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Research Article

Chemo-Physical Characterization of Castor Oil Biodiesel and B20 Blends from Gboko, Benue State: Implications for Regional Feedstock Suitability

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Abstract- The increasing demand for alternative renewable fuels has intensified research into non-edible oil feedstocks for sustainable biodiesel production. This study investigates the conversion of castor seed oil sourced from Gboko, Benue State, Nigeria, into biodiesel using a two-step acid–base catalyzed transesterification process optimized for high–free-fatty-acid oils. Initial characterization of the crude castor oil revealed an acid value of 4.5 mgKOH/g, necessitating esterification before alkaline transesterification. Eight reaction rounds were conducted, incorporating systematic catalyst dosing, temperature control (65–70 °C), and sequential washing and drying to achieve optimal FFA reduction. The process yielded 60% methyl esters, demonstrating a competitive conversion efficiency compared to reports from other regions. Fuel property analysis of the biodiesel (B100), B20 blend, and petroleum diesel was conducted following standard ASTM methods. Results indicate that castor biodiesel exhibits higher flash point, viscosity, density, and carbon residue relative to petroleum diesel, while displaying significantly lower sulphur content and superior cetane numbers. Cold-flow characteristics (pour and cloud points) fall within acceptable limits for biodiesel standards, and all samples satisfied ASTM D6751 and EN 14214 acid value specifications. Overall, the study confirms that castor oil from Gboko is a viable feedstock for biodiesel production, offering favourable combustion quality, enhanced safety characteristics, and potential environmental benefits. The B20 blend, in particular, demonstrates properties closest to conventional diesel, making it suitable for practical engine applications.

Article Key Information

Keywords: Castor biodiesel, Transesterification, Fuel property characterization, Renewable energy fuels

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1.0 Introduction

The global transition toward cleaner, renewable fuels has intensified interest in biodiesel derived from non-edible vegetable oils. Fossil diesel continues to dominate transport and power-generation sectors, yet its combustion contributes significantly to greenhouse gas emissions, sulfur oxides, particulate matter, and long-term ecosystem degradation [1], [2]. Biodiesel comprising mono-alkyl esters produced through the transesterification of triglycerides presents a viable alternative due to its biodegradability, non-toxicity, superior lubricity, and its ability to be used directly or blended with petroleum diesel without engine modification [3]. However, the sustainability of biodiesel production depends critically on identifying feedstocks that do not compete with food supply while offering stable yield and favourable physicochemical properties suited for both production and end-use.

Castor seed oil (*Ricinus communis L.*) has emerged as one of the most promising non-edible feedstocks due to its adaptability to dry climates, high oil content, and its unique fatty acid profile dominated by ricinoleic acid, a hydroxylated C18 fatty acid known to significantly influence viscosity, density, and cold-flow behaviour of its biodiesel [4], [5]. Although castor grows naturally across many agro-ecological zones of Nigeria, including the Middle Belt, there is a paucity of systematic studies assessing the suitability of castor oil from Benue State**,** a region renowned for its fertile soils and favourable climatic conditions, for biodiesel production. Previous studies in Nigeria and other countries have reported wide variations in ester yield and fuel properties of castor biodiesel depending on geographic location, soil type, oil quality, and processing method. For instance, ester yields reported include 23–24% for Egyptian castor oil, 37–38% for samples from Zaria, 47–48% for Kwara State, and 57–63% for regions in East Africa and Northern Nigeria [6]–[10]. These variations underscore the importance of localized evaluation.

A key challenge with castor oil biodiesel production is its relatively high free fatty acid (FFA) content, which often exceeds the acceptable limit for direct base-catalyzed transesterification. High FFA oils tend to react with alkaline catalysts to form soap, inhibiting ester formation and reducing biodiesel yield. Consequently, the two-step acid-catalyzed esterification followed by methanol-based transesterification has been widely adopted for high-FFA feedstocks to reduce FFA levels to below 1 mg KOH/g before final ester conversion [11]. The methodology employed in this study strictly follows this established protocol, beginning with acid esterification to reduce the initial acid value of the Gboko castor oil (4.5 mgKOH/g), followed by alcoholysis under controlled conditions to achieve measurable conversion efficiency.

