining the sustained combustion potential and heat output. **Sample A** shows a decline in fixed carbon from **31.75% at 25% starch content** to **27.55% at 35% starch level**. **Sample B** follows a similar decrease, from **31.21%** to **27.56%** as the starch proportion increases. The inverse relationship between fixed carbon and volatile matter reflects a trade-off. As starch increases, the material becomes richer in volatiles at the expense of fixed carbon. Since fixed carbon is directly responsible for long-lasting combustion, briquettes with **25% starch** are expected to burn more steadily and produce higher heat for longer periods.

Compared to the proximate analysis test on raw PKS and wood fuel reported by Chen et al. [11], the PKS briquettes ash content, moisture content and volatile matter were reduced by 26.08%, 6.67% and 24.86, respectively, and the fixed carbon was increased by over 42.86%. The **optimal performance** in terms of **high fixed carbon, acceptable moisture, and lower ash content** is observed at the **25% starch ratio** for both samples. Moreover, increasing starch content improves **volatile matter**, aiding ignition, but **reduces fixed carbon**, which could compromise sustained heat output. Comparison between the two samples shows that **Sample A** consistently exhibits **slightly lower ash and moisture** and **higher fixed carbon**, suggesting better combustion characteristics overall. The proximate analysis clearly identifies the **25% starch composition as the most suitable ratio** for producing PKS briquettes with favorable combustion and fuel characteristics. This aligns with the goal of creating a clean, efficient, and environmentally friendly biomass fuel alternative.

Table 1: Proximate analysis of Palm kernel shell briquettes.

Parameter	PKS Sample A			PKS Sample B		
	25% starch	30% starch	35% starch	25% starch	30% starch	35% starch
Ash content (%)	4.51	4.32	4.01	4.62	4.35	4.21
Moisture content (%)	6.28	6.47	6.58	6.32	6.52	6.67
Volatile matter (%)	57.46	60.24	61.86	57.85	59.57	61.56
Fixed carbon	31.75	28.97	27.55	31.21	29.56	27.56

3.2 Ultimate Analysis Result

The **ultimate analysis and calorific value** results of palm kernel shell (PKS) briquettes for both **Sample A** and **Sample B,** with starch binder ratios of **25%, 30%, and 35% are presented in Table 2.** The ultimate analysis determines the elemental composition (C, H, O, N, S), while the calorific value indicates the energy content of the briquettes.

3.2.1 Carbon Content (%)

The carbon content decreases significantly as starch content increases. This reduction is due to the dilution effect of cassava starch, which has a lower fixed carbon content than the biochar derived from PKS. Since carbon is the primary energy-contributing element, this drop negatively affects the fuel's energy density. Sample B consistently shows slightly higher carbon content across all binder levels, suggesting marginally better combustion potential.

3.2.2 Hydrogen Content (%)

The hydrogen content increases as starch content increases. This is due to the fact that starch is rich in hydrogenous compounds. As the binder ratio increases, more hydrogen is introduced, which can aid ignition and combustion, but too much may reduce fuel stability. Samples A and B briquettes show a similar trend, with only minor differences in hydrogen content.

3.2.3 Oxygen Content (%)

The oxygen content in both samples decreases with increasing starch content. The decline indicates increased carbonization. Lower oxygen content is favorable for combustion efficiency because high oxygen content can reduce energy density (oxygen doesn't contribute to combustion energy). Sample A has slightly higher oxygen values at lower binder levels, possibly due to variation in feedstock origin or degree of pyrolysis.

3.2.4 Nitrogen Content (%)

The nitrogen content increases with more starch. The increases might be due to the presence of organic nitrogen compounds in the starch or incomplete pyrolysis. High nitrogen content is generally undesirable as it may produce nitrogen oxides (NOx) during combustion, contributing to air pollution. Sample B shows a higher nitrogen level at 35% binder, indicating potential for higher NOx emissions.

3.2.5 Sulphur Content (%)

The sulphur remains low across all binder levels, fluctuating slightly. The low sulphur content is desirable because it minimizes sulphur dioxide (SO_2) emissions, which cause acid rain and respiratory problems. Both samples are well within acceptable limits, indicating minimal environmental hazard from sulphur emissions.

3.2.6 Calorific Value (MJ/kg)

The calorific value decreases with increasing starch binder. This trend reflects the carbon content trend. As starch increases and carbon content decreases, the energy content drops. Starch contributes less to heat generation compared to the fixed carbon in biochar. Sample A has slightly higher calorific values at 25% and 35% starch, indicating it may be a better energy source at those levels.

Table 2: Ultimate analysis and calorific value of Palm kernel shell briquettes.

