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Catalyst-Dependent Property Variations in Biodiesel from Palm Kernel Oil Via Base Transesterification: A Comparative Study

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Abstract: *The global energy transition to sustainable alternatives from petroleum diesel has accelerated research into biodiesel production from renewables. This study investigated the comparative performance of Potassium Hydroxide (KOH) and Sodium Hydroxide (NaOH) as alkaline catalysts for biodiesel production from Crude Palm Kernel Oil (CPKO) via base-catalyzed transesterification. The reactions were conducted under identical operating conditions: temperature of 75 °C, methanol-to-oil molar ratio of 6:1, and catalyst loading of 1.0 wt%. The results revealed differences in catalyst effectiveness and product quality. KOH exhibited superior performance, achieving a biodiesel yield of 83.44%, compared with 58.03% obtained using NaOH. This significant disparity is primarily attributed to improved phase separation during processing, as potassium soaps are more water-soluble and less prone to forming stable emulsions than sodium soaps. Fuel property analysis further confirmed the advantages of KOH-derived biodiesel which showed a lower acid value (1.27 mg KOH/g versus 1.72 mg KOH/g), a higher cetane number (70.50 compared to 65.22), a reduced iodine value, and a marginally improved pour point (−8.7 °C versus −7.1 °C), indicating enhanced combustion quality and cold-flow behavior. For most key parameters, both biodiesel samples complied with the requirements of ASTM standards. However, the flash point of the KOH biodiesel (138 °C) was lower than that of the NaOH biodiesel (197 °C), suggesting residual methanol content slightly above recommended limits. Overall, the study demonstrated that KOH is the more effective catalyst for biodiesel production from CPKO, offering higher yields and improved fuel quality when supported by adequate purification strategies.*

Keywords: *Biodiesel, Alkaline catalysts, Palm kernel oil, Potassium Hydroxide, Sodium Hydroxide, Transesterification*

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I. INTRODUCTION

The increasing demand for energy due to rapid industrial growth and socio-economic development has risen exponentially [1].. Coal, oil, and gas (fossil fuels) have been at the heart of the world's energy for generations and have driven industrialization and modern life but have also generated environmental degradation [2]. Fossil fuel burning is the largest source of human-induced greenhouse gas emissions in the form of carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter, all of which are pollutants that have been linked to respiratory and cardiovascular disease [3] and the major cause of global climate change: the result is rising sea levels, extreme weather, and ecosystem extinction [4].

Transitioning to sustainable energy sources is not only an environmental imperative but an economic and social imperative [1], [4]. The search is for alternatives that are not just environmentally friendly but also economically attractive and simple to apply to current infrastructure. Globally, bioenergy has the potential to deliver 25–33% of primary energy by 2050 as a substitute for fossil fuels in transport [5]. Biodiesel is a large component of renewable alternatives, which was 9% of U.S. biofuel use in 2022, and it is mostly made from canola and soybean oils. Renewable diesel, which is chemically similar to petroleum diesel, adds more diversity to current alternatives and is produced from fats such as Crude Palm Kernel Oil (CPKO) [6].

In Africa, Nigeria is one of the highest producers of oil palm and can produce up to an estimated 2.3 million metric tonnes of oil palm fruit per year. The resulting large supply of PKO makes it a low-cost regional feedstock for biodiesel [7]. In addition, the direct edible use of PKO is minimal, and so does not compete with other uses of vegetable oils for the edible food application, avoiding the food vs. fuel controversy for biodiesel production [5]. Among the various types of biofuels, biodiesel is the most commercially produced. Palm kernel oil, which is extracted from the seed of the oil palm fruit (*Elaeis guineensis*), is particularly well suited for biodiesel production in tropical regions such as Nigeria, Malaysia, and Indonesia, where oil palm is widely cultivated and readily available [8].

Chemically, biodiesel has a high cetane number, typically between 45 and 60, which reflects a high ignition quality and combustion efficiency [9], [10]. Biodiesel also has higher lubricity than conventional diesel, which may contribute to longer life of engine components. Environmentally, combustion of biodiesel results in a net CO_2 uptake, as the CO_2 that will be emitted during combustion will be reabsorbed from the atmosphere in the growth of the feedstock crops [10]. The combustion of biodiesel results in lower emissions of particulate matter, unburned hydrocarbons, carbon monoxide, and sulfur oxides, thus creating a perception of biodiesel as a cleaner fuel [11].

