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RESEARCH ARTICLE

Biodiesel Production from Crude Jatropha Oil and Engine Performance

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ABSTRACT

This study aimed to investigate the efficiency of converting crude Jatropha oil (CJO) into Jatropha biodiesel (JB) via the transesterification process, to optimize the operating conditions required for effective conversion, to determine the physicochemical properties of the resulting JB, and to evaluate diesel engine performance using various JB–diesel blends. Both one-step and two-step transesterification methods were explored in order to identify the most suitable approach for processing CJO. The findings revealed that only the two-step method produced satisfactory results, primarily due to the high free fatty acid (FFA) content present in the crude oil, which inhibits the effectiveness of a single-step alkaline transesterification process. Through systematic experimentation, optimal reaction conditions and variable ratios were determined, which yielded the highest biodiesel output of 84%. The optimum conditions consisted of a 0.02:1 ratio of acid catalyst to oil and a 1:1 ratio of alcohol to oil during the first step (lasting 1 hour), followed by a 0.03:1 ratio of base catalyst (NaOH) to oil and a 5:1 alcohol-to-oil ratio during the second step (lasting 2 hours). The produced JB was thoroughly characterized using Fourier Transform Infrared Spectroscopy (FT-IR), a bomb calorimeter, a density meter, and a flash point tester. The analyses established key fuel properties, with a calorific value of 35.23 MJ/kg, a density of 898 kg/m³, and a flash point of 165 °C, confirming that the biodiesel met essential quality requirements. Subsequently, blends of JB with mineral diesel at varying proportions were tested as fuel in a diesel engine to assess operational performance. Among all tested blends, the 20% JB blend demonstrated performance closely comparable to pure mineral diesel, achieving the lowest total and specific fuel consumption, while also delivering the highest engine speed, brake horsepower, and mechanical efficiency.

1. INTRODUCTION

The escalating cost of petroleum, the continuous decline in global petroleum reserves, and the environmental degradation resulting from fossil fuel combustion have collectively intensified the global demand for renewable and sustainable energy sources, including biodiesel (Kessler & Sperling, 2016; Reddy et al., 2016; Saleh et al., 2024). Over the past few decades, the world has witnessed substantial growth in industrialisation and transportation, both of which heavily rely on fossil-derived fuels. This dependency has not only strained the limited reserves of crude oil but has also contributed significantly to rising greenhouse gas emissions, air pollution, and climate change. Consequently, researchers, industries, and governments have increasingly turned their attention toward alternative fuels that can mitigate environmental impacts while ensuring long-term energy security.

Biodiesel has emerged as one of the most promising renewable fuels capable of addressing these challenges. Chemically, biodiesel consists primarily of fatty acid alkyl esters–commonly methyl or ethyl esters–which are produced from biologically renewable feedstocks such as vegetable oils, animal fats, waste cooking oils, and certain types of microbial oils. Since these raw materials are derived from biomass, biodiesel is considered carbon-neutral in principle, as the carbon dioxide emitted during combustion is offset by the amount absorbed by the source organisms during growth.

One of the most notable advantages of biodiesel is its versatility. It can be used on its own as pure biodiesel (B100) or blended with petroleum diesel in any proportion to produce biodiesel blends such as B5, B20, or B50. These blends offer flexibility for end-users and allow for a gradual transition from fossil diesel to renewable fuel alternatives. Moreover, biodiesel is compatible with all standard diesel engines without requiring major modifications, making it easy to incorporate into existing fuel infrastructures.

Environmentally, biodiesel offers several clear benefits over conventional petroleum-derived diesel. It is biodegradable, non-toxic, and exhibits considerably lower emissions of carbon monoxide, hydrocarbons, particulate matter, and sulphur oxides. Additionally, biodiesel combustion generally results in reduced smoke and soot formation, contributing to improved air quality. Studies have also shown that biodiesel possesses superior lubricity, which can enhance engine longevity and decrease wear on engine components. These advantages make biodiesel an attractive option for both environmental protection and mechanical performance (Emil et al.,2009; Reddy et al.,2017a; Reddy et al.,2017b; Syam et al.,2009).

Several production methods have been developed to convert various feedstocks into biodiesel. These methods include direct use or blending of raw oils, pyrolysis, micro-emulsion techniques, and the most widely adopted approach–transesterification. Among these, transesterification is the preferred method because it is efficient, cost-effective, and capable of producing high-quality biodiesel with desirable fuel properties (Wilson, 2010). In this process, triglycerides in oils or fats react with an alcohol–typically methanol–in the presence of a catalyst to form fatty acid esters and glycerol. The simplicity and scalability of this method have made it the dominant technology in commercial biodiesel production worldwide.

