Volume 10, Issue 7, July – 2025 International Journal of Innovative Science and Research Technology
ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/25jul518

Sustainable Production and Comparison of Biodiesel from Non-Edible Seeds: Neem and Almond Oils

Jackson Eleze[1]; Akuma Oji[2]; Peter Muwarure[3*]

[1, 3*]Centre for Gas, Refining and Petrochemical Engineering,
[2]Department of Chemical Engineering, University of Port Harcourt, Port Harcourt, Nigeria.

Publication Date: 2025/07/15

Abstract: The increasing global energy crisis and the ongoing environmental degradation have heightened the urgency for the development of alternative and sustainable fuel sources. This research examines the feasibility of utilising neem (Azadirachta indica) and almond (Terminalia catappa) seed oils—both non-edible and abundantly accessible in tropical areas—as effective feedstocks for biodiesel synthesis. Biodiesel was synthesised and characterised through Soxhlet extraction and a two-stage transesterification process, adhering to ASTM D6751 and EN 14214 standards. The assessment included various physicochemical properties such as kinematic viscosity, density, cetane number, calorific value, and acid value, in addition to an evaluation of cold flow properties and sulphur content. Advanced spectroscopic and microscopic techniques—FTIR, XRD, and SEM—were utilised to examine the structural characteristics and surface morphology of the biodiesel and catalysts produced from agricultural waste materials, including eggshells and fish bones. The findings indicated that neem biodiesel demonstrated a higher cetane number of 58.13 and an energy content of 40.15 MJ/kg. In contrast, almond biodiesel presented better cold flow properties and a lower acid value. Both biodiesels conformed to international standards, underscoring their viability for local and industrial energy applications. The study highlights the practicality of transforming non-edible biomass into clean fuel, enhancing energy security, promoting environmental sustainability, and optimising waste utilisation in emerging economies. Future work should focus on extensive validation efforts, prolonged engine testing, and the advancement of catalyst technologies to optimise process economics and efficiency.

Keywords: *Biodiesel; Non-Edible Seed Oil; Neem; Almond; Sustainability; Transesterification.*

How to Cite: Jackson Eleze; Akuma Oji; Peter Muwarure (2025) Sustainable Production and Comparison of Biodiesel from Non-Edible Seeds: Neem and Almond Oils. *International Journal of Innovative Science and Research Technology,* 10(7), 610-620. https://doi.org/10.38124/ijisrt/25jul518

I. INTRODUCTION

In order to reduce greenhouse gas emissions, biodiesel is a non-petroleum fuel made of mono-alkyl esters of long-chain fatty acids that are sourced from vegetable oils or animal fat. Global biodiesel production climbed from 9.2 Mtoe in 2000 to 95 Mtoe in 2018 [1]. Biodiesel production and consumption are dominated by the US and Europe. Biodiesel consumption in 2005 was 3.02 MT in Europe and 3.32 MT in the US. These account for 0.5–1% and 2% of biofuels used in US and European transportation, respectively. Many governments encourage biodiesel use in transportation, boosting global biodiesel consumption. The 56 nations reported 26.8 million tonnes of biodiesel consumption in 2016, with five countries using 58% [2].

Many countries encourage biodiesel production and transportation usage. China, India, and Malaysia are producing and using biodiesel like Europe and the US. China and India want to blend 15% biodiesel with petro-diesel by 2020. The Malaysian government introduced B10 (10% biodiesel blended with petro-diesel) in 2019 and aims to increase it to B20 in 2020 [3].

Second-generation biodiesel comes from non-edible oils. Second-generation feedstock includes non-edible plants such jatropha, rubber seed, jojoba, tobacco seed, sea mango, neem, candlenut, mahua, karanja, and yellow oleander [4]. Biodiesel may also be made from chicken fat, swine lard, and cow tallow [5]. Recently, waste edible oils like yellow grease and leftover cooking oils have been utilised to make biodiesel [3, 6]. The toxic chemicals in Jatropha, sea mango, rubber seed, and candlenut oils make them unfit for human consumption. Jatropha seed oil purifies and curcas [7]. Rubber seed oil has cyanogenic glucosides. Thus, oil from non-edible crops may be used to make biodiesel, solving the food vs. fuel problem. Global wastelands may be used to grow non-edible oil plants, decreasing deforestation and food supply issues. Oil yield and agricultural output from the planted region make a feedstock biofuel-friendly. Due to their liquid shape, renewability, efficient combustibility, low sulphur and scent, and biodegradability, non-edible oils may be suitable biodiesel sources [8]. Raw ingredients account for 70–90% of biodiesel production costs. Non-edible oil crops like Jatropha (2500 kg/ha/year) [9], candlenut (1600 kg/hectare), neem (2670 kg/hectare), karanja (900–9000 kg/hectare) Yellow oleander (5200 kg/ha/year) [13], sea mango (1900–2500 kg/hectare/year). [14] multiply. These plants may grow on sandy and saline soils, which are unsuited for food crop production. Therefore, using non-edible oil as a feedstock would lower biodiesel production costs due to cheaper raw ingredients. Growing non-edible oil crops is cheaper than growing food. Edible crop growth requires high soil fertility, a good irrigation system, and careful management to conserve nutrients and moisture. Oil content percentage (wt%) is another important criterion in determining the biodiesel production feasibility of non-edible oil. Jatropha, rubber, mango, candlenut, polanga, and yellow oleander have far higher oil content percentages than edible oil crops like rapeseed (37–50 wt%), soybean (20 wt%), and palm (20 wt%) [2].