Base-catalyzed transesterification is the most commonly used method for producing biodiesel from palm kernel oil (PKO) because it is straightforward to operate, energy-efficient, and capable of delivering high conversion within a short time [12], [13], [14]. In this process, the triglycerides naturally present in palm kernel oil are chemically transformed into biodiesel—technically known as fatty acid alkyl esters—by reacting them with a short-chain alcohol, most often methanol, in the presence of an alkaline catalyst [15], [16], [17]. Typically, potassium hydroxide (KOH) or sodium hydroxide (NaOH) are commonly employed which is first dissolved in methanol to produce a reactive alkoxide solution [18], [19], [20]. This solution is then introduced into the palm kernel oil under carefully controlled conditions, usually at temperatures between 55 and 65 °C, atmospheric pressure, and with continuous stirring to ensure good contact between phases [21], [22], [23].

The simplicity and effectiveness of this reaction pathway make base-catalyzed transesterification an attractive option for converting palm kernel oil into a clean, renewable fuel suitable for diesel engines [12]. The alkoxide attacks the ester bonds of triglycerides, converting them into fatty acid methyl esters (FAME) and glycerol according to the reaction:

Triglyceride + 3 Methanol ⇌ 3 Fatty acid methyl esters (FAME) + Glycerol

$C_3H_5(OOCR)_3 + 3\ CH_3OH \rightleftharpoons 3\ RCOOCH_3 + C_3H_5(OH)_3$

The reaction proceeds through three consecutive, reversible steps :

Step 1: Triglyceride + Methanol ⇌ Diglyceride + FAME

Step 2: Diglyceride + Methanol ⇌ Monoglyceride + FAME

Step 3: Monoglyceride + Methanol ⇌ Glycerol + FAME

The reaction generally proceeds rapidly, with substantial conversion achieved within 30–90 minutes.

Several research have been conducted to synthesize biodiesel from palm kernel oil, vegetable oil and animal fats using the base-transesterification process as outlined in Table 1.

Table 1: Biodiesel production using different feedstocks and catalyst types

S/No	Feedstock/Biomass	Reaction Temperature (^{o}C)	Reaction Time (mins)	Yield (%)	Catalyst	Reference
1	Palm Kernel Oil	60	120	70 - 73	KOH	[18]
2	Water Melon Seed Oil	60	90, 120, 150	70, 53, 49	NaOH	[16]
3	Palm Kernel Oil	70	120	31 - 35	KOH	[17]
4	Palm Kernel Oil	70	100	88	$Ca(OH)_2$	[26]
5	Palm Kernel Oil	55	90	84	CH_3ONa	[23]
6	Groundnut oil	55	90	88	CH_3ONa	[23]
7	Palm Kernel Oil	65	90	67.4	KOH	[11]
8	Waste Cooking Oil	65	90	53.8	KOH	[11]
9	Palm Kernel Oil	60	90	85.0	NaOH	[19]

Despite the potential, some challenges are yet to be addressed: optimizing the transesterification reaction to increase the yield and enhance the conformity to international fuel specifications, such as ASTM D6751, remains critical. Apparently, the process efficiency and product quality are greatly influenced by several reaction parameters, including the type and concentration of the catalyst, reaction temperature, methanol to oil molar ratio, and the quality of the starting feedstock [23].

Selection of the most appropriate catalyst is also a significant factor that influences the reaction kinetics, the final yield, as well as the resulting biodiesel's fuel properties [27]; [28]; [29]; [30]. Hence, a gap exists in comparison studies that evaluate the effects of NaOH and KOH catalysts on biodiesel properties from PKO under controlled conditions. The comparison will enable biodiesel producers to make informed decisions: which catalyst to invest in, under what specific conditions each catalyst performs optimally, enabling producers to select the most appropriate catalyst for their particular situation (feedstock, scale up considerations, market requirements, and economic constraints). To achieve this, the following objectives were considered in the study:

1. Produce biodiesel from palm kernel oil (PKO) using the transesterification method in presence of two homogeneous alkaline catalysts (potassium hydroxide and sodium hydroxide).
2. Compare the yields and properties of biodiesel produced with International Biodiesel Standards.

It is important to note that converting less valued oils such PKO to biodiesel, is a right and timely step in developing our economy and improving the health of our environment [5]. Hence, this research has the following benefits: reduction in total reliance on petroleum and crude oil products, reduction in emissions of greenhouse gases, economic growth in the form of employment in rural areas and reduction or elimination of waste oil pollution. Again, this research aligns particularly with the Sustainable Development Goals (SDGs): Goal Numbers: 7 (Affordable and Clean Energy) and 13 (Climate Change). A sustainable world is where people can access affordable and clean energy without contributing to Climate Change.

