PRODUCTION AND OPTIMIZATION OF BIODIESEL FROM CASTOR OIL VIA ALKALI-CATALYSED TRANSESTERIFICATION

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Abstract
Growing environmental concerns and the depletion of fossil fuel reserves have intensified the need for sustainable alternatives to petroleum diesel, with biodiesel gaining prominence due to its renewability, biodegradability, and reduced emissions; however, reliance on edible oils raises economic and food security issues, necessitating exploration of non-edible feedstocks such as castor oil. This study aimed to produce and optimize biodiesel from castor oil via alkali-catalyzed transesterification, assessing its suitability and determining optimal reaction conditions for maximum yield and quality. The extracted oil was first characterized to establish its physicochemical properties and compatibility with base catalysis, after which transesterification was conducted using methanol and potassium hydroxide, while systematically varying temperature, catalyst concentration, and methanol-to-oil ratio. The biodiesel produced was purified and evaluated for key fuel properties, including density, viscosity, flash point, cloud point, pour point, and boiling point. Optimal conditions of 75 °C, 2.0 wt% catalyst, and 3:1 methanol-to-oil ratio yielded about 92% biodiesel with properties within standard limits, indicating efficient combustion, improved lubricity, and safe handling, thus, the study demonstrates the novelty and effectiveness of an integrated optimization compounding approach, recommending further scale-up, engine testing, emission analysis, and storage stability studies for industrial application.

Keywords
Trans-esterification, Biodiesel, Castor oil, Vegetable oils, Catalyst, Physicochemical properties

1. INTRODUCTION

The rapid increase in global energy demand due to industrialization, urbanization, and population growth has intensified the consumption of fossil fuels worldwide. Petroleum-based fuels remain the dominant energy source for transportation and industrial processes, accounting for a significant portion of global energy consumption. However, the continued dependence on fossil fuels presents several environmental and economic challenges, including greenhouse gas emissions, climate change, and depletion of non-renewable resources. According to recent global energy reports, fossil fuels currently account for more than 80 % of the world's energy supply, highlighting the urgent need for sustainable alternatives [1].

The combustion of petroleum fuels releases harmful pollutants such as carbon monoxide (CO), nitrogen oxides (NO_2), sulphur oxides (SO_2), and particulate matter, which contribute to atmospheric pollution and adverse health effects. These emissions have been associated with respiratory diseases, environmental degradation, and global warming [2]. Consequently, considerable research efforts have been directed toward developing renewable and environmentally friendly energy sources capable of reducing dependence on fossil fuels.

Biodiesel has gained considerable attention as a viable renewable alternative to conventional diesel fuel. It consists of fatty acid methyl esters (FAME) obtained from vegetable oils or animal fats through transesterification. Compared with petroleum-based diesel, biodiesel is environmentally friendly, as it is biodegradable, less toxic, and produces lower emissions of particulate matter and sulphur compounds. In addition, its superior lubricating properties and compatibility with existing compression ignition engines without the need for major modifications enhance its practicality as a sustainable energy option [3].

The viability of biodiesel production is strongly influenced by the type of feedstock utilized. Traditionally, edible oils such as soybean, sunflower, and palm oil have been widely used. However, their large-scale application has raised concerns due to competition with food resources and the associated increase in food costs. This has led to growing interest in alternative feedstocks that do not compromise food security [4].

Consequently, non-edible oil crops have become a focus of research in biodiesel development. Oils obtained from sources such as jatropha, neem, rubber seed, and castor have shown significant potential, particularly because these crops can thrive on marginal lands and still yield substantial oil content. Among these, castor oil derived from *Ricinus communis* stands out due to its high oil yield, resilience to drought, and ability to adapt to varying environmental conditions [5]. Its composition, which is rich in ricinoleic acid, imparts distinctive chemical characteristics, including relatively high viscosity, making it an interesting candidate for biodiesel production.