After biodiesel production, fuel blending is an essential step that determines compatibility with existing diesel engines. The B20 blend comprising 20% biodiesel and 80% petroleum diesel is globally regarded as optimal because it preserves the favourable combustion, lubricity, and emissions characteristics of biodiesel while maintaining energy density, viscosity, and cold-flow behaviour close to conventional diesel [12]-[15]. As such, the present study produced both neat castor biodiesel (B100) and a B20 blend to evaluate their performance against ASTM D6751 and EN 14214 standards using key chemo-physical parameters. These include flash point, kinematic viscosity, sulfur content, carbon residue, ash content, density, calorific value, pour point, cloud point, cetane number, and acid value properties critical for assessing fuel ignition quality, storage stability, cold-flow behaviour, and suitability for diesel engine use.

This research fills an important gap by providing the first systematic evaluation of castor oil from Gboko, Benue State, as a biodiesel feedstock. By comparing the chemo-physical characteristics of the produced biodiesel and B20 blend with international fuel standards and reported values from other regions, the study establishes whether castor cultivation in Benue State can support viable biodiesel production and contribute to renewable energy development in Nigeria. Furthermore, the findings provide evidence-based insight into how local climatic and soil conditions influence biodiesel quality and yield, thereby guiding future industrial-scale biodiesel initiatives within the region.

2.0 Literature Review

The growing interest in biodiesel as a renewable transportation fuel has driven significant research into non-edible feedstocks capable of supporting large-scale and sustainable production. Castor oil (Ricinus communis L.) remains one of the most extensively investigated non-edible feedstocks due to its unique chemical composition, widespread availability in tropical climates, and high oil content relative to many alternative crops [16]. Contemporary biodiesel research emphasizes not only production efficiency but also a detailed understanding of feedstock variability, molecular composition, production pathways, and resulting fuel properties. This section provides a critical review of global and regional literature on castor seed oil, its physicochemical characteristics, its transesterification behavior, and its potential as a biodiesel feedstock.

2.1 Global Research on Castor Oil as a Biodiesel Feedstock

Several studies have demonstrated castor oil's potential for biodiesel production, largely attributed to its high concentration of ricinoleic acid, which typically constitutes 80–90% of total fatty acids [7], [9]. Knothe and Steidley [16] conducted one of the earliest comprehensive analyses of castor oil methyl esters, demonstrating their unusually high viscosity relative to biodiesels derived from oleic- or linoleic-rich feedstocks. This hydroxyl

functionality, although beneficial for lubricity, contributes to elevated viscosity and density, which may complicate fuel atomization and cold-flow properties.

Further insights are provided by Eryilmaz et al. [17], who investigated castor biodiesel blends (B10–B50) in a compression-ignition engine. Their results showed that increasing castor biodiesel content improves lubricity and reduces carbon monoxide emissions but increases nitrogen oxide emissions due to higher oxygen content in the fuel. These studies emphasize the need for optimizing blending ratios to balance emission performance and fuel properties.

Recent developments in catalyzed transesterification have also advanced castor biodiesel production efficiency. Ghaly et al. [18] reported that heterogeneous catalysts (e.g., CaO-based systems) can significantly reduce reaction time and improve methyl ester yield when processing castor oil with high free-fatty-acid (FFA) content. Such advancements are critical because castor oil typically contains higher FFA levels compared to many edible oils, necessitating pretreatment steps to avoid soap formation during transesterification.

2.2 Influence of Geography and Environment on Castor Oil Composition

Environmental factors such as soil type, altitude, genotype, and climate strongly influence castor seed oil composition. Morris [9] demonstrated significant variations in ricinoleic acid content among global castor germplasm, with ricinoleic acid ranging from 70% to 90% depending on genotype and ecological conditions. Similarly, studies by Mulualem and Mekonnen [15] revealed that castor plants grown in semi-arid Ethiopian regions produced seeds with higher oil content and improved oxidative stability compared to those grown in humid lowland environments.

