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Synthesis of Biodiesel from Ricinus communis Oil Using Acid and Base Catalysts: Experimental Insights

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Abstract

The escalating global demand for petroleum products has led to a consistent rise in the prices of conventional fuels such as petrol and diesel. With fossil fuel reserves depleting at an accelerated pace, it is anticipated that by 2025, the world may encounter a critical shortage of petroleum-based energy sources. Consequently, there is an urgent need to explore and develop sustainable alternatives to fossil fuels. Among the various renewable energy options, biodiesel has emerged as a viable and environmentally benign substitute. Biodiesel is defined as the mono-alkyl esters of long-chain fatty acids derived from vegetable oils or animal fats. It is characterized by favorable attributes such as biodegradability, non-toxicity, and negligible sulfur and aromatic content, making it a cleaner-burning fuel.

In the present study, a detailed experimental investigation was conducted to synthesize methyl esters from non-edible feedstocks, specifically castor oil, utilizing acid (H_2SO_4) and base (NaOH) catalysts. The influence of key process parameters such as reaction temperature and residence time on the biodiesel yield and physicochemical properties (including viscosity, specific gravity, and acid value) was systematically evaluated. The comparative analysis of acid- and base-catalyzed transesterification processes revealed significant differences in performance and product characteristics, thereby contributing valuable insights into catalyst selection and process optimization for biodiesel production.

Keywords: *Biodiesel; Methyl Esters; Transesterification; Castor Oil; Acid Catalyst; Base Catalyst; Physicochemical Properties.*

INTRODUCTION

Energy has always been a fundamental requirement for human civilization, serving as the cornerstone for industrialization, transportation, agriculture, and domestic activities. While various renewable energy sources such as solar, wind, and hydropower are available, fossil fuels namely petrol, diesel, and kerosene remain the predominant global energy source. These fuels are extensively consumed across multiple sectors, including industrial, automotive, agricultural, and residential domains. According to Rafaat et al. (2008), the global consumption of fossil fuels exceeds 10 million tons per day, a figure that continues to rise with economic and population growth.

Amid rising fuel prices and the impending depletion of fossil fuel reserves, there is a growing emphasis on identifying and developing sustainable alternatives. Among the renewable energy options, biodiesel a fuel derived from vegetable oils or animal fats has gained prominence as an environmentally friendly substitute for conventional diesel. The feasibility of biodiesel production from non-edible oil sources offers economic and environmental advantages, as these resources are renewable and do not compete with food supply chains. Biodiesel is chemically defined as a mono-alkyl ester of long-chain fatty acids (Knothe, 2005), and its renewable nature makes it a compelling alternative to finite petroleum resources. Several non-edible feedstocks such as Jatropha, cottonseed, and Karanja oil have been explored for biodiesel production. Among these, castor oil (Ricinus communis L.) stands out due to its high seed yield, ability to grow on marginal lands, and tolerance to semi-arid climates. Castor oil contains a high proportion of ricinoleic acid, making it chemically distinct and functionally suitable for biodiesel production. However, limited research is available on the fuel-related properties of pure castor methyl esters (B100) or their blends with petro-diesel (e.g., B10).

Biodiesel is typically produced via transesterification, a chemical process in which triglycerides react with alcohol (commonly methanol), in the presence of a catalyst, to yield esters and glycerol as a byproduct. In the present study, the technical viability of biodiesel derived from castor oil was assessed. Key fuel properties were compared against the ASTM D6751 standards for both B100 and B10 blends. The distillation temperature (397 °C) and kinematic viscosity (15.11 mm^2/s) of B100 exceeded the permissible limits, whereas the B10 blend complied with all specifications.

While edible oils such as soybean and corn oil are commonly used for biodiesel synthesis, their rising costs and competition with food applications make them economically unsustainable. In contrast, castor oil offers an affordable and readily available alternative. It comprises approximately 80–90% ricinoleic acid, with smaller fractions of linoleic, oleic, and saturated fatty acids (Pazir & Muhammad, 1991), making it chemically suitable for biodiesel applications.