Recent research outcomes have shown that biodiesel obtained from castor oil possesses suitable fuel properties and can be successfully utilized in diesel engines when blended with petroleum diesel. Research conducted by Patel and Sankhavara [6] reported that optimized transesterification conditions significantly improved biodiesel yield and fuel quality. Similarly, Silitonga et al. [7] highlighted that biodiesel produced from non-edible oils exhibits good lubrication properties and reduced exhaust emissions compared with petroleum diesel.

Despite the growing body of research on biodiesel production, several challenges remain regarding process optimization, feedstock utilization, and fuel property evaluation. In particular, limited studies have investigated the optimization of biodiesel production from castor oil using locally available materials under developing-country conditions while simultaneously evaluating the resulting fuel properties relative to international biodiesel standards. Addressing these gaps is essential for promoting sustainable biodiesel development and enhancing renewable energy utilization.

Therefore, this study aims to investigate the production and optimization of biodiesel from castor oil through alkali-catalyzed transesterification and to evaluate the physicochemical properties of the produced biodiesel in comparison with established biodiesel fuel standards.

2. MATERIALS AND METHOD

Castor oil used in this study was obtained from locally sourced castor seeds, while methanol and potassium hydroxide catalyst were procured from a standard chemical supplier. The experimental work was carried out in the mechanical engineering laboratory using standard laboratory equipment including a magnetic stirrer, water bath, viscometer, thermometer, separating funnel, hydrometer, and density bottle.

Before initiating biodiesel synthesis, the extracted castor oil was assessed to establish its suitability for transesterification. Key physicochemical parameters including free fatty acid (FFA) content, acid value, iodine value, saponification value, density, and pH were determined using established standard procedures. These properties provide essential insight into oil quality and help in selecting appropriate processing conditions for efficient biodiesel production.

The acid value and FFA content were evaluated through a titration method. A 2 g portion of the oil sample was introduced into a beaker and combined with 50 ml of a neutral solvent mixture of petroleum ether and ethanol. The solution was agitated for about 30 minutes to ensure proper mixing. Afterward, a few drops of phenolphthalein indicator were added, and the mixture was titrated against 0.1 M potassium hydroxide (KOH) until a stable pink coloration was observed, indicating the endpoint.

For the determination of saponification value, the procedure outlined in ISO 3657 was followed. A measured 2 g sample of the oil was placed in a conical flask, and 25 ml of freshly prepared alcoholic KOH was added. The mixture was heated in a water bath for 30 minutes with occasional agitation. After cooling, phenolphthalein indicator was introduced, and the solution was titrated with 0.5 M hydrochloric acid (HCl) until the endpoint was reached.

The density (specific gravity) of the oil was determined using the hydrometer approach in line with ASTM D1298. A clean 50 ml density bottle was first weighed empty, then filled with distilled water and later with the oil sample. The recorded masses were used to compute the specific gravity of the oil.

The **iodine value** was determined following ISO 3961 (1989). The oil sample was dissolved in carbon tetrachloride, treated with Dam's reagent, and allowed to react in the dark. Potassium iodide and distilled water were added before titration with sodium thiosulphate using starch indicator.

Finally, the **pH value** of the oil sample was measured using a calibrated pH meter after mixing the oil with hot distilled water and cooling to room temperature.

Biodiesel was synthesized via an alkaline transesterification route in which methanol reacted with the triglycerides in castor oil to yield fatty acid methyl esters and glycerol as a secondary product. The catalyst solution was first prepared by dissolving potassium hydroxide in methanol to generate potassium methoxide. The castor oil, preheated to reduce viscosity, was then introduced into this mixture, and the reaction was maintained at a controlled temperature using a heated magnetic stirrer to ensure proper mixing and heat distribution.

To evaluate process performance, the reaction temperature was systematically adjusted within the range of 55–75 °C. In addition, variations in catalyst loading and methanol-to-oil molar ratio were investigated to identify conditions that maximize biodiesel yield. Upon completion, the reaction mixture was poured into a separating funnel and left undisturbed for several hours, allowing clear stratification into biodiesel (upper phase) and glycerol (lower phase).