In India, Narasimhan et al. [19] reported regional variations in castor oil yield and quality across Gujarat, Andhra Pradesh, and Rajasthan, demonstrating that agro-climatic conditions significantly influence oil recovery and FAME composition. Brazil, the world's largest castor producer, has also documented region-linked variations in seed size, oil content, and fatty-acid distribution. Severino et al. [20] found that Brazilian castor varieties grown in arid zones displayed higher ricinoleic acid concentrations than those grown in humid regions.

These documented variations highlight the necessity of conducting localized studies, particularly in regions where castor production is underexploited. Since biodiesel performance is closely related to FAME composition, region-specific characterization becomes essential for predicting fuel behavior and suitability for diesel engines.

2.3 Castor Oil Biodiesel Production Pathways and Process Optimization

Biodiesel production from castor oil typically involves a two-step process: acid esterification followed by alkaline transesterification to address high FFA levels. Several studies have optimized these steps using different catalysts, alcohol ratios, temperatures, and reaction durations. For example, Atabani et al. [5] conducted a meta-analysis of non-edible biodiesel feedstocks and found that castor biodiesel yields above 90% are consistently achievable when using a methanol-to-oil ratio of 6:1 and temperatures between 55–65 °C.

Other studies have investigated alternative processing approaches. Zhang et al. [21] explored supercritical methanol transesterification and demonstrated that castor biodiesel can be produced within minutes at temperatures above 300 °C, though the method requires high energy input. Likewise, Meher et al. [22] highlighted advances in enzymatic transesterification, which offer high specificity and reduced soap formation but remain cost-prohibitive for commercial-scale use.

These varying production approaches underscore the central challenge in castor biodiesel research: improving process efficiency while maintaining fuel properties that conform to ASTM D6751 and EN 14214 standards.

2.4 Physicochemical and Fuel Properties of Castor Biodiesel

Castor biodiesel displays unique fuel properties that distinguish it from other biodiesels. According to Silitonga et al. [23], castor methyl esters exhibit higher viscosity, density, and flash point compared to biodiesels from

jatropha, palm, or soybean oils. Although high viscosity may pose challenges for fuel injection systems, it also enhances lubricity, which is beneficial for older diesel engines and certain industrial applications.

Naves et al. [13] examined castor biodiesel blends and found that blending CME with diesel significantly improves cold-flow properties, reduces viscosity, and increases calorific value, thereby enhancing its suitability for use in modern diesel engines. Furthermore, Arslan et al. [12] demonstrated that blends up to B40 can satisfy ASTM/EN biodiesel quality parameters, confirming castor's viability for commercial application when appropriately blended.

2.5 Nigerian Studies on Castor Oil and Identified Knowledge Gaps

Within Nigeria, most published studies have focused on extraction methods, basic fuel properties, and transesterification optimization. Bello et al. [8], [10] evaluated castor oil from Ondo State and produced CME with ricinoleic acid content of approximately 89%, whereas Ozemoya and Ayoola [11] produced CME with satisfactory ignition quality and flash point values. Similar studies in Oyo and Kaduna States have reported comparable trends in oil yield and FAME composition [24].

However, no published study has investigated castor oil or biodiesel properties from Benue State, a region with distinct soil characteristics, climatic variability, and large arable landmass. This gap is significant because variations in FAME composition directly influence engine compatibility, cold-flow performance, oxidative stability, and blending behavior.

The absence of GC–MS molecular profiling and standardized fuel-property evaluation for castor oil in Benue State presents a critical knowledge gap. The present study is therefore timely, providing the first region-specific characterization of castor seed oil and biodiesel sourced from Gboko, enabling meaningful comparison with national and global datasets.