II. MATERIALS AND METHODS

2.1 Materials

The following were some of the major apparatus and reagents used in this study: Palm-kernel-oil (PKO), obtained from Elele, Rivers State of Nigeria. Erlenmeyer flasks (250 mL), Analytical balance, measuring cylinders, Heating mantle and stirrer, Thermometer, Sample bottles for storage, Methanol (≥99.8%) – produced by Aldrich Chemicals Co. Ltd, England, Sodium Hydroxide (NaOH pellets, reagent grade), Potassium Hydroxide (KOH pellets, reagent grade), Isopropanol (C_3H_8O, titration solvent), Phenolphthalein indicator, Distilled Water, used for diluting and cleaning.

2.2 Methods

2.2.1 **CPKO preparation and Biodiesel Production via Transesterification**

Crude Palm kernel oil (Fig. 1) was filtered with Whatman filter paper to remove suspended food particles and other solid impurities that may be present (Fig. 2). The filtered oil was kept in a clean, dry conical flask until ready for use

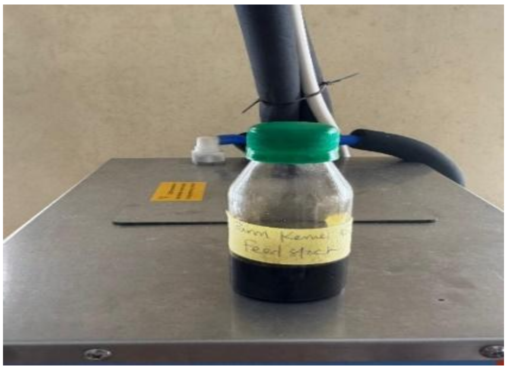

Fig. 1. Palm kernel oil feedstock

Fig. 2. Preparation of Palm Kernel Oil

The experimental conditions followed for optimum production and purification of biodiesel from PKO in this study are shown in Table 2.

Table 2. Optimum Operating Conditions

Experimental conditions	Value
Reaction temperature (°C)	75
Reaction Time (mins)	90
Quantity of raw material (g)	100
Methanol to oil ratio	6:1
Catalyst loading	1.0wt%

Biodiesel was produced from PKO according to the procedure outlined in [17], [25] using alkaline-catalyzed transesterification process. Based on FFA content, the required amount of catalyst was calculated to account for both neutralization and reaction catalysis. 100 g of the prepared PKO was weighed into 500 mL beaker. The methanol requirement for a 6:1 molar ratio was calculated:

Molecular weight of PKO was 877g/mol, amount of PKO feed was 100g and amount of solvent (methanol) = xg. A methanol to oil ratio 6:1, is needed to drive the reaction to the product side.

$$\frac{grams\ of\ oil}{molecular\ weight\ of\ oil\ (\frac{g}{mol})} = \frac{xg}{6 \times mol.weight\ of\ methanol} \tag{1}$$

The total KOH requirement was calculated:

$$\text{Total KOH} = \text{KOH}_{\text{neutralization}} + \text{KOH}_{\text{transesterification}} \tag{2}$$

$$\text{KOH}_{\text{neutralization}} = \frac{\%\ FFA \times mol.\ mass\ of\ KOH \times oil\ weight}{mol.\ mass\ of\ oleic\ acid} \tag{3}$$

Theoretical mass of KOH 1.21g was dissolved in methanol 22.7g in another beaker to prepare potassium methoxide. Palm kernel oil was then heated to 75°C using heating mantle with stirring. Potassium methoxide prepared above was added to heated palm kernel oil. The reaction mixture was kept at 75°C with vigorous stirring for 90 minutes for complete conversion **[17]**. The same procedure was strictly carried out for NaOH catalyst to have a direct comparative study of the properties obtained.

The resultant mixture was transferred into separating funnel and allowed to settle for 24 hours for complete phase separation. After settling, the lower glycerol layer was drained off, leaving upper biodiesel layer (Fig. 3) The biodiesel was collected and its mass was recorded (Fig. 4). The percentage yields were calculated using:

$$\%\ \text{Yield} = \frac{weight\ of\ biodiesel\ produced}{initial\ weight\ of\ oil} \times 100 \tag{4}$$