This study sought to make biodiesel from neem and almond oils. The research fills important gaps. Biodiesel manufacturing from non-edible seed oils is optimised to provide a sustainable and cost-effective fossil fuel alternative. It also emphasises agriculture and plants' role in cleaner, more sustainable energy generation. This supports the worldwide objective of growing renewable energy, which is cleaner for contemporary engines.

II. MATERIALS AND METHODS

A. Research Design

The study adopted a sequential experimental design comprising three distinct phases, integrating feedstock preparation, biodiesel production, and comprehensive characterization of biodiesel.

B. Sample Collection and Preparation

Raw neem and almond seeds were sourced from Kadima Market in Jos, Plateau State, Nigeria. Seeds were manually cleaned, dried for 7 days, crushed, and kept in airtight containers at room temperature until oil extraction.

After Phase 2 transesterification, separation, washing, and drying, biodiesel was kept in amber glass bottles at 4°C until characterisation (Phase 3).

All experiments, including materials preparation, oil extraction, and biodiesel synthesis, were done at Austino Research & Analysis Laboratory Nigeria Limited in Alakahia Port Harcourt, Rivers State.

C. Research Methodology

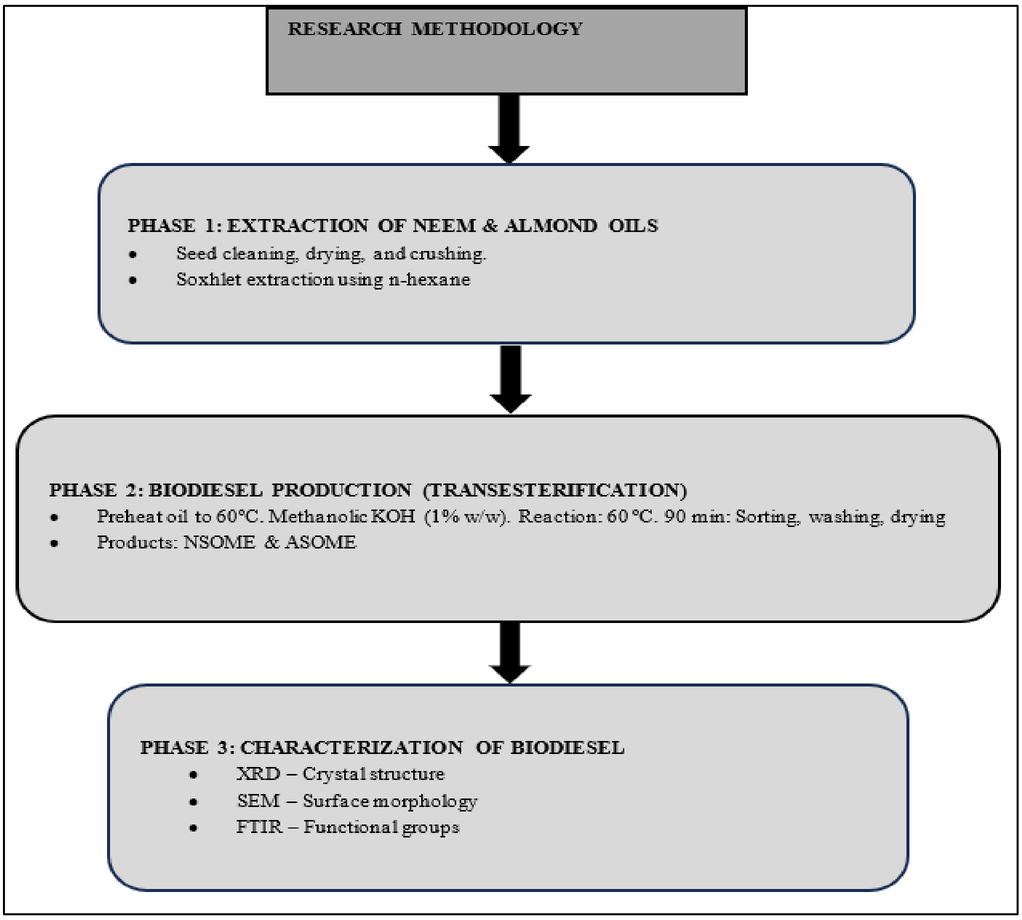

Fig 1 Research Methodology

D. Experimental Procedures

- *Feedstock Preparation*

A hot continuous extraction (Soxhlet) technique successfully recovers non-edible seed oil from finely milled Neem and Almond seeds by exhaustively contacting solvent vapour and the solid matrix while recycling a limited amount of solvent. This method saves solvent and energy compared to batch extractions, making it cost-effective for laboratory and pilot-scale lipid recovery. Evaporation and oven-drying purify crude oil for solvent-free physicochemical and spectroscopic analysis.

After manually dehulling the seeds, they were washed with deionised water to remove surface contaminants. Seeds were cleaned and oven-dried at 105 °C for 12-24 hours to produce a consistent mass and total moisture removal. In a desiccator, dried seeds were cooled before being crushed into a fine powder. To ensure consistent particle size, the powder was sieved through 0.5 mm. After powdering, samples were sealed with a desiccant and held at 4 °C until extraction.

- *Procedure*

After weighing 10 g of seed powder, a cellulose thimble was put in the Soxhlet extraction chamber. Next, 200 mL n-hexane was added to a 250 mL round-bottom flask. To maintain condensation, the Soxhlet extractor and Allihn condenser were linked to cooling water.

Using a heating mantle, the flask was heated to maintain a continuous solvent reflux at 68 °C, the boiling point of hexane. The extraction took 6 hours and 20–25 syphon cycles. Monitoring continued until the solvent returned practically colourless, indicating most of the oil was removed.