The choice of catalyst significantly influences biodiesel production efficiency. Although homogeneous catalysts such as NaOH and KOH are widely used, they often result in soap formation and require complex post-processing steps, including neutralization and washing, thereby generating wastewater. In recent years, the use of heterogeneous solid catalysts has gained traction due to their recyclability, ease of separation, and minimal environmental impact. These solid catalysts can be regenerated and reused without contributing to effluent generation.

This study focuses on the optimization of castor oil-based biodiesel production by evaluating the influence of catalyst type and concentration on biodiesel yield and physicochemical properties, aiming to contribute to sustainable fuel alternatives in line with global energy demands.

MATERIALS AND METHODS:

Biodiesel production from oils and fats can generally be accomplished through three principal routes:

a) Base-catalyzed transesterification of the oil,
b) Direct acid-catalyzed transesterification, and
c) Conversion of oil to free fatty acids (FFAs) followed by esterification.

Among these, the base-catalyzed transesterification process is the most widely adopted due to its operational advantages, including low reaction temperature and pressure, high yield (up to 98%), minimal side reactions, and shorter reaction times (Anonymous, 2007). This process has proven to be cost-effective and scalable for commercial biodiesel production.

Extensive literature surveys indicate that various alcohols such as methanol, ethanol, propanol, butanol, and amyl alcohol—have been investigated as reactants in transesterification reactions. Of these, methanol and ethanol are the most commonly used. While ethanol is considered more environmentally friendly and renewable, particularly when derived from agricultural biomass, methanol remains the preferred choice in most processes due to its lower cost, strong polarity, and short-chain molecular structure, which enhances its reactivity and reduces reaction time. The superior physicochemical properties of methanol result in faster conversion kinetics during the transesterification process.

The primary feedstock selected for this study is castor oil, extracted from the seeds of Ricinus communis L., a significant non-edible oilseed crop cultivated predominantly in arid and semi-arid regions. Castor is recognized globally for its high oil content, resilience to harsh climatic conditions, and wide industrial applicability. India is currently the largest global producer of castor seed, contributing over 60% of the world's total production, with an annual output of approximately 800,000 to 850,000 tons. Domestically, the estimated consumption of castor oil and its derivatives exceeds 300,000 tons, reflecting its substantial demand in sectors ranging from lubricants to cosmetics and pharmaceuticals.

In this study, castor oil was selected as the biodiesel feedstock due to its abundance, cost-effectiveness, and chemical composition. The transesterification reaction was carried out using both acid (H_2SO_4) and base (NaOH) catalysts under controlled conditions. The focus was to optimize key process parameters and evaluate the impact of catalyst type on the yield and physicochemical properties of the resulting biodiesel.

Experimental Setup:

The transesterification reaction was carried out in a three-neck round-bottom batch reactor, designed to facilitate continuous monitoring and control of reaction parameters. The central neck of the reactor was fitted with a mechanical stirrer to ensure uniform mixing of the reactants. One of the side necks was equipped with a mercury thermometer for real-time temperature monitoring, while the third neck was connected to a reflux condenser to prevent the loss of methanol during the reaction process (refer to Figure 1 for schematic representation).

To maintain the desired reaction temperature consistently throughout the experiment, the entire reactor assembly was immersed in a constant-temperature water bath. This setup allowed for precise thermal regulation, which is essential for ensuring reproducibility and accuracy of the experimental outcomes.

In this study, sulfuric acid (H_2SO_4) and sodium hydroxide (NaOH) were employed as acid and base catalysts, respectively. A series of experimental runs were conducted by systematically varying key process parameters, including residence time, oil-to-methanol molar ratio, and reaction temperature, in order to optimize biodiesel yield and quality under different catalytic conditions.

