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# Nonlinear Trade-Off Between Agitator Speed and Biodiesel Quality in Transesterification: A Lab-Scale Study

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## Abstract

The agitator speed controls the intensity of interaction between the immiscible oil and methanol phases during transesterification. This, in turn, shapes the overall reaction environment during the biodiesel production process. While higher agitation rates are often associated with increased mass transfer, their impact on the resulting fuel properties is not always proportional. In a controlled laboratory setting, the effect of agitator speed was examined at 300, 500, 700, and 900 rpm, with particular attention paid to biodiesel yield, density, kinematic viscosity, and flash point. A gradual shift in system behavior became apparent as the agitation rate increased. In the intermediate range of 500–700 rpm, the process tended to stabilize, producing biodiesel with relatively consistent characteristics. The measured kinematic viscosity was between 4.42 and 4.45 cSt, accompanied by a density of approximately 861 kg/m<sup>3</sup>. However, pushing the system to higher agitation rates led to a different response. At 900 rpm, the yield dropped sharply to 49.53%, and the viscosity increased to 4.92 cSt. This behavior indicates the onset of unfavorable hydrodynamic conditions, where intensive mixing likely disrupts phase separation and promotes the formation of a stable emulsion. Meanwhile, the flash point continued to increase from 124.7 °C to 166.8 °C, indicating a progressive decrease in residual methanol. Overall, these observations suggest that the influence of stirrer speed is governed by competing mechanisms rather than a simple monotonic trend. Operation in the 500–700 rpm range appears to offer a more reliable compromise, where conversion and fuel properties remain balanced. From an engineering

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perspective, this range provides a useful reference for establishing operating conditions in biodiesel reactors, especially when considering process development beyond the laboratory scale while maintaining consistent product quality.

**Keywords:** Biodiesel; transesterification; agitator speed; kinematic viscosity; yield; flash point

## 1. Introduction

Sustainable energy availability is a strategic challenge due to increasing fuel consumption and dwindling fossil fuel reserves [1]. Biodiesel plays a significant role as an alternative fuel [2], [3]. This is because biodiesel is sourced from renewable energy, is biodegradable, and can reduce exhaust emissions compared to conventional diesel [4], [5]. However, these benefits are achieved only if biodiesel meets quality standards, particularly regarding viscosity, density, and flash point, which affect engine performance and reliability.

Transesterification is the most common method for producing biodiesel, but this process has limitations because the reaction occurs between two phases: oil and alcohol [6], [7]. Poor interphase contact often results in low reaction conversion and inconsistent product quality [8]. To address this, mechanical agitators are used to create a more homogeneous mixture and accelerate mass transfer [9]. The agitator's rotational speed is a critical factor that affects flow, phase distribution, and reaction rate during transesterification [10], [11].

Increasing agitator speed is generally associated with higher reaction efficiency, but this approach does not always result in a commensurate improvement in biodiesel quality [12]. From a fluid dynamics standpoint, changes in agitator speed modify droplet size distribution, interfacial area, and flow regime, all of which influence mass transfer rates and reaction pathways. Excessive mixing intensity can lead to the formation of stable emulsions, inhibit glycerol separation, and reduce the stability of methyl esters. This condition can reduce biodiesel yield and increase viscosity, negatively impacting fuel characteristics [13]. This phenomenon indicates a non-linear relationship and trade-off between process efficiency and final product quality [14], [15].

Most previous research has focused on optimizing the alcohol-to-oil ratio, catalyst type, concentration, and reaction temperature. At the same time, the effect of agitator speed is often treated as an ancillary parameter or reported only in limited quantities [16], [17]. Despite these efforts, the role of stirrer speed as a governing hydrodynamic parameter remains unclear. In particular, previous studies have rarely established a direct relationship between stirrer speed, phase behavior, and the resulting fuel properties within a single experimental framework. Consequently, the operating limits at which increasing stirring begins to degrade biodiesel quality