All heating was switched off and the device cooled after extraction. The solvent-oil combination was transferred to a rotary evaporator for hexane recovery at 40 °C under decreased pressure. The remaining crude oil was oven-dried at 70 °C for 2 hours to remove solvents and moisture. After cooling in a desiccator, the dried oil's mass was recorded to calculate extraction yield.

- *Non-Edible Seed Oil Physiochemical Analysis*

Oil characterization encompasses both physicochemical and spectroscopic analyses to assess quality, composition, and functional properties. The following properties on the extracted oil: Density (g mL^{-1}), Kinematic viscosity (mm^2 s^{-1}), Cloud point (°C), Flash point (°C), Pour point (°C), Total sulfur (%), Acid value (mg KOH g^{-1}), Calorific value (MJ kg^{-1}), Cetane number, and Water content (%)

- *Procedure*

The oscillating U-tube digital density meter was calibrated at 25°C with dry air and distilled water. Then, 1–2 mL of oil was put into the clean, dry U-tube without air bubbles. After recording the instrument's computed density (g mL^{-1}) at 25°C, the U-tube was cleaned using hexane solvent.

The oil sample was placed in a calibrated glass capillary viscometer tube and submerged in a 40°C ± 0.1°C temperature-controlled bath for 30 minutes. We timed the seconds it took the oil meniscus to pass between two carved markings. Kinematic viscosity (mm^2 s^{-1}) was determined by multiplying flow duration by viscometer constant. Measurements were taken three times and averaged.

Before being suspended in an ice/ethanol chilling bath, a 45-mL oil-filled test jar was thermometer-equipped. The sample chilled 1–1.5°C each minute under constant monitoring. A noticeable haze ("cloud") initially emerged evenly across the sample at the observed temperature (°C).

The Pensky-Martens closed-cup tester sample cup was filled with oil to the required amount. An ignition source was inserted into the vapour area at 1°C intervals while the sample was heated at 5–6°C per minute with continuous stirring. This was the lowest temperature (°C) at which vapours briefly ignited upon flame application.

The oil sample was warmed to 45°C and placed in a jacketed cooling equipment test jar. Cooling was done in 3°C increments (e.g., 0°C → -3°C → -6°C). Each interval, the jar was tilted horizontally for 5 seconds. The pour point was the temperature (°C) when tilting did not move oil.

An XRF sample cup held 3–5 g of homogenised oil. The material was bombarded with X-rays and evaluated for sulfur-specific fluorescence intensity (Kα line, 2.307 keV). The total sulphur content (%) was measured against a recognised sulphur standard calibration curve.

In a potentiometric titration vessel, 5g oil was dissolved in 50 mL 50:50 toluene-isopropanol. Under pH monitoring, 0.1M ethanolic KOH was titrated with stirring. The pH 8–11 inflection point was the terminus. Acid value (mg KOH g^{-1}) was determined using $(V \times M \times 56.1)/W$, where V = KOH volume (mL), M = molarity, and W = sample mass (g 0.5g of oil was pelletised and placed in the bomb calorimeter crucible. Sealing, oxygenating, and submerging the bomb in a water-filled calorimeter. The sample's temperature increase was monitored after electrical ignition. To calculate calorific value (MJ kg^{-1}), the calorimeter's heat capacity constant was calibrated using benzoic acid.

The oil sample was tested in a 900-rpm CFR diesel engine. The compression ratio was altered to meet top dead centre ignition delay. This delay was compared to reference fuels (cetane 0–100), and the cetane number was interpolated from the calibration curve.

The Karl Fischer titration cell was filled with 25 mL of anhydrous methanol, and blank titration neutralised remaining moisture. Next, 0.5–1 g of oil was introduced into the cell. Water interacted stoichiometrically with electrogenerated iodine in Hydranal reagent for titration. Water content (%) was calculated as $((Q \times 0.0001112))/((10 \times W))$ where Q was charge passed (mC) and W was sample mass (g).

➢ *Procedure for Biodiesel Production*

• *Sample Preparation/Pretreatment*

Pretreatment of the oil feedstock removed moisture and reduced free fatty acids (FFAs), which may disrupt transesterification. First, coarse filter paper removed suspended particles and particulates from raw oil. To reduce viscosity and enhance methanol miscibility, the oil was gently heated to 38 °C after filtering.

To dry the oil, it was heated to 105 °C for one hour or vacuum-dried until the water content was below 0.1 wt%. Mass loss following drying or ASTM D2709 Karl Fischer titration confirmed this.

After titration, the oil's FFA concentration was determined. The oil was acid-catalyzed esterified if FFA exceeded 2% (or 4 mg KOH/g). The technique included mixing the oil with methanol at a 20:1 ratio (methanol: FFA) and adding 1–5% H_2SO_4 by weight to the FFA concentration. To convert FFAs into methyl esters, the mixture was heated at 55-65 °C for 1-2 hours.

Esterification was followed by oil settling and layer separation. After washing with warm water to neutral pH, it was dried using the same procedure to eliminate any leftover moisture. The oil was ready for base-catalyzed transesterification.

• *Procedure*

Pretreated oil weighing 200 g was put into a reaction flask for transesterification. To achieve equal temperature distribution, the oil was heated to 60 °C while swirling constantly. To create the catalyst solution, dissolve 1 g of KOH in 20 mL of methanol, resulting in a ~25 wt% methoxide solution. Complete catalyst dissolution was achieved by stirring the liquid until clear.

For transesterification, the methoxide solution was added to the flask once the oil reached the necessary temperature. To convert triglycerides to methyl esters, the reaction was allowed to continue at 60 °C with 400 rpm stirring for 90 minutes.

After the reaction period, the mixture was cooled to room temperature without heating. Phase separation was achieved by placing the cooled liquid in a separatory funnel and leaving it for 8–12 hours. For faster separation, a 3,000-rpm centrifuge was utilised for 10 minutes. This created two layers: biodiesel and glycerol.