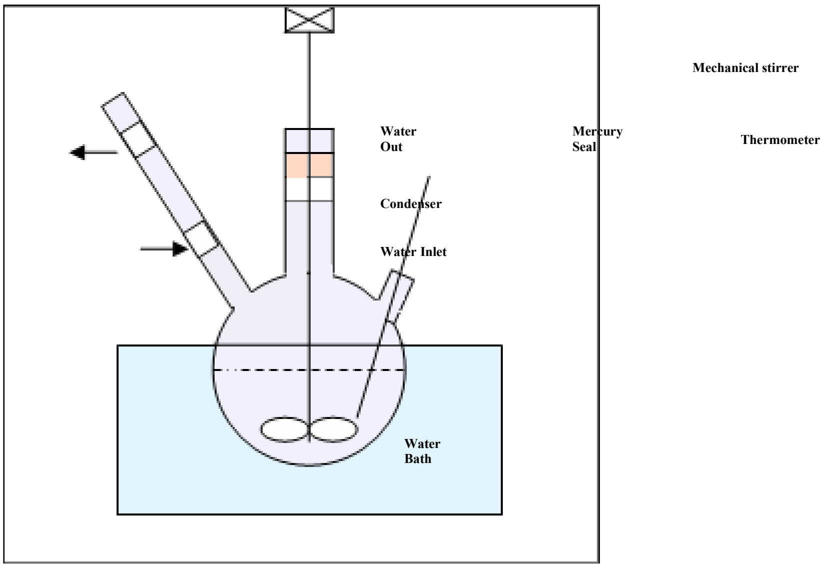

Figure: 1: Experimental setup - Biodiesel Synthesis.

Effect of residence time:

To investigate the influence of residence time on the physicochemical properties of biodiesel, a series of experimental runs were conducted using both acid (H_2SO_4) and base (NaOH) catalysts in a batch reactor. The residence time was varied from 30 minutes to 90 minutes, specifically at intervals of 30, 45, 60, and 90 minutes, as detailed in Table 1.

The results indicated that at the lowest residence time of 30 minutes, the viscosity of the produced biodiesel was relatively high for both catalysts. For sulfuric acid, the viscosity decreased significantly from 16.56 cSt at 30 minutes to 11.28 cSt at 45 minutes. However, with further increases in residence time to 60 and 90 minutes, the viscosity began to rise again, reaching 13.93 cSt at 90 minutes. A similar trend was observed when using sodium hydroxide as the catalyst, where the minimum viscosity of 13.10 cSt was achieved at 45 minutes.

These results suggest that 45 minutes of residence time yields the optimal viscosity for biodiesel under the given experimental conditions. Reactions using sulfuric acid were performed at 55°C with a 3 vol% catalyst concentration, whereas those with sodium hydroxide were conducted at 30°C using 1 wt% catalyst concentration.

The trend in specific gravity with residence time mirrored that of viscosity. For sulfuric acid, the specific gravity decreased from 0.9108 at 30 minutes to 0.9009 at 45 minutes, followed by an increase to 0.9052 at 90 minutes. Likewise, for sodium hydroxide, the specific gravity dropped from 0.9106 to 0.8892 as residence time increased to 45 minutes, then rose again to 0.9039 at 90 minutes.

A similar observation was made in the case of the acid value, which also reached its lowest point at 45 minutes for both catalysts. This further supports the conclusion that 45 minutes is the optimum residence time for achieving desirable biodiesel properties under the studied conditions.

Table-1 Effect of residence time on parameters such as viscosity, specific gravity and acid value

Time of experimental run(min.)	30	45	60	90
Kinematic Viscosity (cSt) for Sulphuric acid as a Catalyst	15.50	11.10	11.44	13.55
Kinematic Viscosity (cSt) for Sodium hydroxide as a	20.88	12.80	13.90	18.00

Catalyst				
Specific gravity for Sulphuric acid as a Catalyst	0.9018	0.9001	0.9040	0.9022
Specific gravity for Sodium hydroxide as a Catalyst	0.911	0.890	0.9050	0.9048
Acid value for Sulphuric acid as a Catalyst	0.89	0.56	0.57	0.56
Acid value for Sodium hydroxide as a Catalyst	0.94	0.35	0.44	0.55