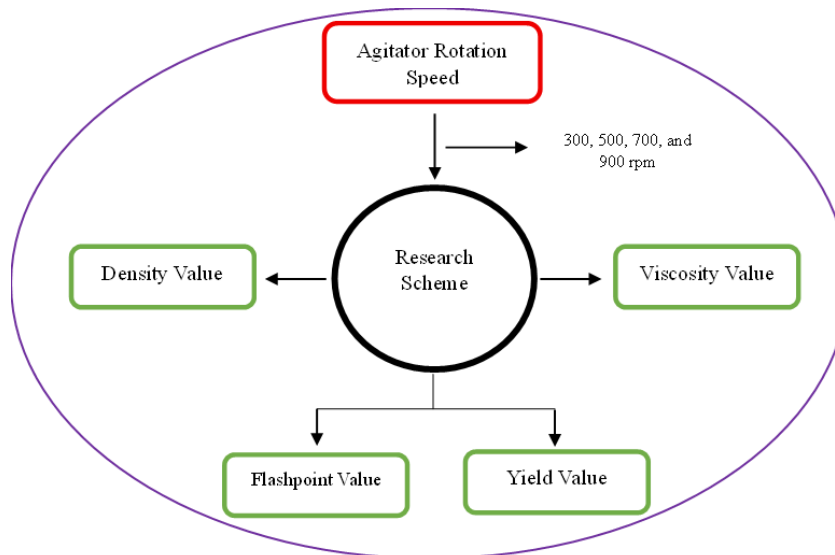
remain insufficiently defined. Studies systematically evaluating agitator speed as a primary variable and linking it to fuel quality parameters relevant to real-world applications are relatively rare [18], [19]. Consequently, the optimum limit between increasing mixing intensity and biodiesel quality degradation has not been clearly defined.

The contribution of this work lies in capturing the nonlinear interaction between agitator speed, reaction performance, and biodiesel fuel properties through direct experimental observation. By linking mixing intensity with both yield and fuel quality parameters, the present study provides a more integrated perspective compared to previous approaches that treat these aspects separately. The agitator speed was varied over 300–900 rpm, with comprehensive evaluation of methyl ester yield, dynamic and kinematic viscosity, density, and flash point. The main novelty of this research lies in the direct mapping of the trade-off between mixing intensity and biodiesel quality characteristics, based on repeated experimental data, thereby enabling identification of the optimal agitator speed range that balances reaction efficiency and fuel quality. These findings are expected to provide practical and scientific contributions in the design and optimization of more reliable and sustainable biodiesel production processes.

## 2. Methods

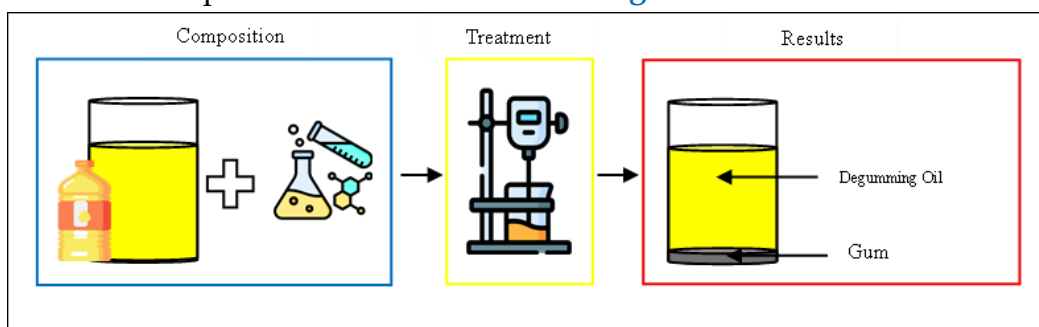
This experimental work investigates the effect of Agitator speed on biodiesel yield and fuel properties during the transesterification process under controlled operating conditions. The raw material used in this study was cooking oil. In this study, the variables used were Agitator speeds of 300, 500, 700, and 900 rpm. The selected agitator speed range (300–900 rpm) was chosen to represent low to high mixing intensity conditions commonly reported in laboratory-scale biodiesel reactors. This range enables the observation of both enhanced mass transfer at moderate agitation and potential hydrodynamic limitations at excessive mixing. The biodiesel quality used as a reference for the research results was based on density, viscosity, flash point, and yield. The research scheme is shown in [Figure 1](#).

This research begins with the collection of raw materials. Raw materials (used cooking oil) are processed through 4 stages: degumming, transesterification, washing, and evaporation. The degumming process removes impurities, or gum, from raw materials. The degumming process is carried out by adding Phosphoric Acid ( $H_3PO_4$ ) at a level of up to 1% of the total mass of raw materials or oil.  $H_3PO_4$ , which has been mixed with used cooking oil, is stirred for 30 minutes at 60 °C using a stirrer. The result of the degumming process is oil that has separated from the gum and appears in two layers. The degumming process scheme is shown in [Figure 2](#).