Parameter	Sample A			Sample B		
	25% starch	30% starch	35% starch	25% starch	30% starch	35% starch
Carbon (%)	51.97	32.32	21.50	53.31	32.03	23.54
Hydrogen (%)	8.83	9.13	9.57	8.12	9.01	9.22
Oxygen (%)	38.58	21.44	17.23	35.12	22.06	17.11
Nitrogen (%)	0.54	1.23	1.42	0.61	1.01	1.70
Sulphur (%)	0.08	0.13	0.10	0.09	0.11	0.10
Calorific value (MJ/kg)	19.53	15.11	12.46	18.72	15.81	11.53

3.3 Combustion Performance Test Result

The combustion test results are presented in **Table 3. These results** provide insights into the performance characteristics of palm kernel shell (PKS) briquettes derived from two different sources (Sample A and Sample B), both using **25% starch binder**. The parameters analyzed include ignition time, burning rate, briquette density, water boiling efficiency, and specific fuel consumption. From the ignition test result (Table 3.3), the time taken for the briquettes to ignite was 1 min 10 secs and 1 min 15 secs for PKS briquette samples A and B, respectively. This result is in satisfactory agreement with the ignition time obtained by Adeniyi et al. [8]. Sample A ignites slightly faster. Shorter ignition time is desirable as it reduces the time and energy needed to initiate combustion. This suggests better ignition properties for Sample A, likely due to a higher volatile matter or better porosity.

The results of the water boiling test were used to calculate the burning rate and specific fuel consumption of the briquettes samples, which are shown in Table 3.3. For the same level of binding agent, it was observed that the burning rate of briquette sample A was lower than that of briquette sample B. This implies that more fuel might be required to cook with briquette produced from PKS sample B. Moreover, when compared to the burning rate of charcoal reported by Bonsu et al. [16], the PKS briquette samples burn for longer time. Sample B has a higher burning rate, which may indicate faster combustion. However, this could also suggest less fuel efficiency if the energy is not effectively transferred (as indicated by less water evaporated). A high burning rate with low energy transfer points to potential energy loss.

The calculated specific fuel consumption for the PKS briquette shows that the briquette sample A is 10.20 g/ml with lowest specific fuel consumption while the highest specific fuel consumption is 12.05 g/ml which is sample B. Thus, the specific fuel consumption which measures the quantity of the fuel required to boil water shows that PKS briquette sample A will be more economical than the use of briquette sample B. Sample A performs better in this regard, confirming it is more fuel-efficient. The higher SFC for Sample B suggests it consumes more fuel for the same output, possibly due to higher ash content or less effective combustion.

In conclusion, Sample A (25% starch binder) outperforms Sample B in most combustion metrics. It ignites more quickly, uses less fuel to achieve more effective boiling, and has lower specific fuel consumption, indicating superior fuel efficiency. Despite Sample B's higher density and burning rate, these did not translate into better energy performance. Thus, Sample A briquettes with 25% starch binder demonstrate the most balanced and efficient combustion characteristics, making them the more suitable choice for domestic or small-scale energy applications.

Table 3: Combustion test results of the PKS briquettes.

Test	Data on PKS sample A briquette (25% starch)	Data on PKS sample B briquette (25% starch)
Total weight of briquettes used for the test (g)	204	204
Number of briquettes at the beginning of test	6	6
Mean weight of each briquette lump (g)	34	34
Total weight of briquettes after boiling water (g)	102.40	100.32
Initial volume of water in pot (ml)	100	100
Final volume of water in pot after boiling (ml)	90.04	91.4
Briquette density (kg/ml)	1.22	2.23
Ignition time (s)	1 min 10 secs	1 min 15 secs
Burning rate (g/min)	2.87	3.15
Specific fuel consumption (kg/ml)	10.2	12.05

4. Conclusion

This study has demonstrated the viability of converting palm kernel shells (PKS), an agricultural waste product into efficient and environmentally friendly solid biofuels through briquetting with cassava starch as a binder at 25%, 30% and 35%. The research evaluated the fuel properties of PKS briquettes in terms of proximate and ultimate composition, calorific value, and combustion performance. The results indicate that a starch binder ratio of 25% offers the most favorable balance of fuel characteristics, including higher fixed carbon content, acceptable moisture levels, low ash residue, and the highest calorific value. These properties contribute to efficient, clean, and sustained combustion.

Moreover, the combustion tests confirmed that briquettes made from PKS, especially Sample A, possess excellent ignition behavior, energy efficiency, and low specific fuel consumption. Compared to traditional biomass fuels such as wood and raw PKS, the briquetted form not only improves energy yield but also reduces environmental and health hazards associated with open burning or inefficient combustion.

In conclusion, the briquetting of PKS represents a practical and sustainable solution for bioenergy generation in Nigeria and similar contexts, where palm oil production is prevalent, and biomass waste remains underutilized. Promoting the use of PKS briquettes can reduce deforestation, minimize waste, improve rural energy access, and create economic opportunities in renewable energy markets. Further research and policy support are recommended to scale up adoption and improve awareness of this promising renewable energy alternative.

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