The glycerol was properly drained and biodiesel collected. We cleaned the biodiesel three times with warm deionised water (40 °C) using 10% v/v water until it attained a neutral pH of 7.

Anhydrous sodium sulphate (Na_2SO_4) was added to biodiesel as a drying agent to eliminate remaining water and methanol. After filtering, the biodiesel was vacuum-dried at 40 °C for 30 minutes. The biodiesel was refined, filtered, and kept in amber bottles at 4 °C until analysis.

➢ *Biodiesel Physiochemical Analysis*

Product quality is confirmed by measuring acid value, kinematic viscosity, density, iodine value, flash point, and ester content per ASTM D6751 (USA) and EN 14214 (EU) standards. The following properties are measured to verify compliance with fuel standards: Density (g/mL), Kinematic viscosity at 40 °C (mm^2/s), Cloud point (°C), Flash point (°C), Pour point (°C), Sulfur content (%), Acid value (mg KOH/g), Calorific value (MJ/kg), Cetane number, Water content (%).

• *Procedure*

An electronic analytical balance (readability: 0.1 mg) calibrated with verified weights measured biodiesel density. A calibrated pipette was used to dispense 5.00 mL of biodiesel, previously equilibrated at 20 °C, into a clean, dry volumetric container. After gently blotting the container, the filled mass was recorded and the sample mass was estimated by subtracting the tare weight. The density was calculated by dividing mass by volume ($\rho = m/V$). Triplicate measurements were taken to determine the mean and standard deviation. An acceptable relative standard deviation (RSD) was < 0.1%.

A clean, dry Ostwald viscometer was used to test viscosity in a constant-temperature bath at 40 ± 0.05 °C. Before using the viscometer, biodiesel samples were heated to 60-65 °C for 1 hour to dissolve precipitates. After a 10-minute bath equilibration, flow time between timing marks was measured. Multiple the mean flow time by the viscometer constant to get the kinematic viscosity. Precision was achieved by averaging triplicate runs.

A conventional test jar with a thermometer received 50 mL of biodiesel. The material was chilled at 1–3 °C per minute in an ice-salt bath. The jar was tilted at 45° for 5 seconds at 3 °C intervals. The pour point was reported at 3°C above the temperature where biodiesel did not move.

A calibrated thermometer was placed in a test tube with biodiesel. This tube was carefully monitored in a cold bath. The cloud point was the sample temperature when a hazy cloud developed.

Pensky-Marten's device determined the flash point. The sample was heated in the cup with continual stirring following ASTM D93 Procedure A. The flash point was determined by applying the test flame at regular 1 °C intervals and recording the lowest temperature at which a flash occurred.

UV fluorescence analysers assessed sulphur levels according to ASTM D5453. Toluene was used to dissolve and spike the sample with dibutyl sulphide as an internal standard. The calibration curve was used to determine findings from sulphur standards (10–100 ppm).

0.20 g biodiesel was combined with 25 mL diethyl ether and ethanol to evaluate acid value. To titrate with 0.1 N NaOH, phenolphthalein was used. Acid value was calculated:

$$\text{Acid Value} = \frac{(56.1 \times \text{N} \times \text{V})}{\text{W\_sample}} \qquad \text{Eqn 1}$$

where N is NaOH normality, V is volume, and W_sample is sample weight.

Bomb calorimeters measured calorific value according ASTM D240. The fuel sample (~1 g) was enclosed in a crucible with a nickel ignition wire in an oxygen (30 atm) bomb. The explosive was in a 16–17 L deionised water jacket. We started burning and measured the temperature increase. Calories were calculated as:

$$\mathrm{C.V.\_sample} = \frac{[(\mathrm{T} \times \mathrm{w}) - \mathrm{C.V.\_t} - \mathrm{C.V.w}]}{m} \qquad \text{Eqn 2}$$

where T is the temperature rise, w is water equivalent, C.V._t is the heat of the ignition thread, C.V._w is the heat of the ignition wire, and m is the mass of the sample. Results were converted to MJ/kg by multiplying by 4.184.

The cetane number was estimated using empirical relations based on saponification value (SV) and iodine value (IV) as proposed by Hosamani and Hiremath [15], and Dasin *et al.* [16]:

$$\text{Cetane Number} = \left(\frac{46.3 + 5458}{\mathrm{SV}}\right) - 0.225 \times \mathrm{IV}.$$

Eqn 3.

This parameter reflects the ignition quality of the biodiesel. Water content was determined using the centrifuge method. Equal volumes of the biodiesel sample and water-saturated toluene were placed in a tapered centrifuge tube and centrifuged according to ASTM D4007. The volume of water settled at the bottom was read directly from the tube's graduation marks.

III. RESULTS AND DISCUSSION

Table 1: Physicochemical Properties of Non-Edible Seed Oil (Raw Neem Oil and Raw Almond Oil).

Parameter	Raw Oil (Neem)	Raw Oil (Almond)
Density (g/ml)	0.942	0.92
Kinematic Viscosity @ 40°C (mm²/s)	19.63	17.09
Cloud Point (°C)	5.7	2.4
Flash Point (°C)	210.8	218.3
Pour Point (°C)	4.8	-13.4
Sulphur (%)	0.03	0.004
Acid Value (mgKOH/g)	7.9	0.37
Calorific value (MJ/kg)	38.69	38.74
Cetane Number	42.87	0.18
Water content (%)	0.18	0.02

Non-edible oils' physicochemical features, specifically processing requirements, fuel attributes, and engine performance, determine their biodiesel feedstock acceptability. This research investigated the biodiesel-producing ability of neem (*Azadirachta indica*) and almond (*Terminalia catappa*) raw oils. As shown in Table 1, these oils have qualities that affect biodiesel quality and conversion efficiency.