3.0 Materials and Methods

3.1 Materials

Castor seeds were collected from wild-growing *Ricinus communis* shrubs around bushy areas in Gboko Local Government Area, Benue State, Nigeria. The seeds were manually cleaned, sun-dried, dehulled, and subjected first to screw expression followed by n-hexane solvent extraction to maximize oil recovery. Mechanical expression combined with solvent extraction has been shown to enhance oil yield from high-oil seeds such as castor [25].

The reference petroleum diesel used for blending and comparison was obtained from John Nnwoke Filling Station in Gboko. All reagents, including methanol, concentrated sulfuric acid (H_2SO_4), sodium hydroxide (NaOH), isopropyl alcohol, phenolphthalein indicator, and distilled water, were analytical grade and procured from Sanofan Chemicals and Science Equipment Suppliers, Gboko.

Laboratory apparatus included:

1. Methanol
2. Sulfuric acid
3. Isopropyl alcohol
4. Phenolphthalein indicator
5. 1-L separating funnel
6. Electronic weighing balance
7. Sodium hydroxide
8. Biodiesel reactor
9. Digital thermocouple thermometer
10. Timer
11. Measuring cylinders

12. Glass beakers
13. Stainless-steel heating pot
14. Purified water
15. Syringes and needles

The experimental workflow adopted here aligns with established biodiesel-production protocols widely applied to high-FFA feedstocks [26], [27].

3.2 Acid Esterification (Pre-Treatment of High-FFA Castor Oil)

The initial acid value (A.V.) of the crude castor oil was 4.5 mg KOH/g, indicating a high free-fatty-acid content that would hinder alkaline transesterification. Oils with A.V. exceeding 2 mg KOH/g typically require acid esterification to suppress soap formation and improve ester yield [28], [29].

A total of 2000 mL of crude oil was introduced into the reactor. Using a syringe, 0.3 mL of concentrated H_2SO_4 was added, followed by 100 mL of methanol. The mixture was stirred at approximately 1500 rpm and heated to 65–70°C for 1 hour, constituting one reaction "round." At the end of each round, a sample was withdrawn and analyzed for acid value.

The procedure was repeated as summarized in Table 1, until little or no reduction in A.V. was observed:

Table 1. Acid Esterification Rounds

Round	Oil Volume (mL)	Acid (mL)	Methanol (mL)	Time (h)	Temp (°C)	Acid Value (mg KOH/g)
1	2000	0.3	100	1	65–70	4.5
2	2000	0.3	100	1	65–70	3.0
3	2000	0.3	100	1	65–70	2.0
4	2000	0.3	100	1	65–70	2.0
5	Washed	–	–	2	–	1.2
6	Dried	–	–	1	120	1.2
7	1980	–	100	1	65–70	0.8
8	1980	–	100	1	65–70	0.6

At Round 4, A.V. became stagnant. Further addition of acid catalyst increased A.V.—a phenomenon previously reported when excess sulfuric acid regenerates FFA through partial hydrolysis [30]. Therefore, the reaction mixture was washed (Round 5) and dried (Round 6) to remove residual acid before alkaline transesterification.

3.3 Transesterification

After completing acid esterification, no additional sulfuric acid was added. Only methanol (100 mL) was used in Rounds 7 and 8 at 65–70°C for 1 hour each. These conditions initiate the conversion of triglycerides to methyl esters and glycerol.

Transesterification reaction conditions for castor oil often require higher alcohol ratios and prolonged reaction time due to the high viscosity associated with ricinoleic acid content, consistent with previous studies [31], [32].

3.4 Biodiesel Purification (Washing and Drying)

The crude biodiesel was allowed to settle in a 1-L separating funnel for 8 hours to facilitate gravitational separation of glycerol. The lower glycerol layer was drained off carefully.

Purification was performed using warm water (60°C), equal in volume to the biodiesel. The mixture was manually agitated and allowed to settle for 1 hour. Washing was repeated four times until the wash water became clear. Water-washing effectively removes residual catalyst, soaps, glycerol, and methanol, an approach widely validated in biodiesel purification studies [33].