The biodiesel layer was carefully decanted and purified through repeated washing with warm distilled water to eliminate residual catalyst, glycerol, and other contaminants. It was subsequently dried at an elevated temperature to remove any remaining moisture.

Finally, the purified biodiesel was characterized by determining its key physicochemical properties, including density, viscosity, and flash point, cloud point, pour point, and boiling point. These parameters were measured using standard ASTM methods and compared with international biodiesel fuel specifications.

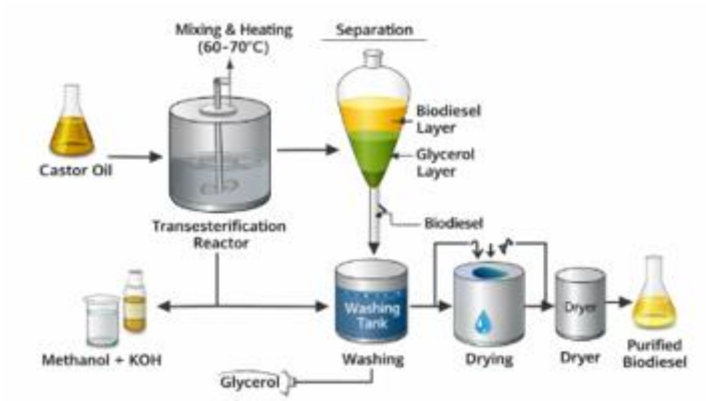

Figure 1: Schematic diagram of biodiesel production process [18]

3. RESULTS AND DISCUSSION

The characterization of castor oil revealed that the oil possessed suitable physicochemical properties for biodiesel production. The free fatty acid content was within acceptable limits for alkali-catalyzed transesterification, indicating that the oil could be directly processed without the need for acid pre-treatment.

The experimental results demonstrated that reaction temperature significantly influenced biodiesel yield. Increasing the reaction temperature enhanced the rate of transesterification due to improved mass transfer and reaction kinetics. However, temperatures above 70 °C did not produce significant improvements in yield due to increased methanol evaporation. The maximum biodiesel output of approximately 92 % was obtained at a reaction temperature of 70 °C.

Figure 2 shows the effect of reaction temperature on biodiesel production during alkali-catalyzed transesterification of castor oil. The output increases with temperature up to an optimum near 70 °C due to improved reaction kinetics.

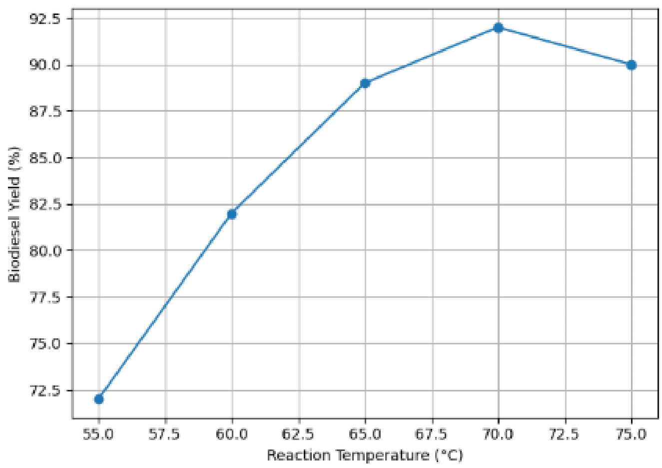

Figure 2: Graph of Reaction Temperature on Biodiesel Yield

Catalyst concentration also played a critical role in biodiesel production. Increasing potassium hydroxide concentration improved biodiesel yield up to an optimal value of 1.5 wt %. Beyond this concentration, excessive catalyst resulted in soap formation, which negatively affected biodiesel separation and reduced yield [22].