To understand the oils' behaviour during transesterification and fuel application, density, kinematic viscosity, cloud point, pour point, flash point, sulphur content, acid value, calorific value, cetane number, and water content were measured. These factors affect fuel quality, including combustion efficiency, cold flow, oxidative stability, and storage.

These properties are also compared to international biodiesel standards like ASTM D6751 and EN 14214 to assess fuel quality and diesel engine compatibility. Compared to almond oils, neem has benefits and disadvantages in biodiesel synthesis. Variations in viscosity and acid value affect transesterification pre-treatment and catalyst selection.

- *Density*

Raw neem oil (0.942 g/mL) and almond oil (0.920 g/mL) have density values within the biodiesel feedstock range. However, neem oil had a slightly greater density than almond oil, which affected fuel atomisation, injection timing, and combustion efficiency. Higher-density oils may modify injection spray patterns, altering air–fuel mixing and engine performance.

The density of neem oil surpasses that of Hamadou *et al*. [17], who found density values from 0.833 to 0.850 g/mL, depending on source and extraction technique. Remaining moisture or unsaponifiable components like azadirachtins and triterpenoids in neem oil's complex matrix may cause this discrepancy [18].

This research found almond oil density of 0.920 g/mL, somewhat greater than Adama *et al.* [19]'s 0.855 g/mL for tropical almond seed oil. This variation may be due to seed variety, moisture, and oil extraction technique.

To optimise atomisation and combustibility, higher-density oils like neem may need engine recalibration or combination with biodiesel. Such changes are necessary to ensure that biodiesel from high-density feedstocks functions consistently in compression ignition engines without sacrificing fuel economy or pollution norms, according to Atabani *et al*. [20].

- *Acidity and Pretreatment Necessity*

The acid value (AV) of feedstock oils indicates free fatty acid (FFA) concentration, which affects biodiesel production efficiency and output. The AV of neem oil (7.9 mgKOH/g) was much greater than almond oil (0.37 mgKOH/g). The high AV in neem oil matches the FFA concentration reported by Ismaila *et al.* [21], which was 1.22 ± 0.029 %, beyond the normal limits for base-catalyzed transesterification. While almond oil's low AV predicts little FFAs, alkaline catalysis may convert it without pretreatment.

Neem oil's AV surpasses the 2.5 mgKOH/g threshold needed to prevent soap production during alkaline transesterification [20]. Hamadou *et al.* [17] observed neem oil AVs of 8.97 to 9.16 mgKOH/g, which greatly lowers biodiesel output due to soap generation. Therefore, acid-catalyzed pretreatment processes like esterification or neutralisation are necessary to decrease FFA levels before base-catalyzed transesterification [22]. The high AV of neem oil may be due to hydrolytic rancidity during storage in tropical regions, where high temperatures and humidity expedite triglyceride breakdown into FFAs [23].

However, almond oil's AV of 0.37 mgKOH/g is excellent for direct base-catalyzed biodiesel synthesis [20]. This simplifies operations and reduces acid and neutralising agent use. Ogunsuyi and Daramola [24] observed an anomalously high AV of 40.14 mgKOH/g for Nigerian almond oil, showing that seed variety, maturity stage, and extraction procedures might affect AV. Adama *et al.* [19] found that acid esterification lowered tropical almond seed oil's AV from 2.811 to 0.380 mgKOH/g. These results emphasise the need to evaluate and pretreat even low-FFA oils to assure biodiesel output and quality.

- *Cold Flow Properties*

Cloud and pour points of vegetable oils determine biodiesel operability during cold flow. Neem oil had a cloud point of 5.7 °C and a pour point of 4.8 °C, whereas almond oil had 2.4 °C and –13.4 °C.

Cloud point is the temperature at which wax crystals first appear, signalling filter obstruction, whereas pour point is the lowest temperature at which gasoline is fluid enough to pump [25]. Because it contains more saturated fatty acids like palmitic and stearic acids, which crystallise at higher temperatures, neem oil has greater cloud and pour points [5]. Almond oil's lower pour point, due to its high content of unsaturated fatty acids like oleic and linoleic acids, improves cold flow. Refining and transesterification may improve cold flow performance, as Adama *et al.* [19] found a cloud point of –2 °C for biodiesel made from refined almond oil.

If high pour point biodiesel is used in Jigawa State, where temperatures may drop to 21 °C [26], these thermophysical qualities might cause fuel gelling or filter clogging. Thus, neem-based biodiesel may need cold flow improvers such polymethyl acrylate or blending with lower-pour point fuels to preserve pumpability at low temperatures [27]. Due to its subzero pour point, almond-derived biodiesel is suitable for year-round use in Nigeria's different climates.

- *Flash Point*

Neem and almond oils have flash temperatures of 210.8 °C and 218.3 °C, respectively, which surpass the ASTM D6751 standard of 130 °C, suggesting low volatility and decreased fire dangers during storage and handling. Long-chain triglyceride-rich oils with low light-end volatile constituents have high flash points, indicating thermal stability as biodiesel feedstocks [28]. This supports Banik *et al.* [29], who found neem oil flash points over 200 °C, confirming its safety throughout processing and shipping. Adama *et al.* [19] found a flash temperature of 157 °C for almond biodiesel, showing that both raw oils and their biodiesels had flash points beyond safety standards. High flash points in this research indicate that neem and almond oils are thermally stable and pose little danger of igniting under conventional storage and handling settings, making them acceptable biodiesel precursors.