Fig. 3. PKO Biodiesel Separation Process

Fig.4. PKO Biodiesel Yield

2.2.2 Property Analysis Using ASTM Standards.

1. Determination of Specific Gravity
   ASTM D5355-95 procedure was employed to determine the ratio of the mass (g) of oil to that of an equal volume of water [31]. The density bottle was cleaned, weighed and filled with distilled water, then immersed in a water bath at 20°C until the water content reaches 20°C, wiped and weighed. The bottle was emptied, dried and filled with the oil sample at 20°C. It was then kept in a water bath, wiped and weighed again.
   $$Specific\ gravity = \frac{weight\ of\ oil}{weight\ of\ equal\ vol.of\ water} \tag{5}$$
2. Determination of Viscosity
   The viscosity of the biodiesel was determined using Ostwald's Viscometer according to ASTM D 445-24 [32] standards. The viscometer was filled to the mark; sucking it up into the other side of the fuse,

and setting a stop-clock or stop-watch to time when the oil flows back to the first tube with which the oil was first filled. The viscosity was then calculated using the expression:

$$Viscosity = \frac{4.39\, x\, t}{8} \qquad (6)$$

Where: 4.39 is the centistokes constant; 8 is glucose content and t is the time taken to move in the viscometer

3. Determination of Saponification Value

Saponification value (SV) of the oil samples was determined using ASTM D5558-95 standard procedures [33]. 5g of sample was weighed and transferred into a conical flask. The sample was treated with 25 mL of 0.5 M ethanolic potassium hydroxide (KOH)/(NaOH) solution and refluxed for 60 min to ensure complete saponification of triglycerides. After cooling, the mixture was titrated with a standardized 0.5 M hydrochloric acid (HCl) solution, with phenolphthalein serving as the visual indicator. The endpoint of the titration was defined as the persistent disappearance of pink color. A blank titration (containing no oil sample) was performed using the same procedure. Saponification value (SV) in mg KOH/g oil was calculated by the following formula;

$$\text{Saponification value (S.V.)} = \frac{(B\text{-}S)\;\; 0.5M\, HCl}{Mass\ of\ Oil\ (g)} \qquad (7)$$

Where; B – ml of HCl required by blank, S – ml of HCl required by sample and M – Molarity of HCl

4. Determination of acid value

Acid values of the samples were determined according to ASTM D664-18 [34]. 5g of sample was weighed into 250ml conical flask. 50ml of neutralized ethyl alcohol was added. The mixture was heated on a water bath to dissolve the sample. The solution was titrated against 0.1M KOH using phenolphthalein as indicator. The acid value was determined after which the free fatty acid was calculated respectively as follows;

$$Acid\ Value = \frac{A\ x\ M\ x\ 56.1}{W} \qquad (8)$$

Where, A = ml of 0.1M KOH/NaOH consumed by sample, M = Molarity of KOH/NaOH, W = weight in grams of the sample

Then;

$$Free\ Fatty\ Acid\ (\%) = \frac{Acid\ Value}{2} \qquad (9)$$

5. Iodine Value:

Iodine value (IV) was used as a measure of unsaturation in fats and oil, it is expressed in grams of iodine taken up per 100 g of the sample (g I_2/100g). ASTM D5768-15 standard method employing the Wijs method with safer solvent like cyclohexane/iso octane [35]. An exact weight of oil (0.5g) was dissolved in 10 ml carbon tetrachloride and reacted with 20 mL Then, 15 ml of potassium iodide and 100 mL of water were added to the mixture. The solution was titrated with 0.1M sodium thiosulfate using starch indicator. A blank titration was performed at the same time.

$$\text{Iodine Value} = \frac{\text{(Blank Titre - Sample Titre)}\;\; 12.69}{\text{Weight of sample (g) (0.5g)}} \qquad (10)$$

6. Peroxide value

This parameter indicates the extent of oxidation in the oil and helps assess its stability over time. It is represented in Mol/Kg. ASTM D3703-18 [36] method was employed where 2g of the oil sample and 1g of potassium iodide in powdered form were added in 2 test tubes separately each containing 20ml of solvent mixture (2 vol. glacial acetic acid + 1 vol. of chloroform) i.e. (60:30). Step 1 was performed in a blank tube (without sample). The tubes were placed in a water bath and boiled vigorously for 30 seconds. The contents were poured quickly into a conical flask containing 10ml of 5% potassium iodide solution. The tubes were washed with 5ml of water each and poured into each conical flask with contents, and 4 drops of phenolphthalein was then added into each conical flask and was titrated with 0.01M thiosulphate until a colour change was seen:

$$\text{Peroxide value} = \frac{(Sample\ Titre\ \ -\ \ Blank\ Titre)\ 0.011000}{\text{Weight of sample (g)}} \qquad (11)$$

7. Cetane number

The cetane number was determined according to ASTM D613-25a method, using electromagnetic induction which uses the dielectric properties of the fuel [37]. The instrument's operation is based on the different insulating magnetic permeability values of the hydrocarbon bonds and uses calibrated data models to associate the dielectric measurement with combustion properties [27]. The analysis was conducted using an Octane Meter IM analyzer, following standard procedure. The probe was pushed in as far as it would go, a 10 mL sample was placed in a clean cuvette, and the automatic run was initiated. Sensitive sensors detected subtle changes in the dielectric material, and in line with the fast analysis specifications, the cetane number was displayed on the screen in under 30 seconds.