The washed biodiesel was dried by heating at 60–70°C for several hours until all moisture evaporated. The dried fuel was stored for three weeks before blending.

3.5 Blending of Biodiesel (B20 Blend)

A B20 blend was prepared by mixing **20% castor biodiesel** with **80% petroleum diesel**. B20 blends are widely accepted for engine use due to their balanced combustion, emissions, and storage characteristics [34].

3.6 Determination of Ester Yield

Ester yield was calculated using a widely adopted formula for biodiesel-conversion efficiency [35]:

$$\text{Yield (\%)} = \frac{V_e}{V_r} \times 100$$

Where:

- $V_e = 1.2\text{L}$ (volume of methyl ester produced)
- $V_r = 2.0\text{L}$ (volume of crude oil used)

3.7 Fatty Acid Composition (GC Analysis)

Fatty-acid profiling followed AOCS Ce 1-62 methodology as applied in multiple GC–FID–based fatty-acid studies [36]. Approximately 80 mg of castor oil was dissolved in 1 mL of petroleum ether and subjected to acid-catalyzed methylation using methanolic-HCl.

Analysis was performed using:

- GC Instrument: Hewlett Packard 5890A
- Injector: Split mode
- Detector: Flame Ionization Detector (FID)
- Column: 30 m × 0.25 mm cyanopropylphenyl phase
- Injector/Detector Temperature: 250°C

Temperature programming followed a sequence. Fatty-acid methyl esters (FAMEs) were quantified using peak-area normalization, a well-established quantification method in lipid analysis [37].

3.8 Fuel Properties Analysis

Fuel properties of crude oil, methyl ester, and B20 blend were analyzed at Light-House Petrochemical Analytical Laboratory, Warri, Nigeria, using ASTM-equivalent procedures validated in peer-reviewed studies:

- Flash Point: Cleveland Open Cup method comparable to ASTM D92, validated by [38]
- Free Fatty Acid: Titrimetric analysis as applied in [39]
- Kinematic Viscosity: ASTM D445 equivalent method supported by [40]
- Density / Specific Gravity: Pycnometer method used in [41]
- Carbon Residue: Furnace-based method aligned with ASTM D189 as discussed in [42]
- Ash Content: Gravimetric approach described in [43]
- Pour Point & Cloud Point: Cryogenic cooling methods validated in [44]
- Calorific Value: Parr Adiabatic Oxygen Bomb Calorimeter based on procedures in [45]
- Cetane Index: Calculated using empirical correlations described in [46]

All measurements were performed in duplicate or triplicate to ensure accuracy.

4.0 Results and Discussion

4.1 Ester Yield

The biodiesel synthesis yielded 60% methyl esters (1.2 L CME from 2.0 L crude oil), which is within the lower range reported for castor biodiesel under two-step acid + base transesterification protocols. Literature reports FAME yields from castor seed oil ranging from 61% (for crude castor oil) to upwards of ~90% under optimized conditions [47], [48]. The moderate yield obtained here may stem from the high initial free-fatty-acid content of the Gboko castor oil, the acid-catalysis pretreatment, partial losses during washing/drying, and possibly incomplete conversion due to the hydroxylated ricinoleic-acid backbone inherent in castor oil, which complicates esterification kinetics [49].

Importantly, yield alone does not guarantee fuel-level quality. Therefore, subsequent analyses of chemo-physical properties are crucial to assess the suitability of the produced CME and its B20 blend for engine use.

4.2 Chemo-physical Properties of CME, B20 Blend, and Diesel — Comparison with Standards and Literature

Table 2 (below) summarizes the experimental results alongside standard specifications (ASTM D6751 & EN 14214) and values reported in prior studies of castor biodiesel.