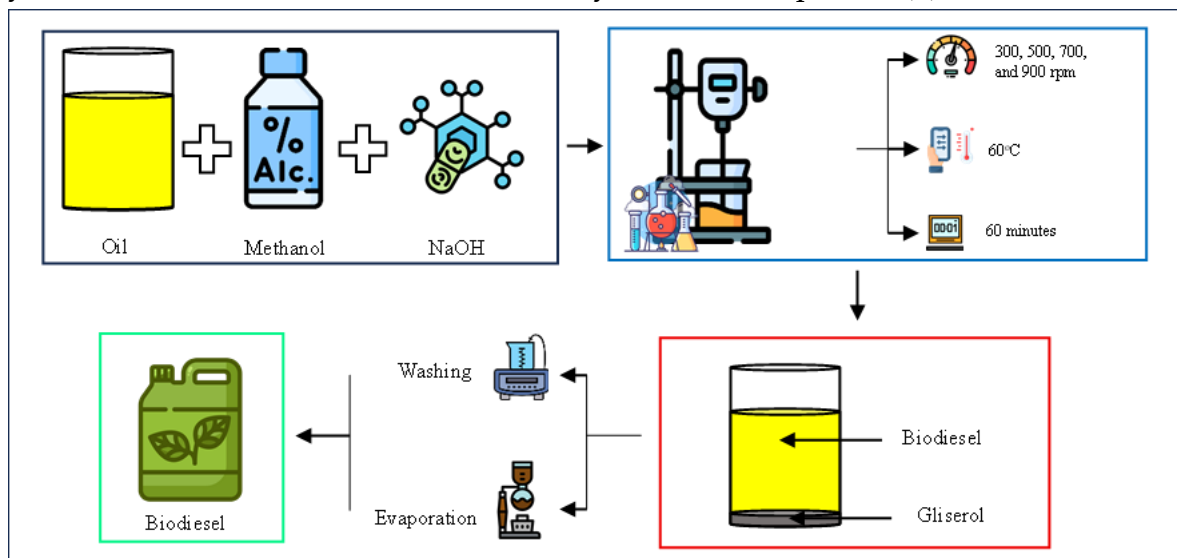
**Figure 1.** Research Scheme

After the degumming process, the transesterification process continues. The transesterification process uses degummed oil as a source of triglycerides and methanol as the reactant alcohol. The mass ratio of oil to methanol is 1:0.5. The two materials are mixed in a beaker with the addition of a catalyst, NaOH, at one percent of the total oil mass. The stirrer is set to rotate the agitator at precise rotation speeds. The reaction is carried out at agitator speeds of 300, 500, 700, and 900 rpm. The temperature is 60 °C, with a process time of 60 minutes. The selected operating conditions were based on commonly reported parameters in biodiesel transesterification studies. A reaction temperature of 60 °C was chosen to enhance reaction kinetics while minimizing methanol evaporation. The catalyst concentration of 1 wt.% NaOH was used to ensure sufficient catalytic activity while reducing the risk of soap formation, and the methanol-to-oil ratio was selected to support effective conversion. Increasing agitator speed is associated with higher Reynolds numbers, indicating a transition from laminar to transitional or turbulent flow regimes depending on the operating conditions. This transition plays a significant role in determining mixing efficiency and phase dispersion behavior. The transesterification process scheme is shown in **Figure 3**.



**Figure 2.** Degumming Process Scheme

The biodiesel phase formed was separated and purified. The purification process involved washing with a 1:1 biodiesel-to-distilled water mixture. Washing was performed using a stirrer at 80 °C for 5 minutes. Washing was repeated five times until the biodiesel was clean. After the washing process, an evaporation process was carried out. This process was carried out to remove any remaining water and methanol in the biodiesel. The evaporation process was carried out by heating to 80 °C for 5 minutes, allowing the remaining water and methanol to evaporate from the biodiesel. The washing and evaporation process scheme is shown in **Figure 4** (a), while the evaporation scheme can be seen in **Figure 4** (b). After completion, the yield value is calculated. To calculate the yield value, Equation (1) is used.