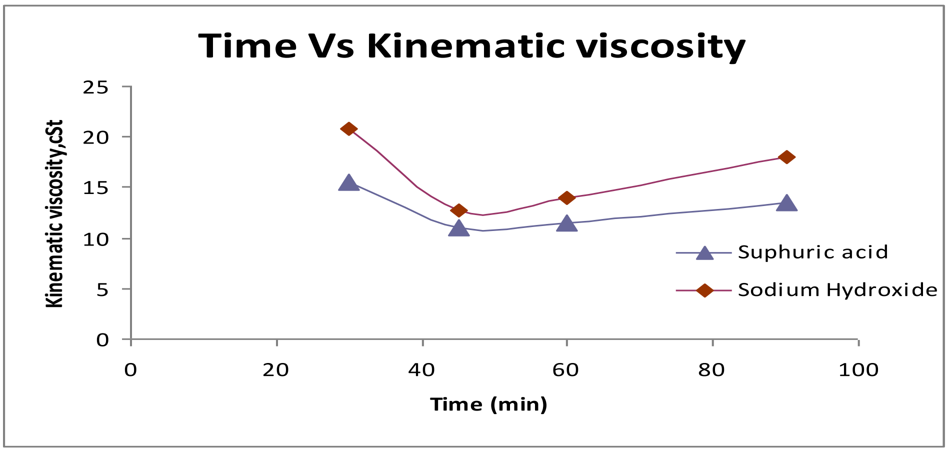

Figure-2: Variation of Kinematic Viscosity Vs Time

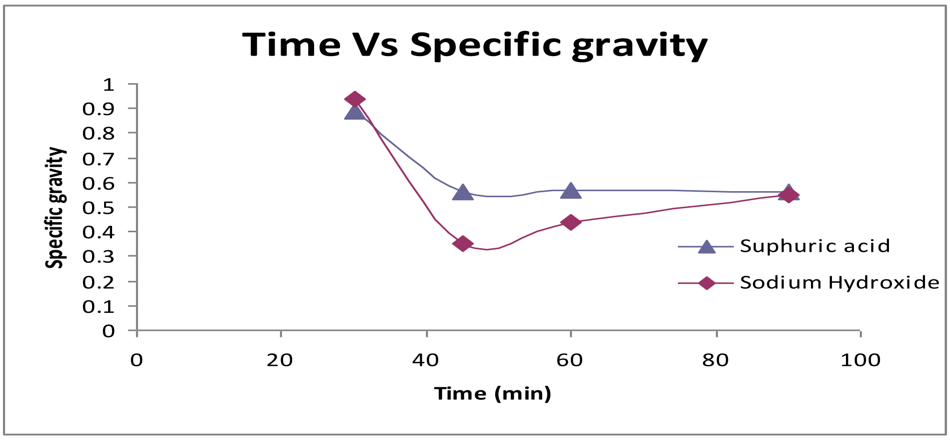

Figure-3: Variation of Specific gravity vs Time

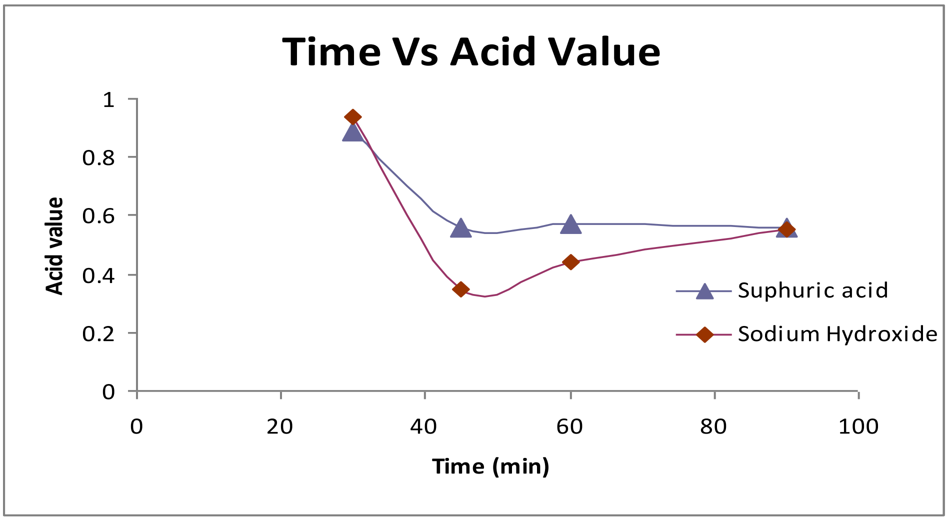

Figure:4: Variation of Acid value vs Time

Effect of Oil-to-Methanol Molar Ratio:

The oil-to-methanol molar ratio plays a crucial role in determining the efficiency of the transesterification reaction and the quality of the resulting biodiesel. In this study, various molar ratios ranging from 1:6 to 1:15 were investigated for both sulfuric acid (acid catalyst) and sodium hydroxide (base catalyst) to evaluate their impact on viscosity and specific gravity.

For the sulfuric acid catalyst, an increase in the oil-to-methanol molar ratio from 1:6 to 1:15 resulted in a significant reduction in biodiesel viscosity, decreasing from 19.96 cSt at 1:6 to 6.63 cSt at 1:15. Similarly, in the case of the sodium hydroxide catalyst, increasing the molar ratio from 1:6 to 1:9 led to a decrease in viscosity from 15.68 cSt to 13.10 cSt. However, at a further increased ratio of 1:12, the formation of two distinct layers was not observed, indicating that phase separation did not occur. This suggests that no effective transesterification reaction took place at excessively high methanol concentrations for either catalyst.

The specific gravity of the biodiesel also showed a clear dependence on the oil-to-methanol molar ratio. For the sulfuric acid system, the specific gravity decreased from 0.9023 to 0.9006 as the molar ratio increased from 1:6 to 1:12, then slightly increased to 0.9015 at 1:15. A similar trend was observed for sodium hydroxide, where the lowest specific gravity of 0.8892 was recorded at a 1:9 molar ratio, indicating optimal conversion.

From the above findings, it can be concluded that the optimum oil-to-methanol molar ratio is 1:9 for the sodium hydroxide catalyst and 1:10 for the sulfuric acid catalyst, under the given experimental conditions. Additionally, these results reaffirm that the residence time of 45 minutes is optimal when combined with the respective molar ratios for maximizing biodiesel yield and quality

Table-2: Effect of Oil-to-Methanol Molar Ratio on Viscosity, Specific Gravity, Acid Value, and Saponification Value of Biodiesel.

Oil to alcohol mole ratio	1:06	1:09	1:10	1:12	1:15
Kinematic viscosity, (Cst) for sulphuric acid as catalyst	19.96	11.28	10.56	9.7	6.63
Kinematic viscosity, (Cst) for sodium hydroxide as catalyst	21.57	13.1	15.51	16.56	Nil
Specific gravity for sulphuric acid as catalyst	0.9023	0.9006	0.9006	0.9009	0.9015
Specific gravity for sodium hydroxide as catalyst	0.9145	0.8892	0.9047	0.9092	Nil
Acid value for sulphuric acid as catalyst	0.61	0.58	0.56	0.52	0.49
Acid value for sodium hydroxide as catalyst	0.576	0.37	0.426	0.48	0.48