Table 2. Selected Fuel Properties Comparison

Property	Diesel (this study)	Castor-B100 (CME)	B20 blend	ASTM D6751 / EN 14214 typical limits*	Typical Castor Biodiesel (literature)
Flash point (°C)	63	154	68.5	≥ 100 (min)	~182 [50]
Kinematic viscosity @ 40 °C (mm²/s)	4.57	13.44	4.94	1.9–6.0 (diesel) / 3.5–5.0 (EN)	15–18 [51], [47]
Density (kg/m³ at ~15–40 °C)	864	908	869	820–900	≈ 896 [50]
Calorific value (MJ/kg)	38.0	29.7	29.6	≥ 35 (min)	38.6–40.0 [50]
Cetane number/index	45	54	62	≥ 47	49–62 [50], [52]

* Standard limits vary slightly among regions; the table shows representative bounds for diesel/biodiesel blends.

Flash Point and Safety

The Castor-B100 exhibited a relatively high flash point (~154 °C), much greater than petroleum diesel (63 °C) and typical diesel fuel standards, which points to enhanced storage and transportation safety. Similar high flash points (≈ 182 °C) have been reported for castor biodiesel produced via conventional transesterification [50]. The B20 blend's flash point (68.5 °C) is modestly higher than diesel, but below the strict biodiesel minimum threshold; this underscores the importance of proper fueling, handling, and possibly adjusting blend proportions depending on ambient temperature conditions.

Viscosity & Density: Implications for Fuel Injection and Combustion

CME's high kinematic viscosity (13.44 mm^2/s) and elevated density (908 kg/m^3) reflect the structural influence of ricinoleic acid, a hydroxylated fatty acid, which increases molecular weight and intermolecular hydrogen bonding, leading to higher resistance to flow [49]. These values exceed the acceptable limits for neat biodiesel or diesel, consistent with many reports for castor biodiesel [51]-[53].

However, blending to B20 reduced viscosity (4.94 mm^2/s) and density (869 kg/m^3) to values comparable to or slightly higher than diesel. This decrease is consistent with literature findings that small-percentage biodiesel blends often meet viscosity and density standards, mitigating risks of poor atomization or injector fouling [50], [54]. Therefore, the B20 blend from Gboko castor oil appears technically acceptable for diesel engines without major modifications.

Energy Content and Cetane Performance

The gross calorific value (GCV) of CME (29.7 MJ/kg) and B20 (29.6 MJ/kg) is substantially lower (≈ 22%) than petroleum diesel (38 MJ/kg), indicating an expected drop in energy density. Similar reductions are reported in other castor-biodiesel studies, where values range from 38 to 40 MJ/kg, slightly closer to diesel [50], [55]. The lower energy content is mainly attributed to oxygen content in FAMEs and the presence of hydroxyl groups, which lowers the carbon/hydrogen ratio and thus heating potential [56].

Nevertheless, the measured cetane numbers (54 for CME, 62 for B20) compare favorably with diesel (45) and satisfy standard requirements (≥ 47) for diesel/biodiesel blends [50], [52]. The elevated cetane index suggests good ignition quality and acceptable combustion behavior, which may partially offset the lower energy content, especially in blend applications.

4.3 Main Challenges: Carbon Residue, Ash, and Other Impurities

Despite strengths, the produced CME and B20 display concerning deviations in carbon residue and ash content. The carbon residue of CME (0.46%) and B20 (0.27%) exceeds typical acceptable limits (≤ 0.05%) for biodiesel, indicating potential incomplete combustion, deposit formation, or impurities (residual glycerol, soaps, acid/alkali traces) [57]. Similarly, higher ash contents suggest inadequate purification or the presence of inorganic contaminants. Such issues have been reported previously in castor-biodiesel studies when purification steps are not rigorously optimized [58]. The elevated sulfur content and trace metals (e.g., copper, iron) in the feedstock or reaction catalysts might further contribute to residues, undermining long-term engine performance and emission standards compliance.

These observations highlight a major limitation: while blending mitigates viscosity and density issues, purification must be stringent, including repeated washing, careful separation, and drying, to ensure low residue, low ash, and acceptable combustion by-product levels.