- *Sulphur Content*

Neem oil (0.03%) and almond oil (0.004%) have low sulphur content, meeting the EN 590 standard of 0.05% for petrodiesel which makes them viable low-sulfur biodiesel feedstocks. Almond oil's ultralow sulphur content improves environmental compatibility by lowering SO_x emissions during burning and airborne pollutants [20]. The greater sulphur percentage in neem oil may be due to glucosinolates in the seeds [23], which might cause slightly increased SO_x production if left uncontrolled. While neem oil's sulphur content is below biodiesel standards (ASTM D6751 and EN 14214 recommend ≤0.0015%), targeted desulfurization using activated carbon from agricultural waste may be necessary to meet strict fuel standards [30]. Low sulphur levels in both oils are typical of non-edible, plant-derived feedstocks, where soil absorption is reduced [31, 32]. Adama *et al.* [19] found low ash and moisture levels in tropical almond biodiesel, indicating its potential for clean-burning, low-sulfur emissions.

- *Energy Density and Combustion Performance*

Both neem (38.69 MJ/kg) and almond (38.74 MJ/kg) oils release enough energy for biodiesel applications. While somewhat lower than petrodiesel (about 42-45 MJ/kg), these values are consistent with most plant-based oils [17, 33]. Hamadou *et al.* [17] found that neem oil has a calorific value of 39.64 MJ/kg, making it a viable renewable fuel with a low energy trade-off compared to fossil diesel.

Both oils have similar energy densities, however almond oil's unclear cetane characterisation requires more confirmation to reconcile stated figures. Although near-standard, neem oil's cetane number may need additions or blending to meet ASTM D6751 standards and maintain cold-start performance. Standardised testing techniques and fatty acid profiling are essential for assessing non-edible oils for biodiesel generation due to reported variances.

- *Viscosity and Engine Compatibility*

Neem (19.63 mm²/s) and almond (17.09 mm²/s) oils have greater kinematic viscosities than conventional petrodiesel (2–4.5 mm²/s) and surpass ASTM D6751 (1.9–6.0 mm²/s) and EN 14214 (<5 mm²/s) biodiesel specifications. Unmodified diesel engines with high viscosity have poor atomisation and spray characteristics, resulting in incomplete combustion, carbon deposits, and lower engine lifespan [33, 34]. Transesterification is necessary to create FAMEs with viscosities acceptable with current compression-ignition engines.

Transesterification decreased crude neem oil's high viscosities 26.34–26.67 cSt, confirming the importance of pretreatment in fuel compatibility [17]. Ogunsuyi and Daramola [24] showed that neem-derived biodiesel may fulfil EN 14214 criteria with viscosities of 4.51–4.89 mm²/s post-transesterification. Adama *et al.* [19] found that catalytic conversion reduces the viscosity of almond oil to acceptable levels, despite its raw viscosity (17.09 mm²/s) being too high for direct application.

Instead of using raw neem and almond oils in diesel engines owing to their high kinematic viscosities, transesterification reliably lowers them to ASTM D6751 and EN 14214 standards. This technique works for both feedstocks, suggesting they might be biodiesel precursors with suitable catalytic processing.

- *Cetane Number*

The cetane number (CN) is a key indicator of compression-ignition engine ignition quality, since it inversely corresponds with ignition delay [35]. In this investigation, neem oil has a CN of 42.87, below the biodiesel range of 40–55. This value falls short of the ASTM D6751 and EN 14214 minimum of 47, indicating moderate ignition characteristics [27]. To optimise engine performance, neem-derived biodiesel may need to be blended with higher-CN fuels or cetane improvers. Almond oil's claimed CN of 0.18 is unsuitable for hydrocarbon-based fuels and may be due to typographical or analytical errors (review needed). It contrasts with Ogunsuyi and Daramola's [24] 62 for transesterified almond biodiesel. Almond oil biodiesel CNs vary from 47 to 55, depending on fatty acid content and processing [35, 36]. Esonye *et al.* [36] found CNs of 48-52 for transesterified almond oil, indicating its acceptability for compression-ignition engines without significant modifications. Methodological discrepancies like direct ignition delay measurement vs predictive computation models or fatty acid profile changes may explain this mismatch. Ogunsuyi and Daramola [24] found 48.40% methyl oleate and 43.04%) methyl palmitate in almond biodiesel, which often generate cetane values over 55.

Almond oil biodiesel's high CNs and methyl oleate and methyl linoleate content improve ignition performance [35]. Neem oil's fatty acid profile, mainly by linoleic (40%) and oleic (35%), supports a mild CN but makes it oxidatively unstable [21].

- *Water Content*

Oil stability and reactivity during transesterification depend on water concentration. This analysis found 0.18% water in neem oil and 0.02% in almond oil. Water removal is necessary because high moisture (>0.05%) promotes triglyceride hydrolysis and soap production, decreasing biodiesel yields and deactivating alkaline catalysts [37]. The denser, more hygroscopic structure of neem oil makes it more wet, requiring stringent drying methods like heating and centrifugation to avoid saponification and maximise conversion. Almond oil's low water content eliminates the requirement for pre-drying, making it more suitable for biodiesel production [19].

E. Biodiesel Analysis

Table 2. Physicochemical Properties of Biodiesel (Neem) from Neem Oil Biodiesel (Almond) from Almond Oil.