**Figure 3.** Transesterification Process Scheme

$$\text{Yield (\%)} = \frac{m_{ME}}{m_{Oil}} \times 100\% \quad (1)$$

where :

- $m_{ME}$ , = massa methyl ester (g)
- $m_{Oil}$  = mass of oil / mass of raw material (g)

The physical properties of biodiesel were characterized by density, viscosity, and flash point measurements. Biodiesel density was measured using a hydrometer according to ASTM D1298. The biodiesel temperature during density measurement was 40 °C. The hydrometer used had a measurement range covering biodiesel densities from 0.80 to 0.90 g/cm<sup>3</sup>, and the measurements were corrected to the reference temperature to improve data accuracy. Viscosity was tested using an Ostwald viscometer using a comparison method with distilled water as the reference fluid. All viscosity measurements were performed at 40 °C to ensure data consistency and compliance with biodiesel testing standards. The flow times of the samples and the reference fluid were carefully recorded and used to calculate

dynamic viscosity, which was then converted to kinematic viscosity according to the ASTM D445 standard based on the density values of each sample. The equation for calculating the viscosity value can be seen in Equation 2, and the unit conversion from mPa·s to cSt can be seen in Equation (3).

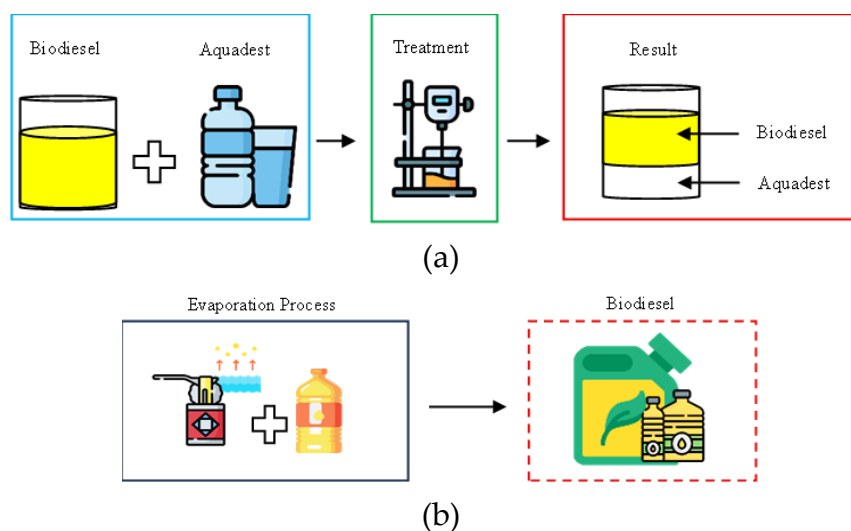


Figure 4. (a) Washing Process, (b) Evaporation Process

$$\mu_{\text{bio}} = \mu_{\text{air}} \frac{\rho_{\text{bio}} t_{\text{bio}}}{\rho_{\text{air}} t_{\text{air}}} \quad (2)$$

where :

- $\mu$ = dynamic viscosity (mPa·s)
- $\rho$ = density (g/cm<sup>3</sup>)
- $t$ = flow time (s)

**Conversion to Kinematic Viscosity (ASTM D445)**

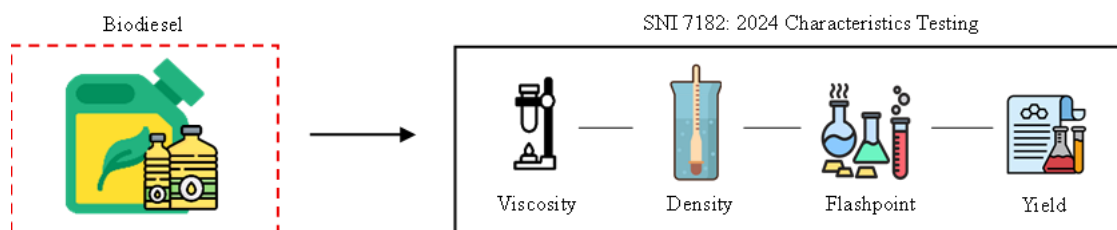
$$\nu = \frac{\mu}{\rho} \quad (3)$$

where :

- $\nu$ = kinematic viscosity (cSt)
- $\mu$ = dynamic viscosity (mPa·s = cP)
- $\rho$ = density (g/cm<sup>3</sup>)