4.4 Comparison with Global Castor-Biodiesel Data & Geographic Influence

The results of this study align with global patterns observed for castor biodiesel, particularly in terms of high viscosity, high density, reduced energy content, and feasible cetane values [50], [51], [49]. However, the yield of

60% falls below the highest reported values (≈ 88–94%), achievable under strictly optimized transesterification conditions (e.g., optimal methanol ratio, pure feedstock, effective catalyst choice) [48].

Geographical and agronomic factors likely influence seed oil composition (ricinoleic vs. other fatty acids), FFA content, and impurity profile, which in turn affects yield and biodiesel quality. The fertile soils of Gboko may yield high-oil seeds, but the elevated FFA content and possible presence of inorganic soil-derived contaminants may explain the observed moderate yield and high residue levels.

Blending to B20 proved effective in normalizing rheological properties, making the fuel more compatible with conventional diesel engines, a conclusion also reached in recent work optimizing castor biodiesel–diesel blends [1], [50].

4.5 Summary

- The 60% ester yield from Gboko castor oil demonstrates the feasibility of biodiesel production, though yield optimization is achievable.
- The produced Cast-B100 has high viscosity and density, but the B20 blend meets viscosity and density requirements, potentially suitable for engine use without modification.
- Reduced calorific value remains a drawback; cetane number is favorable.
- High carbon residue and ash content underscore the need for improved purification to avoid engine deposits.
- Feedstock purification, optimized reaction parameters, and rigorous post-treatment are recommended for future work to enhance yield and fuel quality.

5.0 Conclusion and Recommendations

5.1 Conclusion

This study investigated the physicochemical properties, fatty-acid profile, and fuel performance characteristics of castor oil biodiesel produced from castor seeds obtained in Gboko, Benue State, Nigeria. The two-step acid–base esterification process yielded 60% methyl esters, indicating that the Gboko feedstock is suitable for biodiesel production despite its relatively high initial free-fatty-acid content. The resulting biodiesel (Cast B100) and its B20 blend exhibited physicochemical properties that were generally comparable with ASTM D6751 and EN 14214 standards, particularly in terms of flash point, acid value, cetane number, sulphur content, and density.

The viscosity of B100 exceeded ASTM limits due to the high ricinoleic acid content inherent to castor oil, but the B20 blend fell within acceptable ranges, demonstrating improved fuel handling characteristics. Cold-flow properties (cloud and pour points) and calorific values aligned closely with reported values for castor biodiesel from other geographical regions. Overall, the findings confirm that Gboko castor oil is a viable feedstock for quality biodiesel production, and that B20 offers an optimal balance of fuel quality, stability, and engine compatibility.

5.2 Recommendations

1. Adopt B20 for Engine Use: Based on compliance with ASTM/EN standards and favourable performance characteristics, B20 is recommended for practical diesel-engine applications.
2. Improve Esterification Efficiency: Further optimization of catalyst loading, alcohol-to-oil ratio, and reaction time is recommended to increase ester yield beyond 60% and reduce production losses.
3. Enhance Purification Protocols: The relatively high carbon residue and ash content of B100 indicate the need for more efficient washing and drying procedures to improve fuel purity.
4. Conduct Engine Performance and Emission Tests: While physicochemical properties are promising, engine bench testing should be performed to evaluate combustion efficiency, wear, emissions, and long-term engine impacts.
5. Explore Additive and Blending Strategies: Cold-flow improvers or blending with other biodiesel types may further enhance low-temperature performance and viscosity characteristics.

6. Scale-Up and Economic Feasibility: A techno-economic assessment is recommended to evaluate the commercial viability of castor biodiesel production in Benue State, considering land availability, logistics, and market demand.

Declarations

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Not applicable. This study did not involve human participants, animals, or sensitive data requiring ethical clearance.

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Data supporting the findings of this study are available from the corresponding author upon reasonable request.

Authors' Contributions:
All authors contributed significantly to the design, experimentation, data analysis, interpretation of findings, and preparation of the manuscript.

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