1.1. *Jatropha curcas* Linnaeus (JCL): A Versatile Plant with Biodiesel Potential

Jatropha curcas Linnaeus (JCL) is a resilient plant from the Euphorbiaceae family, known for its chemical properties–some of which are potent enough to fall under restrictions set by the Geneva Conventions on chemical warfare agents. Originally native to Mexico, *Jatropha curcas* was introduced to Asia and Africa through Portuguese trade routes, where it initially served as a hedge plant (Koh et al., 2011).

The genus name *Jatropha* is derived from the Greek words *jatros*, meaning “doctor”, and *trophē,* meaning “food”, reflecting its historical medicinal applications. *Jatropha curcas* offers numerous benefits: it is used for soil stabilization to prevent erosion, land restoration, as a natural living fence, and as a revenue-generating commercial crop. This hardy plant thrives in poor soils and low rainfall areas (as little as 250 mm annually), making it a suitable option for small-scale farmers. Its resilience makes it ideal for planting in marginal areas to reclaim degraded land and prevent soil erosion (Parawira, 2010; Berchmans & Hirata, 2007).

Jatropha curcas is a bushy plant that reaches a height of approximately 3-4 meters, with numerous side branches extending from the main stem. The flowers are yellowish-green and appear in loose clusters, while the ripe fruits are yellow and measure 2-5 cm in length. These fruits contain seeds resemble castor seeds, either ovoid or oblong, and are enclosed in a dull brownish-black capsule. Under optimal conditions, a mature *Jatropha curcas* tree can yield around four kilograms of seeds annually, with a productive lifespan of 30 to 40 years. The trees can be easily propagated from seeds or cuttings and grow quickly, producing seeds within two years of establishment (Punia, 2007)

1.2. The Case for *Jatropha curcas* in Biodiesel Production

Jatropha curcas is highly favourable for biodiesel synthesis owing to its adaptability to extreme environmental conditions, including drought. This resilience makes it economical to cultivate, with rapid growth and easy propagation, ultimately reducing the cost of biodiesel production. Unlike other plant oils, *Jatropha curcas* oil is non-edible due to its toxic components, including curcin (a toxalbumin), cyanic acid (related to ricinoleic acid), and toxic phorbol esters (Syam et al.,2009; Chauhan et al.,2011). This ensures that biodiesel synthesis using *Jatropha curcas* does not conflict with the human right to adequate food, as the seeds are not fit for human consumption.

Additionally, *Jatropha curcas* biodiesel exhibit fuel properties comparable to those of fossil diesel and complies with the latest biodiesel standards. The plant is widely recognized for its potential to combat the greenhouse effect, generate additional income for rural communities, and serve as a significant source of renewable energy (Jain & Sharma, 2010; Shivani et al., 2011)

2. MATERIALS AND METHODS

2.1. Soxhlet Oil Extraction Method

Begin by grinding the *Jatropha curcas* seeds using a grinding machine. Weigh the ground seeds and fill the extraction thimble to approximately three-quarters of its capacity. Pour *n*-hexane into the flask until it is about three-quarters full, then add a few boiling chips to aid in heat distribution and prevent. Switch on the power and water supply, and set the temperature to 69°C, which corresponds approximately to the boiling point of *n*-hexane. Allow the extraction to proceed for eight hours.

Upon completion, carefully remove the solvent from the heating mantle and allow it to cool. Calculate the oil yield using the formula (Saleh et al., 2024):

$$\text{Yield (\%)} = \frac{\text{mass of crude Jatropha oil (g)}}{\text{mass of ground seeds (g)}} \times 100$$

2.2. Measurement of Free Fatty Acid

First, prepare a 0.1M KOH solution in ethanol by dissolving potassium hydroxide in ethanol. Weigh 5 to 10 grams of *Jatropha curcas* oil into a 100 mL conical flask. Prepare a 50 mL solvent mixture consisting of 95% ethanol and diethyl ether in an equimolar ratio and transfer it into the conical flask containing the oil sample. Gently heat the mixture using a magnetic stirrer, then add five drops of phenolphthalein indicator.

Titrate the mixture with the prepared KOH solution until the endpoint is reached, as indicated by a persistent pink color lasting for at least10 seconds. Determine the acid value using the formula:

$$\text{Acid Value} = \frac{(56.1 \times \mathrm{M} \times \mathrm{V})}{W}$$

where V is the volume of KOH used (ml), M is the concentration of KOH solution (0.1M), and W is the weight of the oil (g).