Parameter	Biodiesel (Neem)	Biodiesel (Almond)
Density (g/ml)	0.887	0.874
Kinematic Viscosity @ 40°C (mm²/s)	3.96	3.21
Cloud Point (°C)	4.1	3.8
Flash Point (°C)	142.7	121.6
Pour Point (°C)	2.5	1.2
Sulphur (%)	0.001	0.0009
Acid Value (mgKOH/g)	0.36	0.28
Calorific value (MJ/kg)	40.15	39.24
Cetane Number	58.13	51.77
Water content (%)	0.024	0.031

Biodiesel manufacturing relies on physicochemical qualities that meet international fuel requirements and optimise engine efficiency. Table 2 shows the fuel parameters of transesterified neem (*Azadirachta indica*) and almond (*Terminalia catappa*) biodiesel. Both neem and almond biodiesels meet ASTM D6751 and EN 14214 specifications for density, kinematic viscosity, cetane number, flash point, and sulphur content, proving their viability as renewable fuels for compression-ignition engines [38]. However, each oil's fatty acid makeup and processing behaviour cause modest changes in metrics, highlighting pros and cons. To match almond biodiesel's ignition and low-temperature operability, neem biodiesel may need specialised blending or addition techniques due to variances in cold flow characteristics and cetane numbers.

- *Density*

The density of biodiesel affects fuel injection and combustion in compression-ignition engines. In this investigation, neem biodiesel has a density of 0.887 g/mL, slightly higher than tropical almond biodiesel's 0.874—both values fit within ASTM D6751 and EN 14214 norms (0.86–

0.90 g/mL), demonstrating its acceptability for unmodified diesel engines [19]. Neem's increased density indicates more volumetric energy, improving fuel efficiency at high loads but requiring injector recalibration to prevent overfueling or clogging [16]. Better lubrication and engine operation frequently accompany increased density [16].

In addition to atomisation and spray, density affects ignition quality. Neem biodiesel's density and cetane number of 58.13 indicate shorter ignition delay and smoother combustion, which minimise engine knocking and increase performance [20, 21]. Almond biodiesel has a cetane number of 51.77, indicating its methyl oleate (48.40%) content and lower density [24]. Almond's cetane value is suitable for CI engines, although its lower ignition efficiency may need minor timing changes for maximum performance [27].

- *Kinematic Viscosity*

At 40 °C, neem (3.96 mm²/s) and almond (3.21 mm²/s) biodiesels meet the ASTM D445 standard range of 1.9-6.0 mm²/s [38], indicating that transesterification successfully reduced raw oil viscosities (19.63 and 17.09 mm²/s) to acceptable levels [17]. Since viscosity controls fuel atomisation, spray characteristics, and engine lubrication, both biodiesels are predicted to operate well in compression-ignition engines [39, 34].

Neem biodiesel's greater viscosity (3.96 mm²/s) improves lubrication and reduces engine wear, but lower temperatures may impair atomisation quality, requiring blending or heating for efficient combustion [39, 40]. Neem biodiesel viscosities range from 5.20 to 6.50 mm²/s, depending on seed biotype, as reported by Bhandare and Naik [41]. This supports the necessity of choosing suitable feedstock variations. In contrast, almond biodiesel has a viscosity of 3.21 mm²/s, similar to petrodiesel (2.0-4.5 mm²/s). Adama et al. [19] found that tropical almond biodiesel has a viscosity of 3.52 mm²/s, similar to other low-viscosity feedstocks like sunflower oil [42]. The high oleic acid content improves atomisation, reducing NO_x emissions and injector fouling, and improving cold-start performance [34, 28]. This viscosity advantage maintains despite both biodiesels reaching international standards.

- *Cloud and Pour Points*

Cold flow qualities significantly impact biodiesel performance in low-temperature conditions. Neem biodiesel had a cloud point of 4.1 °C and a pour point of 2.5 °C, whereas almond biodiesel had 3.8 °C and 1.2 °C. NEM biodiesel has more saturated fatty acid methyl esters, which crystallise at higher temperatures, giving it somewhat higher cloud and pour points [19, 21]. Both biodiesels may be utilised year-round, however almond biodiesel's cold flow behaviour minimises wax crystallisation danger in fuel systems, especially during dry seasons when nighttime temperatures can reach 21 °C [26]. For reliable operation in chilly or temperate regions, neem and almond biodiesels may need cold flow improvers or blending with petro-diesel [43].

The feedstocks' fatty acid profiles explain the cold flow discrepancies. The increased monounsaturated content of almond biodiesel, especially oleic acid (35–48.4%), decreases its crystallisation temperature and improves fluidity at colder temperatures [21]. In contrast, neem biodiesel has 40% polyunsaturated linoleic acid, which enhances molecular packing and cloud and pour points [19].

- *Flash Point*

Fuel handling and storage safety depends on flash point. Neem and almond biodiesels have flash points of 142.7 and 121.6 °C, respectively, above the ASTM D6751 requirement of 93 °C, reducing fire danger during storage and shipping [38]. Neem biodiesel's reduced volatility and higher flash point (150–165 °C) make it safer in high-temperature environments [16]. Almond biodiesel's lower flash point may be due to trace residual methanol or lighter esters, requiring additional washing steps to ensure handling safety, but it still has a good safety profile, especially when blended to raise its flash point for hotter climates [40].

- *Sulphur Content*

The sulphur concentration of neem and almond biodiesels is 0.001% and 0.0009%, respectively, much below the ASTM limit of 0.05% and fulfilling the EN 14214 criteria of ≤0.001% [44]. Reduced SO_x emissions during combustion due to ultra-low sulphur levels greatly decrease acid rain and pulmonary pollutants. These biodiesels also work with current after-treatment systems like diesel particle filters and selective catalytic reduction units, which are sensitive to high sulphur levels [20]. Bhandare and Naik [41] have noted that neem-based biodiesel's low sulphur content makes it a cleaner-burning feedstock than diesel.