Figure 3 shows the effect of catalyst concentration on biodiesel yield. Maximum yield is observed at approximately 1.5 wt % catalyst concentration, beyond which soap formation reduces yield.

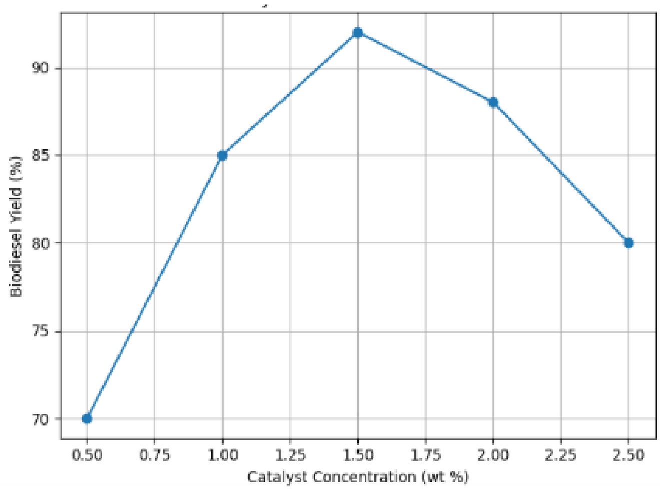

Figure 3: Graph of Concentration of catalyst on the Biodiesel Yield

The ratio of the methanol-to-oil was another important factor affecting biodiesel production. A methanol-to-oil ratio of 3:1 was found to provide optimal conversion of triglycerides to methyl esters. Higher methanol ratios did not significantly improve biodiesel yield and resulted in increased processing costs.
Figure 4 shows the comparison of selected fuel properties of castor biodiesel, petroleum diesel, and ASTM biodiesel limits.

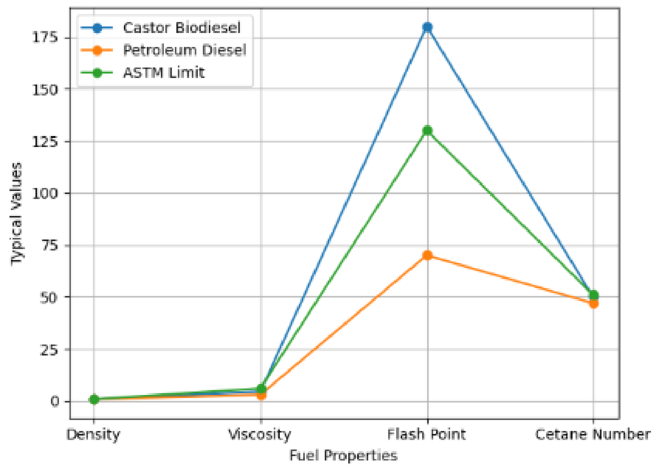

Figure 4: Comparison of Fuel Properties (Castor Biodiesel vs Diesel vs ASTM)

Results of compounding oils
The following are the results obtained on characterization of the oils and biodiesel produced from the non-edible oils, these are presented in table 1-4.

Table 1: Results of Biodiesel composition and compounds

S/No:	Catalyst (%wt)	Solvent VS Oil (ml)	Vol. of Oil (ml)	Temp. (^{O}C)	Time (hrs)	Vol. of Biodiesel (%wt)	Glycerol
1.	0.5	19.5	50.0	55.0	1.0	42.0	0.09
2.	1.0	20.5	50.0	60.0	1.0	60.0	0.02
3.	0.75	25.0	50.0	65.0	1.0	41.5	0.06
4.	1.50	30.5	50.0	70.0	1.0	47.0	0.07
5.	2.0	40.5	50.0	75.0	1.0	92.0	0.01

Different mixing ratios of biofuel were used from the fifth trial. The produced biodiesel was evaluated as a fuel according to its thermo physical and chemical parameters such as Relative Density, Flash Point, FFA, Peroxide Value, Accid Value, PH Value, Viscosity, Iodine Value, Saponification, Cloud Point, Pour Point, Boiling Point as presented in table 5.