If the acid value exceeds 4%, proceed with a two-step transesterification process; otherwise, continue with a one-step transesterification (Berchmans & Hirata, 2008)

2.3. One-Step Transesterification

First, filter the crude *Jatropha curcas* oil (CJO) to remove impurities. Measure 25 mL of the filtered CJO and heat it above 100°C to eliminate residual water content. Prepare the methoxide mixture by dissolving potassium hydroxide in methanol, according to the specified ratios of methanol-to-oil and potassium hydroxide-to-oil. Heat the methoxide mixture to 50°C and combine it with the preheated CJO.

Proceed with the transesterification reaction using one of the following methods: (1) Used a magnetic stirrer to maintain continuous stirring and heating at 65 °C for 2 hours, or (2) Use an orbital shaker to stir the mixture at room temperature, maintaining a speed of 250 rpm for 2 hours.

After the reaction, allow the mixture to settle for at least 2 hours or overnight. Once phase separation occurs, carefully remove the lower glycerol layer and retain the upper methyl ester fraction. Wash the methyl ester with sterilized or warm water, allow it to stand undisturbed for approximately 30 minutes, then drain the water. Finally, filter the biodiesel to remove any remaining impurities and heat it to 100°C to evaporate residual moisture, resulting in purified biodiesel.

2.4. Two-Step Transesterification

2.4.1 Acid Catalyzed Esterification (Step 1)

To minimize the free fatty acid (FFA) content in the CJO prior to base-catalyzed transesterification, begin by filtering the CJO to remove impurities. Measure 25 mL of the filtered oil and heat it to above 100°C to remove residual water. Sulfuric acid solution in methanol was porepared according to the specified methanol-to-oil and catalyst-to-oil ratios and heat the mixture to 50°C. Add the heated acid-alcohol solution to the preheated oil and allow the esterification reaction to proceed for 1 hour using a magnetic stirrer at 60°C.

After the reaction, let the mixture settle for 1 hour. Remove the methanol-water layer, then wash the remaining oil with sterilized or warm water. Allow the mixture to stand undisturbed for approximately 30 minutes, then separate and drain the aqueous layer. Finally, heat the treated oil to 100°C to eliminate any residual moisture, preparing it for the subsequent transesterification step.

2.4.1 Base Catalyzed Transesterification (Step 2)

To determine the optimal conditions for biodiesel conversion, investigate the effect of varying catalyst-to-oil and methanol-to-oil ratios. Begin by heating the oily product obtained from Step 1 to 50°C, ensuring it forms a clear fluid. Separately, prepare the methoxide mixture by dissolving potassium hydroxide in methanol and heating the solution to 50°C. Add the methoxide to the preheated oil and initiate the transesterification reaction using one of the following methods: (1) use a magnetic stirrer to simultaneously stir and heat and stir the mixture at 65°C for 2 hours, or (2) use an orbital shaker to agitate the mixture at 250 rpm for 2 hours at room temperature.

After the reaction, allow the mixture to settle overnight. Once phase separation occurs, carefully remove the lower glycerol layer followed by the upper methyl ester (biodiesel) layer. Wash the methyl ester with sterilized or warm water and allow it settle for approximately 30 minutes. Drain the water layer, filter the biodiesel to remove any remaining impurities, and heat it to 100°C to eliminate any residual moisture, resulting in purified biodiesel.

Repeat these procedures using different reaction durations (1 hour, 3 hours, and 4 hours) and evaluate the performance of alternative catalysts, such as sodium hydroxide and calcium carbonate (as a solid catalyst).

2.5 Properties Analysis of Jatropha Biodiesel

Analyze the psychochemical properties of the produced biodiesel using appropriate analytical instruments, including Fourier Transform Infrared Spectroscopy (FT-IR), a density meter, a bomb calorimeter, and a flash point analyzer. These instruments are employed to assess fuel characteristics such as functional group presence, density, calorific value, and flash point, respectively. Additionally, evaluate the performance of a diesel engine operating on various blends of *Jatropha curcas* biodiesel and conventional mineral diesel.

3. RESULT AND DISCUSSION

The titration was performed using a 0.1M KOH solution and repeated three times to obtain an average FFA value, thereby minimizing parallax and procedural errors. The average FFA value for CJO was determined to be 29.55, as presented in Table 1.

Table 1: FFA value for CJO.