The flash point test for biodiesel aims to evaluate fuel safety aspects and ensure compliance with SNI 7182:2024. The SNI 7182:2024 standard requires a minimum flash point of 100 °C. The test uses a flash point tester in accordance with liquid fuel procedures, with results reported in degrees Celsius. All experiments were conducted in triplicate to ensure repeatability. The reported values represent the mean of the measurements, and variability was quantified using standard deviation to assess data consistency. Although formal statistical analysis such as ANOVA was not performed, the consistency of repeated measurements was used to evaluate the reliability of the observed trends. At the same time, the pattern of changes between variations was interpreted to reveal the trade-off relationship between blending

intensity and the quality of the resulting biodiesel. The present study focuses on experimental observations. Although no regression or predictive modeling was applied, the obtained results provide a basis for future development of mathematical models relating agitator speed to biodiesel performance. The test treatment scheme is shown in **Figure 5**. It should be noted that this study was conducted at laboratory scale under controlled conditions. Therefore, direct extrapolation of the results to industrial-scale systems should be approached with caution, as differences in reactor geometry, mixing behavior, and phase separation efficiency may influence overall process performance.

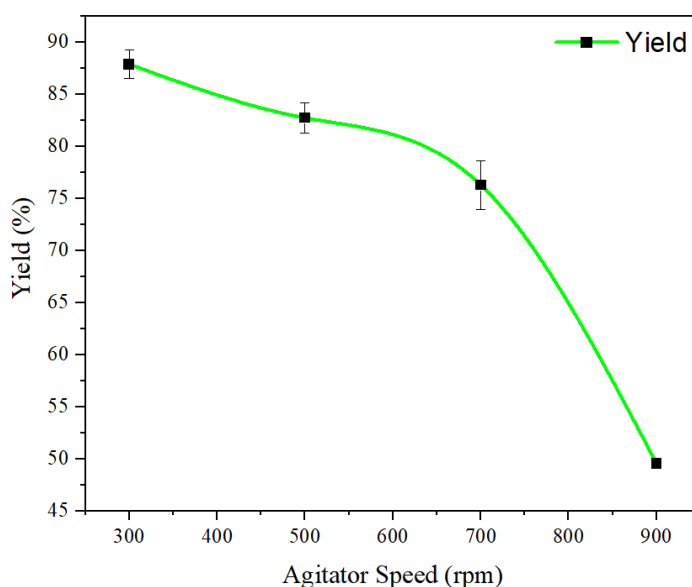


**Figure 5.** Test Treatment Scheme

### 3. Results and Discussion

#### 3.1 The Effect of Agitator Speed on Biodiesel Yield

The initial biodiesel yield indicates the degree of conversion of triglycerides to methyl esters immediately after transesterification, before purification and washing. This parameter is important for assessing reaction performance, particularly in studying the effect of agitator speed on reaction kinetics and interphase mass transfer. **Figure 6** shows the biodiesel yield as a function of agitator speed.



**Figure 6.** Biodiesel Yield at Various Agitator Speeds

The results showed a tendency for the initial yield to decrease with increasing agitator speed. At 300 rpm, the initial yield reached 87.9%. This value was the highest

among the variations tested. This indicates that the mixing intensity at this level was sufficient to create effective contact between the oil and methanol, allowing the transesterification reaction to proceed optimally. Under these conditions, the reaction rate was more influenced by reactant availability than by mass transfer resistance. At 500 rpm, the initial yield decreased to 83.33%. This finding suggests that increasing mechanical energy does not always lead to increased methyl ester formation. Hydrodynamically, higher agitator speeds produce finer phase dispersions and a larger contact surface area. However, this condition can cause excessive stabilization of the oil-methanol interaction, resulting in some energy being ineffective in accelerating the reaction and instead being absorbed in forming a more complex flow pattern [20].

A more significant decrease can be observed at an agitator speed of 700 rpm, but it decreases again to 49.53% at an agitator speed of 900 rpm. These results indicate that an imbalance between the chemical reaction rate and fluid flow dynamics is likely the cause of this condition. High mixing intensity can trigger the formation of microdispersions or emulsification. These results indicate that excessive stirring has a dominant impact in reducing the conversion efficiency. Under high turbulence conditions, high mechanical energy tends to intensify emulsion formation and interfere with the initial separation of methyl esters from glycerol. Furthermore, highly dynamic flow conditions can affect the stability of reaction intermediates, leading to a lower fraction of methyl esters formed [21].