8. Pour Point (PP) and Flash Point (FP).

The pour point (PP) indicates the lowest temperature at which the oil maintains sufficient fluidity to flow. This parameter was determined following the ASTM D97-08 standard method [38]. The biodiesel sample was equilibrated at ambient temperature and subsequently allowed to undergo a gradual thermal transition. The temperature at which complete liquefaction occurred was recorded as the pour point.

The flash point is defined as the minimum temperature at which biodiesel vapors undergo ignition upon exposure to an open flame under standardized testing conditions. The test methods cover the determination of the flash point of biodiesel samples in the temperature range from 40 °C to 370 °C by a manual Pensky-Martens closed-cup apparatus. This measurement was conducted according to the ASTM D93 – 20 test protocol [39]. An ignition source was positioned at a specified distance from the biodiesel samples contained within a closed-cup apparatus, and the temperature corresponding to ignition was documented.

III. RESULTS AND DISCUSSION

3.1 Percentage yield of the biodiesel produced.

The main objective of this study was to compare the efficiency of the two catalysts in converting PKO to biodiesel and to compare the properties of the Biodiesel produced using the different catalysts. The results using equation (4), demonstrated a difference in production efficiency between the two catalysts.

3.1.1 Efficiency of the catalysts

Yields of 83.44% and 58.03% were observed from the KOH-catalyzed reaction and NaOH-catalyst reaction respectively for the production of biodiesel using the experimental conditions in Table 2. The difference is likely due to soap formation [40].

With NaOH: $RCOOH + NaOH \rightarrow RCOONa$ (sodium soap) + H_2O

With KOH: $RCOOH + KOH \rightarrow RCOOK$ (potassium soap) + H_2O

Both reactions consume the catalyst and reduce biodiesel yield, but the solubility characteristics and other properties of the resulting soaps differ significantly [26].

Table 3 Soap properties from NaOH and KOH

Property	Sodium Soap (NaOH)	Potassium Soap (KOH)
Water solubility	Lower	Higher
Glycerol solubility	Poor	Good
Emulsion	Very stable	Less stable
Precipitation	High	Low
Phase separation	Difficult	Easier

The 25% yield difference in biodiesel yield between KOH (83.44%) and NaOH (58.03%) can be largely attributed to differences in the behavior of the soaps formed during transesterification. Sodium-based soaps tend to form stable, hard-to-break emulsions that trap biodiesel within the reaction mixture, while potassium soaps are more soluble and preferentially partition into the glycerol phase [41], [42]. As a result, the use of NaOH often leads to physical entrapment of biodiesel in solid soap precipitates and persistent emulsions, making phase separation and purification more difficult and reducing overall product recovery [43].

These observations are consistent with the findings of [25], who reported higher biodiesel yields from palm kernel oil when KOH was used as the catalyst and highlighted separation challenges associated with NaOH, even though a direct comparison was not the focus of their study. However, [42] reported a lower yield with KOH catalyst which might be due to higher reaction temperature and time. Overall, this outcome underscores the importance of catalyst choice, not only in influencing reaction kinetics but also in determining separation efficiency and final yield [24]. In this regard, KOH clearly emerges as the more suitable catalyst for efficient biodiesel production.

3.2 Analysis of Biodiesel Properties

3.2.1 Acid value and Free fatty acid content

The transesterification process effectively converted triglycerides into fatty acid esters, leading to a substantial reduction in the acid value of the crude feedstock, which initially was calculated to be 5.06 mg KOH/g (equ 8). Following reaction, the acid value decreased by approximately 70% (1.508 mg KOH/g) for the NaOH-catalyzed biodiesel and by about 75% (1.265 mg KOH/g) for the KOH-catalyzed biodiesel (Fig 5). Acid value is a key indicator of biodiesel quality, as it directly affects fuel stability, storage behavior, and compatibility with engine components [44].