Trial	W (g)	V (ml)	M (mol)	Acid value
First	4.387	22.9	0.1	29.28
Second	5.053	26.7	0.1	29.64
Third	6.264	33.2	0.1	29.73

3.1. One-Step Transesterification

The one step transesterification method resulted in a very yield of *Jatropha curcas* biodiesel (JB) from crude oil. This poor yield is primarily attributed to the high FFA content in the CJO, which was approximately 29%. The reaction between the FFAs and the alkali catalyst leads to the formation of soap, causing emulsification and phase separation challenges during the transesterification process. As a result, the one-step method is unsuitable for effective JB production. To enhance the conversion efficiency and maximize biodiesel yield, the FFA content in CJO was reduced through a two-step transesterification process (Jaliliannosrat et al., 2013).

3.2. Two-Step Transesterification

The two-step transesterification method yielded a very low amount of JB from crude oil. This poor yield is primarily attributed to the high FFA content in the CJO, which was approximately 29%. The reaction between FFAs and the alkaline catalyst results in soap formation, leading to significant emulsification and phase separation issues during the transesterification process. Consequently, the two-step method is considered inadequate for efficient JB production.

In addition to FFA content, several other factors can influence biodiesel yield, including reaction temperature and pressure, oil type and source, and the stirring method employed during processing (Mohiddin et al., 2018).

3.3. Effect of Catalyst to Oil Ratio

Figure 1 illustrates the acid value of the ester following the acid-catalyzed esterification process (step 1) at varying catalyst-to-oil ratios. The results show that the FFA concentration in CJO was successfully reduced to below 4% after esterification. The optimal catalyst-to-oil ratio for Step 1 was determined to be 0.02:1, which lowered the acid value to as little as 1.02%.

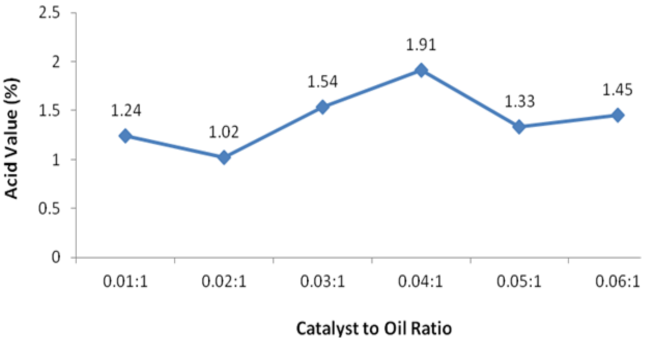


Figure 1: Effect of Catalyst to Oil Ratio on Acid Value for Step 1.

Figure 2 presents the biodiesel yield achieved during the base-catalyzed transesterification process (Step 2) using KOH as a catalyst at varying catalyst-to-oil ratios. The highest yield of 81% was obtained at a catalyst-to-oil ratio of 0.03:1. Increasing the catalyst concentration beyond this point did not result in significant improvement in biodiesel conversion.

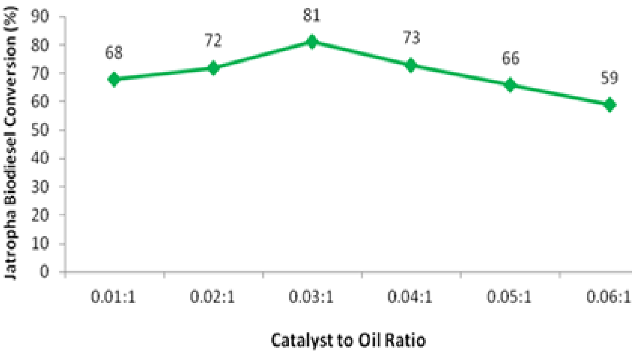


Figure 2: Effect of Catalyst to Oil Ratio on Biodiesel Yield for Step 2 (KOH).

Figure 3 compares biodiesel yield at various sodium hydroxide (NaOH)-to-oil ratios. The optimal NaOH-to-oil ratio of 0.03:1 yielded the highest biodiesel conversion rate at 84%. Overall, NaOH was more effective than KOH in achieving higher concentration rates across different catalyst concentrations.

Despite this, KOH is often preferred over NaOH in biodiesel production due to the softer texture of its by-product, potassium soap, which is easier to handle than sodium soap (Abdullah et al., 2017).