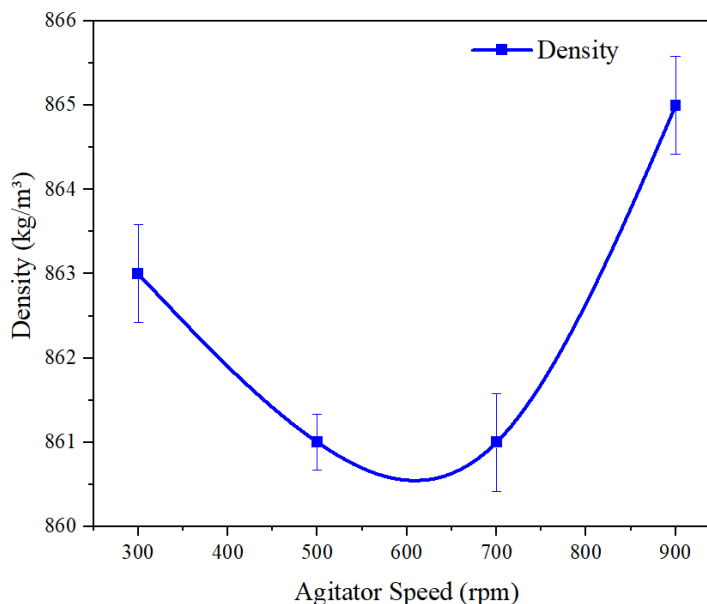
Overall, the relationship between agitator speed and initial biodiesel yield is nonlinear. System performance depends on the balance between the interphase contact area and the reaction's hydrodynamic stability. A speed limit that is too low results in a reactant interaction, while one that is too high reduces efficiency due to the dominance of adverse hydrodynamic phenomena. Optimizing the transesterification process requires selecting an agitator speed that balances reaction kinetics and flow stability.

### **3.2 The Effect of Agitator Speed on Biodiesel Density**

Biodiesel density is a physical property that reflects the molecular composition of the fuel, particularly the ratio of the methyl ester fraction to non-ester components such as residual triglycerides, diglycerides, and monoglycerides. While yield better represents the amount of product formed, density provides information on the quality and uniformity of the transesterification reaction composition. Therefore, density analysis is crucial for a more comprehensive assessment of biodiesel quality. **Figure 7** shows the biodiesel density as a function of agitator speed.

Measurements showed that at agitator speeds of 300, 500, and 700 rpm, the biodiesel density remained within a narrow range of 861–865 kg/m<sup>3</sup>. This consistency indicates that the decrease in initial yield due to increasing agitator

speed was not accompanied by significant changes in the methyl ester composition. Therefore, at low to medium agitator speeds, the reaction system still produced biodiesel with a uniform molecular character. Differences began to appear at 900 rpm, where the density increased to approximately 865 kg/m<sup>3</sup>. Although this increase is numerically small, it physically indicates a change in product composition.



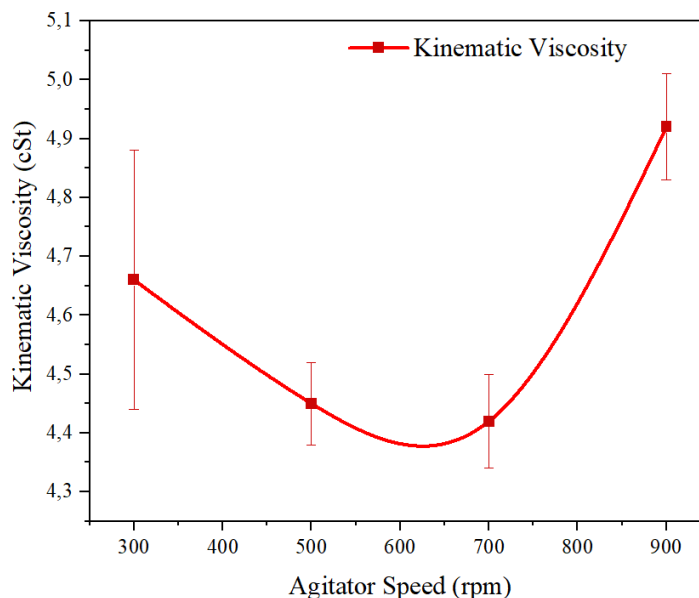
**Figure 7.** Biodiesel Density versus Agitator Speed (40 °C)

The increase in density is typically associated with a higher fraction of heavy components or reaction residues that have not been fully converted to methyl esters. This phenomenon is consistent with the decrease in initial yield at high speeds, indicating reduced conversion efficiency and an increase in the proportion of non-ester compounds in the system [22]. From a hydrodynamic perspective, high stirring intensity results in a very fine and stable phase dispersion. This condition improves the macroscopic homogeneity of the mixture but can inhibit molecular segregation between methyl esters and glycerol [23]. As a result, some reaction components remain dispersed within the same phase, increasing biodiesel density. Overall, changes in density with varying agitator speed indicate that this parameter not only reflects the fuel's physical properties but also the balance between reaction kinetics and fluid flow dynamics. At medium speeds, this balance is maintained, so the density remains within the expected range. Conversely, at high speeds, the dominance of hydrodynamic effects shifts the optimum conditions and degrades the molecular quality of the product [24]. Therefore, optimization of the transesterification process is determined not only by high yield but also by the system's ability to maintain biodiesel density according to fuel quality standards. Excessively intense stirring, although increasing mixing energy, can result in biodiesel with a density less suitable for engine applications.