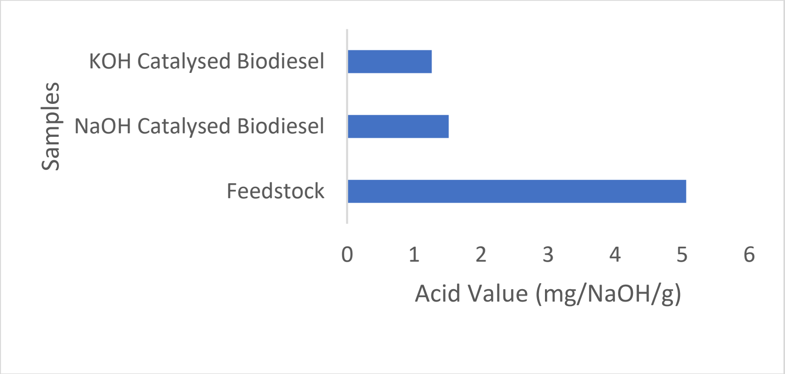

Fig. 5 Acid values for Biodiesel samples

The lower acid value observed in the KOH-derived biodiesel suggests a more effective overall process [25]. This improvement can reasonably be attributed to several factors: more complete transesterification due to improved phase separation, more efficient removal of soaps and residual catalyst during purification, and lower levels of residual alkaline species that could otherwise promote hydrolysis back to free fatty acids [44]. These differences are important from a practical standpoint, since higher acid values are associated with increased fuel corrosivity and faster oxidative and hydrolytic degradation during storage, which can adversely affect engine performance and maintenance requirements [22].

Although KOH catalysis clearly produced a higher-quality biodiesel with better stability characteristics, it is noteworthy that the acid values of both fuels remained above the ASTM D664-18 specification limit of 0.50 mg KOH/g. This indicates the need for additional feedstock pre-treatment or more rigorous post-reaction purification steps, particularly when processing high free-fatty-acid oils, to ensure full compliance with fuel quality standards.

3.2.2 Specific gravity and Viscosity

The density of biodiesel provides required details on the weight of the oil at specific temperatures. From this present study the specific gravities of biodiesel harnessed from palm kernel oil using NaOH and KOH catalyst were 0.855 and 0.861 respectively using equation (5). These values are within the limits of 0.8833 of biodiesel specified by [31] and were also in proximity with various scientific studies carried out by [45] and [46] who reported specific gravities of 0.881 and 0.887 for biodiesel from Mango seed oil and Shea butter oil respectively. Viscosity on the other hand, is a key property which measures the resistance flow of fluids under the effect of gravity [28]. The viscosity value (equ. 6) obtained from biodiesel of PKO using NaOH and KOH catalysts conducted in this experiment were 5.33 mm^2/S and 5.12 mm^2/S respectively. These values were within the limits of 4.0 - 6.0 mm^2/S specified by [32]. The viscosity of biodiesel explains the effective lubricity of fuel; it shows that the biodiesel analyzed in this present study may protect diesel fuel pumps and engines from wear and seepage. Thus enhances the atomicity and combustion as well as reducing emissions of fumes from exhaust engines [47]. The values obtained also showed good correlation with biodiesel values of 7.65 and 5.92 mm^2/S from palm kernel oil and groundnut oil [48] and those of observed by [23] who reported 5.2 and 7.6 mm^2/S for PKO and Groundnut oil respectively using NaOH as catalyst. It was said to be somewhat higher than the values of 3.62 mm^2/S reported in shear butter oil [46] and mango seed oil (5.82 mm^2/S [45]. This may be due to differences in reaction time and temperature in the study.

3.2.3 Saponification Value (SV) and Iodine Value (IV)

The reduction in saponification values (SV) of the produced biodiesel from 212.7 mg/KOH/g to 151.55 mg/NaOH/g and 140.25 mg/KOH/g (equ 7) after transesterification is expected due to the reduction in molecular weight from the decomposition of long-chain triglycerides into the shorter-chain methyl esters [49]. This reduction was also observed in [23] when NaOH was employed as the catalyst of the reaction.

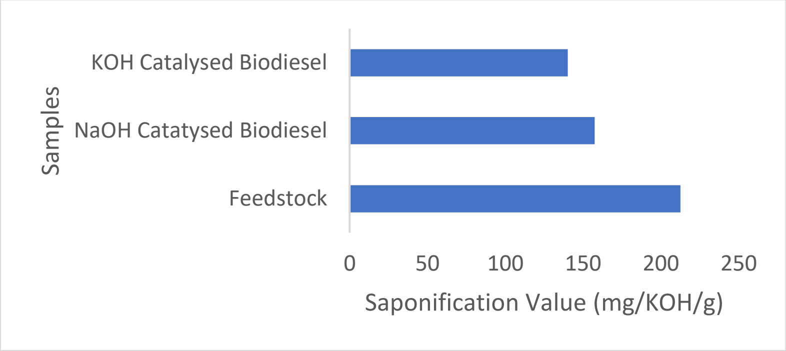

Fig. 6 Saponification values for Biodiesel samples

Again, 69.88 I_2/100g and 65.44 I_2/100g (Fig 7) were obtained from equation (10) as Iodine Values (IV) for biodiesel produced using NaOH and KOH catalysts respectively. The differences observed in iodine values can be explained by a combination of factors, including preferential soap formation from unsaturated free fatty acids, variations in phase separation behavior, and possible thermal effects during processing [50]. This marginal reduction in iodine value is particularly important in tropical environments such as Nigeria, where elevated temperatures can accelerate oxidative degradation and compromise fuel storage stability.