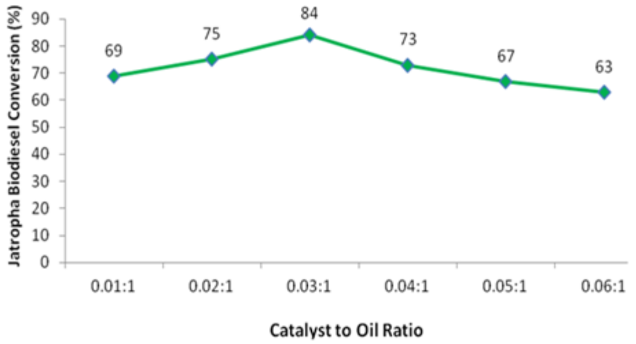


Figure 3: Effect of Catalyst to Oil Ratio on Biodiesel Yield for Step 2 (NaOH).

3.4. The Effect of Methanol to Oil Ratio

Figure 4 presents the effect of varying methanol-to-oil ratios on ester yield during the acid-catalyzed esterification process (Step 1). The results indicate that the optimal methanol-to-oil ratio is 1:1, achieving a maximum ester yield of 96%. As the methanol increases beyond this ratio, ester yield declines. This suggests that an excess of methanol adversely affect ester formation during acid esterification. Therefore, using excessive methanol is both inefficient and economically unfavourable, as cost control is critical for the sustainability of biodiesel production (Harreh et. al., 2018).

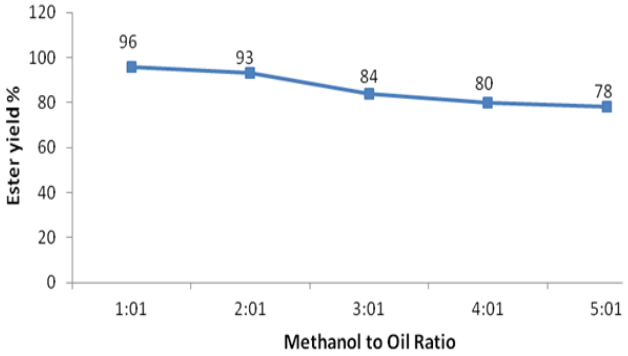


Figure 4: Effect of Methanol to Oil Ratio on Esther Yield for Step 1.

Figure 5 illustrates the influence of methanol-to-oil ratios on biodiesel yield during the base-catalyzed transesterification process using KOH as the catalyst. The biodiesel yield increases progressively with higher methanol-to-oil ratios, peaking at a 5:1 ratio with a conversion rate of 78%. This ratio is considered optimal for maximizing yield under KOH catalysis. Beyond this point, further increases in methanol concentration do not significantly enhance conversion efficiency.

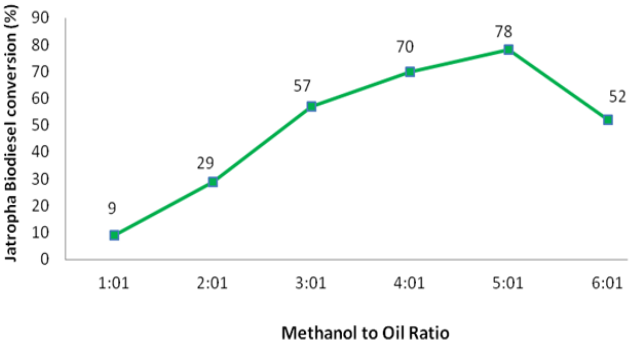


Figure 5: Effect of Methanol to Oil Ratio on Biodiesel Yield for Step 2 (KOH).

Figure 6 shows the effect of methanol-to-oil ratios on biodiesel yield during the base-catalyzed transesterification process using NaOH. The trend is similar to that observed with KOH; however, the maximum conversion rate achieved with NaOH is higher, reaching 82%. These findings indicate that NaOH provides superior catalytic performance compared to KOH, resulting in improved biodiesel yield across the tested methanol-to-oil ratios.

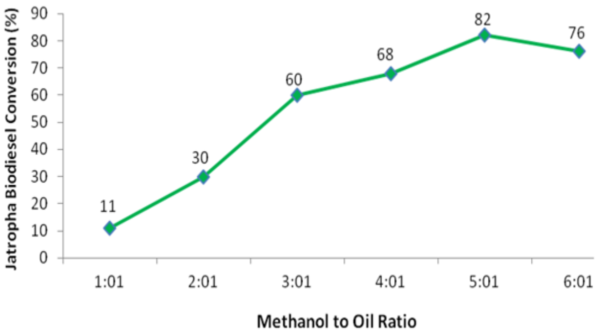


Figure 6: Effect of Methanol to Oil Ratio on Biodiesel Yield for Step 2 (NaOH).