### 3.3 The Effect of Agitator Speed on Biodiesel Viscosity

Biodiesel viscosity is a physical property that significantly influences fuel performance in engine applications, particularly during fogging, air-fuel mixing, and combustion stability. Unlike density, which reflects the mass composition of the fluid, viscosity directly reflects the fluid's molecular structure and the intermolecular interactions formed during transesterification. Test results show that the kinematic viscosity of biodiesel has a nonlinear trend with increasing agitator rotational speed.

**Figure 8** shows the biodiesel viscosity as a function of agitator speed.



**Figure 8.** Biodiesel Viscosity versus Agitator Speed (40 °C)

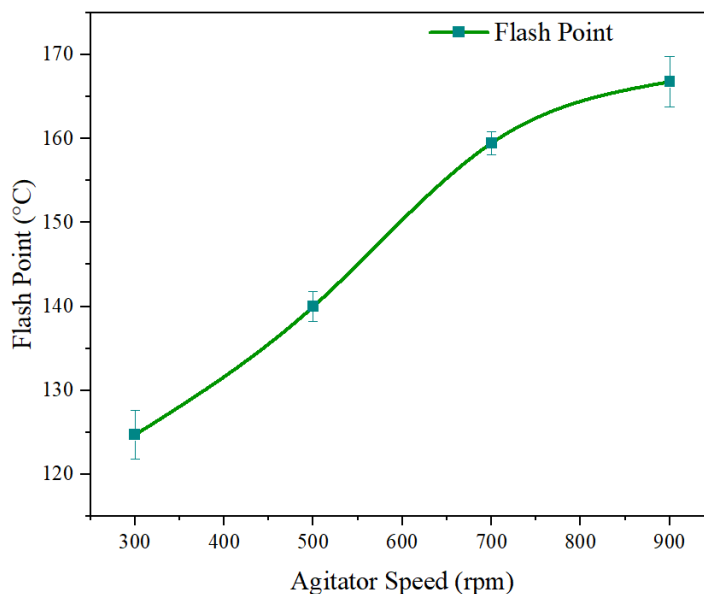
At a agitator speed of 300 rpm, the average kinematic viscosity of biodiesel was recorded at 4.66 cSt. Increasing the speed to 500 and 700 rpm was followed by decreases in viscosity to 4.45 cSt and 4.42 cSt, respectively, the lowest values in this study. However, when the agitator speed was increased to 900 rpm, the viscosity increased significantly to 4.92 cSt. This pattern indicates that stirring at an intermediate rate provides the most conducive conditions for the formation of methyl esters with higher purity and lower residual triglyceride content.

From a reaction kinetics perspective, mixing intensity within this range is sufficient to minimize mass-transfer resistance without causing excessive hydrodynamic disturbances [25]. This condition allows for the formation of a more uniform biodiesel molecular structure, resulting in reduced fluid flow resistance and lower viscosity. Conversely, at high agitator speeds, the reaction system tends to operate in a highly turbulent flow regime. This situation has the potential to trigger the formation of heavy fractions or reaction residues that are not fully converted to methyl esters [26], [27]. Furthermore, emulsion stabilization at excessive mixing intensity can lead to the trapping of non-ester components in the final product, directly contributing to increased viscosity.

The increasing viscosity with increasing density at 900 rpm indicates that changes in flow properties are closely related to changes in the molecular composition of the biodiesel, rather than solely to experimental variations. Higher viscosity under these conditions implies reduced fuel atomization quality, larger droplets during injection, and a potential decrease in combustion efficiency. Overall, these findings confirm that biodiesel viscosity is strongly influenced by the balance between chemical reaction rates and flow dynamics during transesterification. Moderate agitator speeds can maintain this balance and produce biodiesel with viscosity characteristics more suitable for engine applications. Conversely, excessive stirring tends to shift the optimum conditions and degrade product quality, despite the higher mixing energy applied.