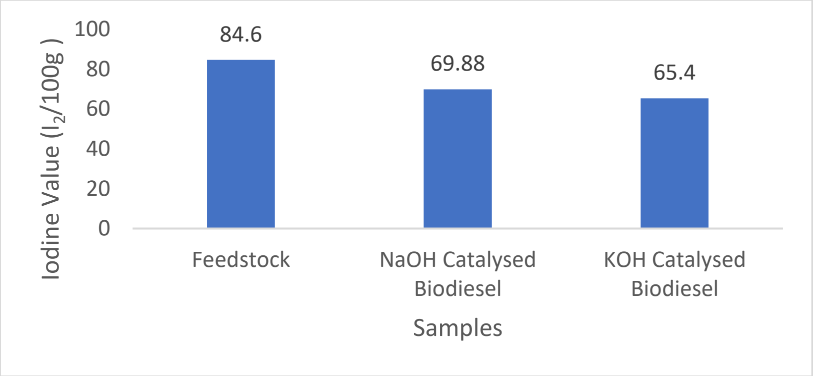

Fig. 7 Iodine Values for Biodiesel samples

It is also noteworthy that the iodine values measured for both biodiesel samples were higher than those reported by [23], who recorded an iodine value of 8.04 g I_2/100 g for palm kernel oil biodiesel produced using sodium methoxide (CH_3ONa) as the catalyst but aligns with trends reported in the literature, including the findings of [12]. Overall, these results further support the suitability of KOH as a preferred catalyst for biodiesel production from palm kernel oil, particularly under conditions where oxidative stability is a key performance requirement.

3.2.4 Peroxide Value (PV)

International biodiesel standards such as ASTM D3703-18 do not explicitly specify peroxide value limits, this parameter is widely recognized as a sensitive marker of early-stage oxidative degradation and remains important for assessing fuel freshness and predicting storage stability [43]. The observed PV for that NaOH-catalyzed and KOH-catalyzed biodiesel samples exhibited similar peroxide values of 21.33 and 22.30 $MeqO_2$/Kg despite differences in other quality parameters such as acid value and iodine value.

[17] reported a PV of 3.12 $MeqO_2$/Kg for PKO using KOH as the reaction catalyst. The reaction time and temperature of the reaction must have been the reason for the clear difference. However, the similarity in PVs for the two biodiesel samples provides valuable mechanistic insights into the oxidation pathways operative during biodiesel production and the relative influence of catalyst choice on initial oxidative status. Fundamentally, it indicates that both catalyst systems produce fresh biodiesel with equivalent initial oxidative states, suggesting that the transesterification process itself, rather than catalyst identity, determines immediate post-production peroxide levels [51].

3.2.5. Cetane Number (CN):

The substantially higher cetane number of KOH-catalyzed biodiesel (70.50) compared to NaOH-based biodiesel (65.22) represents a significant quality advantage arising from the differential processing characteristics of the two catalyst systems. This 5.28-unit enhancement (8.1% relative increase) exceeds analytical uncertainty and reflects genuine compositional differences, most likely enrichment in saturated FAMEs due to more complete triglyceride conversion and superior phase separation with KOH catalysis [30].

Although the CN of both biodiesel samples exceeded that of the ASTM 613 -25a standard [37] of 47, higher cetane numbers generally improve combustion quality, engine performance, and emissions across most operating conditions, but diminishing returns occur above certain thresholds, and potential trade-offs with other fuel properties must be considered [17], [26]. The cetane number advantage of KOH-biodiesel contributes to improved engine performance through reduced ignition delay, smoother combustion, enhanced cold-start capability, reduced noise and vibration, and modest emission benefits [11], [47].