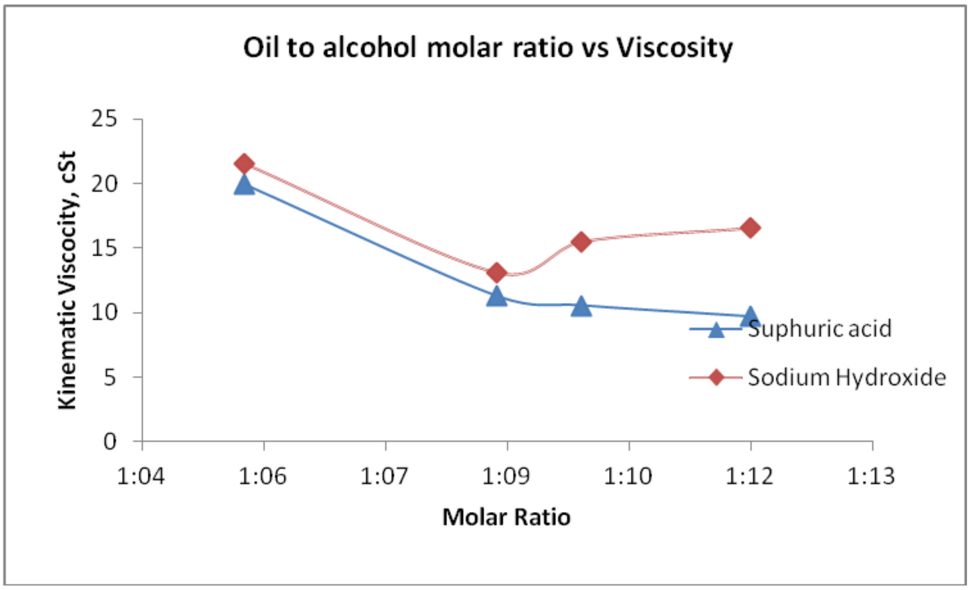

Figure: 5: Variation of viscosity vs molar ratio

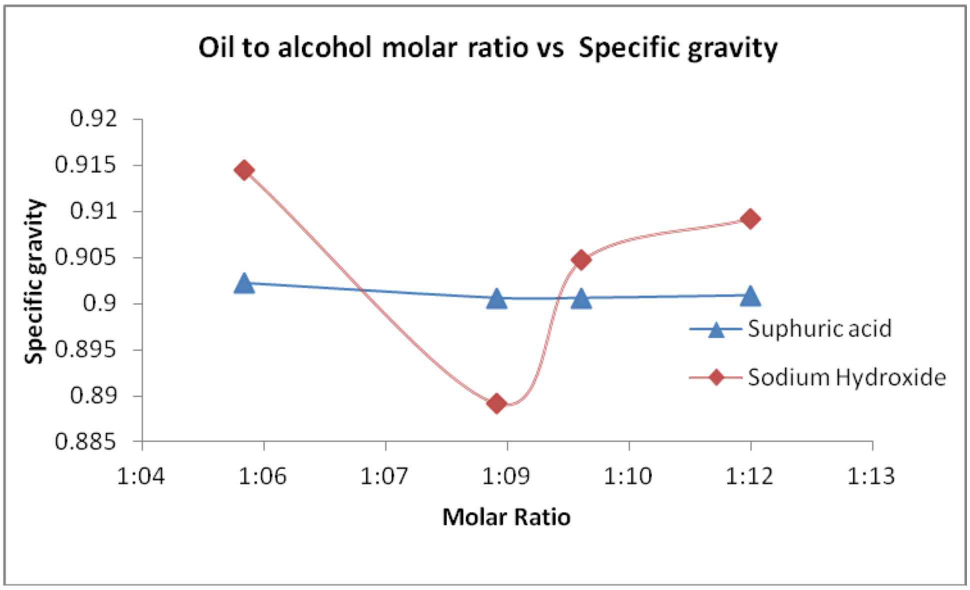

Figure: 6: Variation of Specific gravity vs molar ratio

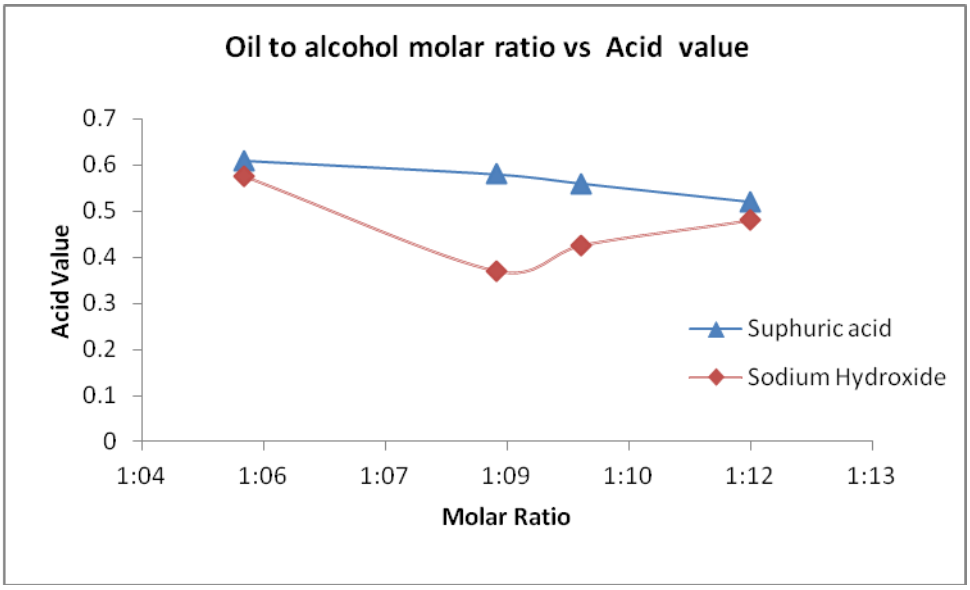

Figure: 7: Variation of Acid Value vs molar ratio

CONCLUSION:

The present study investigated the production of biodiesel from castor oil via the transesterification process using two different catalysts: sulfuric acid (H_2SO_4) and sodium hydroxide (NaOH). Experiments were conducted in a batch reactor, focusing on the effect of three key process variables:

1. Residence time,
2. Oil-to-methanol molar ratio, and
3. Reaction temperature.

The influence of these parameters on biodiesel quality was primarily assessed based on viscosity, a critical specification outlined in the ASTM D6751 standard, alongside specific gravity and acid value.

Conclusions Using Sulfuric Acid as Catalyst:

- Residence Time: Increasing the reaction time from 30 to 45 minutes resulted in a reduction in viscosity from 16.56 cSt to 11.28 cSt. Beyond 45 minutes, viscosity began to increase, identifying 45 minutes as the optimal reaction time.
- Oil-to-Methanol Molar Ratio: Viscosity decreased consistently with increasing molar ratio, reaching 6.63 cSt at 1:15. However, this value slightly exceeds the ASTM acceptable range of 1.9–6.0 cSt, suggesting that while conversion improves, further refinement or blending may be required for standard compliance.
- Reaction Temperature: At a constant residence time (45 min), catalyst concentration (3 vol%), and