### 3.4 The Effect of Agitator Speed on Biodiesel Flash Point

Flash point is a critical parameter in evaluating biodiesel quality and safety because it directly relates to the presence of volatile components, particularly residual methanol, in the final product. A high flash point indicates higher biodiesel purity and lower storage and use safety risks. **Figure 9** shows the biodiesel flash point as a function of agitator speed.



**Figure 9.** Effect of Agitator Speed on Biodiesel Flash Point

Tests showed that the flash point of biodiesel increased consistently with increasing agitator speed. At 300 rpm, the average flash point was recorded at 124.7 °C, increasing to 140.0 °C at 500 rpm, 159.5 °C at 700 rpm, and reaching a peak value of 166.8 °C at 900 rpm. This increase indicates a decrease in residual methanol content in the produced biodiesel. Physically, higher stirring intensity increases turbulence and the interfacial area of the fluid, thereby accelerating the release of volatile components during the reaction and separation stages. Greater mechanical energy also accelerates methanol desorption from the biodiesel phase, thereby

reducing the fraction of low-flash-point compounds. However, an increase in flash point should not be interpreted as a direct indicator of overall biodiesel quality. While a higher flash point reflects a reduction in residual methanol, it does not account for other critical fuel properties. At 900 rpm, although the flash point reaches its highest value, this condition is accompanied by a decrease in yield and increases in both viscosity and density. These changes indicate deterioration in conversion efficiency and fuel flow characteristics. Therefore, biodiesel quality must be evaluated based on a combination of physicochemical parameters rather than a single indicator such as flash point [28], [29]. Therefore, flash point evaluation needs to be integrated with other quality parameters. A agitator speed of 500–700 rpm produces the most balanced conditions, where the flash point increases (140.0–159.5 °C) without a sharp decrease in yield or detrimental increases in viscosity and density. This indicates that within this range, residual methanol can be effectively reduced without compromising overall reaction performance [30].

Overall, these findings confirm that increasing the agitator speed increases the flash point by removing volatile components. However, excessive stirring is not recommended, as it can cause an imbalance in the reaction system and negatively affect other quality parameters. Therefore, optimizing the agitator speed in the transesterification process must balance fuel safety and conversion efficiency to produce biodiesel with comprehensive quality.

#### 4. Conclusion

Agitator rotation speed acts as a governing parameter affects transesterification efficiency and biodiesel quality, with a distinctly nonlinear response arising from the interaction between mass transfer enhancement and hydrodynamic instability.

1. Biodiesel yield decreased with increasing agitator speed, from  $87.90 \pm 2.34\%$  at 300 rpm to  $49.53 \pm 0.58\%$  at 900 rpm, indicating that excessive mixing energy promotes emulsion formation and inhibits effective phase separation, thereby reducing methyl ester recovery.
2. The most balanced fuel characteristics were obtained within the moderate speed range of 500–700 rpm, where kinematic viscosity reached 4.45–4.42 cSt and density remained within 861–865 kg/m<sup>3</sup>, reflecting improved molecular uniformity and favorable flow behavior for combustion.
3. The flash point increased from 124.7°C to 166.8°C with increasing agitator speed, suggesting a reduction in residual methanol. However, this improvement in fuel safety was accompanied by a decline in yield and less favorable viscosity characteristics at higher speeds. The results confirm a trade-off between conversion efficiency and fuel quality, where

improvements in volatility-related properties do not necessarily correspond to overall process performance enhancement.

4. An optimal operating window is identified at 500–700 rpm, where reaction kinetics, hydrodynamic stability, and fuel properties are maintained in a balanced condition. The study contributes by providing a quantitative and integrated evaluation of the relationship between agitator speed, biodiesel yield, and key fuel properties, demonstrating their interdependence within a single experimental framework. From an engineering standpoint, excessive agitation should be avoided, as it not only reduces yield but also increases energy consumption and complicates downstream separation processes.
5. Future work should focus on predictive modeling, CFD-based flow analysis, and scale-up validation to better capture hydrodynamic behavior and process performance under industrial operating conditions.

### Authors' Declaration

**Authors' contributions and responsibilities** - In the acknowledgment section, the author can state the source of research funding and more specifically to the contract number. Make sure the statement complies with the guidelines provided by the funding agency. The author can also express his thanks to reviewers and proofreaders, or technicians who help prepare equipment set-ups or students who assist in surveys.

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