3.2.6 Flash Point (FP):

Flash point represents one of the most critical safety parameters for biodiesel, defined as the minimum temperature at which fuel vapors form an ignitable mixture with air under standardized test conditions [10], [39], [48]. This parameter directly influences fuel classification for transportation, storage regulations, and fire safety protocols. International biodiesel standards specify minimum flash points of 130°C [39], reflecting the inherently low volatility of fatty acid methyl esters (FAMEs) compared to petroleum diesel [12]. The reported flash point of 197°C for NaOH-catalyzed biodiesel falls well within the expected range for pure, properly purified biodiesel (typically 170-190°C for palm oil-based biodiesel), comfortably exceeding both regulatory minima and providing substantial safety margins [27]. In contrast, the KOH-biodiesel flash point of 136°C, while technically meeting [39] requirements, is suspiciously lower—representing a 59°C (30%) reduction that cannot be explained by normal compositional variations in FAME profiles [29]. This substantial flash point depression strongly suggests contamination with volatile components, most likely residual methanol from incomplete purification [51].

3.2.7 Pour Point (PP):

Pour point of -7.1 and -8.7 were obtained in this study for NaOH and KOH biodiesel samples respectively. The marginally lower pour point observed for KOH-catalyzed biodiesel compared to NaOH-catalyzed biodiesel is primarily associated with differences in catalyst solubility, reaction efficiency, and product purification [25]. KOH exhibits higher solubility in methanol, which enhances transesterification kinetics and promotes more complete conversion of triglycerides to fatty acid methyl esters (FAME) [43], [44]. This observation is consistent with the investigation reported by [25] where lower value was obtained for pour point using KOH catalyst.

Reduced soap contamination limits wax crystal formation and viscosity increase at low temperatures, thereby improving pour point behavior [10]. In contrast, NaOH-catalyzed biodiesel may retain slightly higher levels of saturated components and glycerides, contributing to the low-temperature performance [29]. While both catalysts can be used to produce biodiesel from PKO, it is evident that KOH is a much more efficient catalyst based on yield and key fuel parameters. The issues encountered seem to be more related to the need for process optimization, rather than the catalysts being inherently unfit for the application.

Table 4. Summary of the properties of biodiesel produced using the different catalysts

S/No	Properties	PKO feedstock	Biodiesel (NaOH Catalyst)	Biodiesel (KOH Catalyst)	ASTM Standard
1	Acid Value (mg/KOH/g)	5.06	1.518	1.265	D 664 - 18
2	Free Fatty Acid (mg/KOH/g)	2.53	0.759	0.633	
3	Saponification values (SV) (mg/KOH/g)	212.71	157.55	140.25	D5558 - 95 (330)
4	Iodine value (IV) (I_2/100g)	84.60	69.88	65.40	D5768 - 15
5	Peroxide values (MeqO_2/Kg)	35.33	21.33	22.20	D3703 - 18
6	Specific gravity @15°C	0.90	0.855	0.861	D 5355-95 (0.899)
7	Viscosity @40°C (mm^2/s)	7.48	5.33	5.12	D445 - 24 (1.9 – 6.0)
8	Flash point (°C)	187	197	138	D93-20 (100 – 170)
9	Pour point (°C)	11	-7.1	-8.7	D97 - 08
10	Cetane number	52.9	65.22	70.5	D613 – 25a

IV. CONCLUSION AND RECOMMENDATIONS

This study shows that crude palm kernel oil (CPKO), even though it contains a high level of impurities and free fatty acids, can still be converted to biodiesel using the common alkali-catalyzed transesterification method. Among the two catalysts tested, potassium hydroxide (KOH) performed much better than sodium hydroxide (NaOH), producing a significantly higher biodiesel yield. The lower yield observed with NaOH was mainly caused by persistent emulsions and separation problems, which made it difficult to recover the final product efficiently. In addition, biodiesel produced with KOH showed better fuel characteristics, including a lower acid value, a higher cetane number, and slightly improved cold-flow properties, all of which point to better combustion performance and overall fuel quality. Although its flash point was slightly lower—likely due to small traces of methanol.

While both biodiesel samples represented a clear improvement over the raw feedstock, their acid values were still slightly above ASTM standard limits, highlighting the importance of proper pre-treatment and purification when working with high-FFA oils like CPKO. Overall, the results confirm that biodiesel can be efficiently produced from crude palm kernel oil when KOH is used as the catalyst and appropriate processing steps are applied. From a sustainability perspective, converting this readily available but underutilized local resource into biodiesel helps reduce dependence on fossil fuels and improves the economic viability of biofuel production, especially in regions where palm kernel oil is abundant.

The following are some recommendations for future research:

1. Perform a comprehensive techno-economic analysis (TEA) and a life cycle assessment (LCA) to assess the comparative economic and environmental feasibility of KOH and NaOH catalysts when scaling PKO biodiesel production to industrial scale.
2. Perform a scale-up of the optimized process to the pilot plant to obtain a better understanding of the process engineering aspects.

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