molar ratio (1:9), the temperature was varied between 30°C and 55°C. The optimal temperature was identified as 55°C, yielding the lowest viscosity of 11.28 cSt. However, a lower viscosity value of 6.63 cSt was achieved at 1:15 molar ratio, indicating the influence of alcohol excess.

Conclusion Using Sodium Hydroxide as Catalyst:

- Residence Time: Viscosity decreased from 21.57 cSt to 13.10 cSt as residence time increased from 30 to 45 minutes. Beyond this point, viscosity increased, confirming 45 minutes as the optimal reaction time.
- Oil-to-Methanol Molar Ratio: When varied from 1:6 to 1:12, the minimum viscosity of 13.10 cSt was recorded at a 1:9 molar ratio, indicating it as the optimum ratio under the given conditions.
- Reaction Temperature: At constant catalyst concentration (1 wt%), residence time (45 min), and molar ratio (1:9), the temperature was varied from 30°C to 50°C. Unlike the acid-catalyzed process, viscosity increased with temperature, and the optimum temperature was found to be 30°C, where the lowest viscosity of 13.10 cSt was recorded.

Final Remarks:

The study concludes that both acid and base catalysts can effectively convert castor oil to biodiesel; however, the acid-catalyzed process demonstrated better control over viscosity at higher molar ratios and temperatures. While some experimental viscosity values exceeded ASTM standards, optimization and blending strategies may be employed to meet commercial fuel specifications. These findings support the potential of non-edible castor oil as a sustainable feedstock for biodiesel production under carefully controlled reaction conditions.

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