- *Acid Value*

Acid value indicates free fatty acid (FFA) level, affecting fuel stability and corrosion. Neem biodiesel had an acid value of 0.36 mg KOH/g, whereas almond biodiesel had 0.28 mg KOH/g, far below the ASTM D664 maximum limit of 0.50 mg KOH/g [38]. This acid reduction proves that transesterification converts FFAs into esters and reduces soap production. The somewhat greater acid value of neem biodiesel may be due to residual moisture or poor post-production purification, as reported by Bhandare and Naik [41], who found acid values as low as 0.52 mg KOH/g depending on seed biotype. Even with this modest rise, neem biodiesel has high oxidative stability, as Adama et al. [19] found after neutralisation. The lower acidity of almond biodiesel reduces corrosivity and improves storage stability. Furthermore, both fuels meet EN 14214 standards (<0.50 mg KOH/g), suggesting low engine corrosion risk and long-term storage acceptability [44].

- *Calorific Value*

The calorific value of biodiesel measures energy production per mass and is crucial for fuel performance evaluation. The research found that neem biodiesel had a calorific value of 40.15 MJ/kg, somewhat greater than almond biodiesel (39.24 MJ/kg) and within the normal range for fatty acid methyl esters (37-42 MJ/kg), but significantly lower than petrodiesel (≈45 MJ/kg) [39, 33]. Neem's higher calorific value reflects its longer-chain fatty acid esters and reduced oxygen content, resulting in a 2.3% increase in energy yield per unit mass. This can lead to increased energy density, engine torque, and thermal efficiency [33, 21]. The lower acid value of almond biodiesel (0.28 mg KOH/g vs. 0.36 mg KOH/g in neem) improves its oxidative stability during storage, when free fatty acid regeneration increases fuel deterioration [23

- *Cetane Number*

Cetane number (CN) is a key measure of compression-ignition engine ignition quality, affecting ignition delay and combustion stability [15]. This research found that neem biodiesel has a CN of 58.13, compared to 51.77 for almond. Both biodiesels may ignite under compression circumstances since they surpass the ASTM D613 minimum of 47 for diesel fuels [38]. Neem biodiesel has a premium ignition quality because to its higher CN, whereas almond biodiesel is still adequate but ignitions slower.

The ignition delay, engine noise, and combustion smoothness improve with a greater CN [15]. High-performance engine applications benefit from quick ignition and little delay, leading to increased throttle response and decreased unburned hydrocarbons. In essence, neem biodiesel's high CN ignites the fuel-air combination more easily upon injection, reducing incomplete combustion and knock. Almond biodiesel's CN of 51.77, much over the statutory standard, may cause prolonged ignition delays and need slightly altered injection time for proper combustion phasing [41].

Different feedstock fatty acid compositions generate these CN variations. Neem oil has a larger amount of long-chain saturated and monounsaturated fatty acid methyl esters, leading to better ignition and higher CN values [15]. Bhandare and Naik [41] found that feedstocks high in long-chain esters, such neem, regularly show CNs in the mid-50s. Almond biodiesel has more monounsaturated esters (mostly methyl oleate), which improve cold flow but reduce CN [41].

In practice, neem and almond biodiesels' CNs need different engine calibration procedures. Almond biodiesel engines may need to delay injection by 1–2 crank angle degrees to compensate for the delayed ignition initiation. The increased CN of neem biodiesel makes it more like regular diesel, enabling direct usage without much adjustments [15].

Additionally, neem biodiesel's high CN content lowers peak combustion temperatures, reducing NO_x production and providing environmental advantages [15].

- *Water Content*

Biodiesel storage stability, microbiological growth, and engine performance depend on water content. We found that neem biodiesel had 0.024% moisture and almond biodiesel 0.031%, both below the ASTM D2709 maximum limit of 0.05% [38]. Excess water may cause microbial growth, corrosion in storage and fuel systems, and phase separation, compromising fuel integrity and engine dependability (28). For long-distance shipping and extensive storage, neem biodiesel's somewhat lower water content offers a benefit in terms of storage life and decreased contamination risk. Although both fuels have low moisture levels, Bhandare and Naik [41] emphasise the need of full dehydration to avoid hydrolytic processes that compromise fuel quality.

IV. CONCLUSION

This research confirms the technical viability of neem (*Azadirachta indica*) and almond (*Terminalia catappa*) oils as biodiesel feedstocks in Nigeria. Neem oil is ideal for high-performance or heavy-duty applications due to its high availability and outstanding combustion properties, such as cetane number (58.13) and energy density (40.15 MJ/kg). Due to its high free fatty acid concentration (7.9 mg KOH/g), poor cold flow performance, and high moisture levels, pretreatment treatments such acid-catalyzed esterification and cold-flow improvements are necessary to maintain fuel quality.

Almond oil, with its low acid value (0.37 mg KOH/g), sub-zero pour point (–13.4°C), and low moisture (0.02%), is ideal for cold-climate operations and direct transesterification. However, its geographical scarcity and very low cetane measurement (0.18) demand additional validation and judicious mixing to optimise ignition quality. All biodiesel samples, regardless of feedstock, fulfilled ASTM D6751 and EN 14214 requirements for viscosity, density, flash point, acid value, sulphur level, and water content, proving technical acceptability. The ultra-low sulphur levels in all samples meet clean fuel and emission control standards.

It is recommended to study the long-term engine performance and emission profiles of neem–almond biodiesel blends in compression ignition engines and operating conditions and use advanced cold-flow improvers and antioxidants to improve low-temperature operability and oxidative stability.

ACKNOWLEDGMENT

Our appreciation goes to the Centre for Gas, Refining and Petrochemical Engineering, Choba, Port Harcourt, for their support in making this research work a success.

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