Table 2: Properties of different compounding

Diff. Biodiesel / Properties	B1	B2	B3	B4	B5
Flash point	88.0	88.0	88.0	88.0	88.0
Boiling Point	68.0	68.0	68.0	68.0	68.0
Pour Point	-5.0	-5.0	-5.0	-5.0	-5.0
Cloud Point	-7.5	-7.5	-7.5	-7.5	-7.5
Viscosity (mm^2/s)	7.10 @ 20°	6.50 @20°	6.20 @ 20°	6.70 @20°	7.10 @20°

Figure 5: Compounded Samples of Biodiesel

The flash and boiling point results indicate that the produced biodiesel ignites and burns more readily than conventional diesel. Its higher viscosity suggests improved lubrication, potentially extending engine lifespan compared to petroleum diesel. These findings confirm enhanced fuel efficiency. The reaction process yielded negligible glycerol, with the fifth compounding producing the least amount, making it the optimal formulation. Comparative analysis of pure oil, biodiesel, blends, and petroleum diesel (Table 4) shows variations in thermophysical properties. Notably, pure castor oil exhibits the highest density, flash point, and boiling point (Table 6).

Table 3: Comparison of Produced Biodiesel and Conventional Diesel

Properties	Castor Oil	Petrol Diesel	Biodiesel
Density (Kg/m^3)	951.4	808.115	0.983
Flash Point	292	93	88
FFA	11.22	----	----
Acid Value	1.122	----	----
PH Value	7.2	----	6.1
Viscosity (mm^2/s)	7.8 at 20°	7.6 at 20°	7.1 at 20°
Iodine Value	3.1725	----	----
Saponification	133.2375	----	----
Cloud Point (°C)	----	----	-7.5
Pour Point (°C)	----	27	4.1
Ash Content	----	----	0.05
Specific Gravity	0.9635	----	1.006

The physicochemical properties of the produced biodiesel were evaluated against ASTM standards. The density (~0.98 g/cm³) and viscosity (~7.1 mm²/s @ 20°) fall within the ASTM D6751 acceptable range, confirming its suitability as a fuel. The biodiesel exhibited a lower flash point than petroleum diesel, indicating enhanced safety in storage and handling. Its cloud and pour points also demonstrate acceptable cold-flow behavior under moderate climatic conditions [23]. Overall, the results align with previous studies, showing that biodiesel from non-edible oils can achieve properties comparable to conventional diesel while providing environmental advantages [19].

4. CONCLUSION

This study successfully achieved the objective of producing and optimizing biodiesel from castor oil through alkali-catalyzed transesterification. The characterization results confirmed that castor oil possesses suitable physicochemical properties, with acceptable free fatty acid levels for direct processing. Optimization of the transesterification process demonstrated that biodiesel yield is strongly affected by reaction temperature, catalyst loading, and methanol-to-oil ratio. The most favorable conditions were established at 75 °C, 2.0 wt% KOH, and a 3:1 molar ratio, producing a yield of approximately 92%. The biodiesel obtained under these conditions showed acceptable fuel qualities, including density, viscosity, flash point, and cold-flow behaviour, all within ASTM specifications. These characteristics suggest that the fuel is suitable for use as an alternative to conventional diesel, with added advantages in safety and lubrication.

A key contribution of this study is the combined use of process optimization and blending analysis, which helped reduce glycerol formation and highlighted the fifth blend as the most effective formulation. The selection of castor oil, a non-edible resource, also provides a practical solution to the food-versus-fuel challenge while supporting sustainable energy initiatives, particularly in developing regions such as Nigeria.

Overall, the results demonstrate the potential of castor oil as a reliable feedstock for biodiesel production, contributing to cleaner energy development and environmental protection. Future work should extend to engine performance testing, emission profiling, storage stability assessment, and scale-up studies. In addition, the use of heterogeneous catalysts should be explored to enhance process efficiency and environmental compatibility.

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