3.5. The Effect of Methanol to Reaction Time

Reaction time refers to the duration required for both acid esterification and base transesterification processes to take place. Figure 7 illustrates the effect of reaction time on ester yield during the acid-catalyzed esterification stage in (Step 1). The results indicate that, the optimal reaction time is 1 hour. Extending the reaction time beyond this duration does not enhance ester yield, as esterification is a reversible reaction. Prolonged reaction times may lead to reverse reactions, converting esters back into FFA to crude oil, thereby reducing the overall ester yield (Mohiddin et. al., 2018).

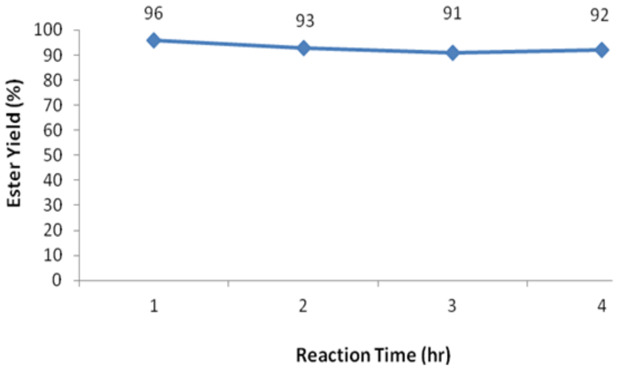


Figure 7: Effect of Reaction Time against Esther Yield for Step 1.

Figure 8 show the impact of reaction time on biodiesel yield during the base-catalyzed transesterification process. A 1-hour reaction time results in a 70% biodiesel yield, while extending the reaction to 2 hours increases the yield to 82%. However, further increasing the reaction time beyond 2 hours does not lead to significant yield improvement and instead contributes to higher energy consumption, which may increase production costs. Therefore, a reaction time of 2 hours is considered optimal for maximizing biodiesel yield while maintaining process efficiency.

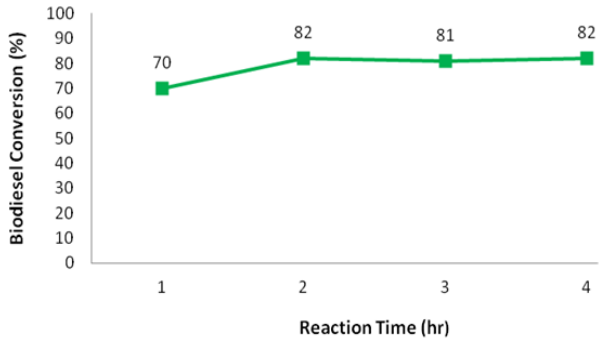


Figure 8: Effect of Reaction Time against Biodiesel Production.

3.6. The Impact of Equipment Type on Biodiesel Production

In the production of JB, two types of equipment are commonly employed for the catalyzed transesterification process: a magnetic stirrer with heating capability and an orbital shaker. Figure 9 illustrates the impact of equipment type on biodiesel conversion efficiency. The result demonstrate that the orbital shaker yields a significantly higher biodiesel conversion rate compared to the magnetic stirrer.

Specifically, the orbital shaker achieved an average biodiesel yield of 80.33%, whereas the magnetic stirrer produced a yield of 69.33%. The superior performance of the orbital shaker is attributed to its ability to provide more uniform and vigorous mixing, which enhances mass transfer and improves the reaction environment. In contrast, the magnetic stirrer's limited mixing capacity leads to incomplete conversion and reduced yield.

Therefore, the orbital shaker is the preferred apparatus for biodiesel conversion, as it ensures higher conversion efficiency under the same reaction conditions.

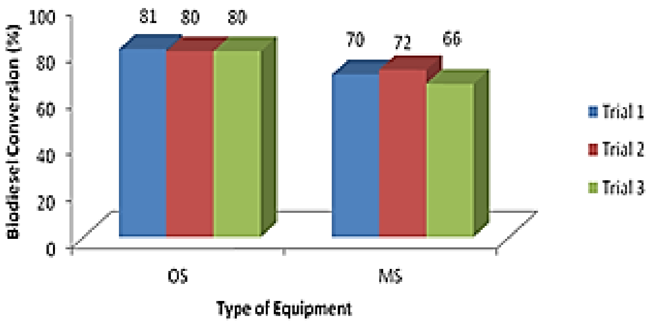


Figure 9: Biodiesel Conversion by Different Type of Equipment Used.

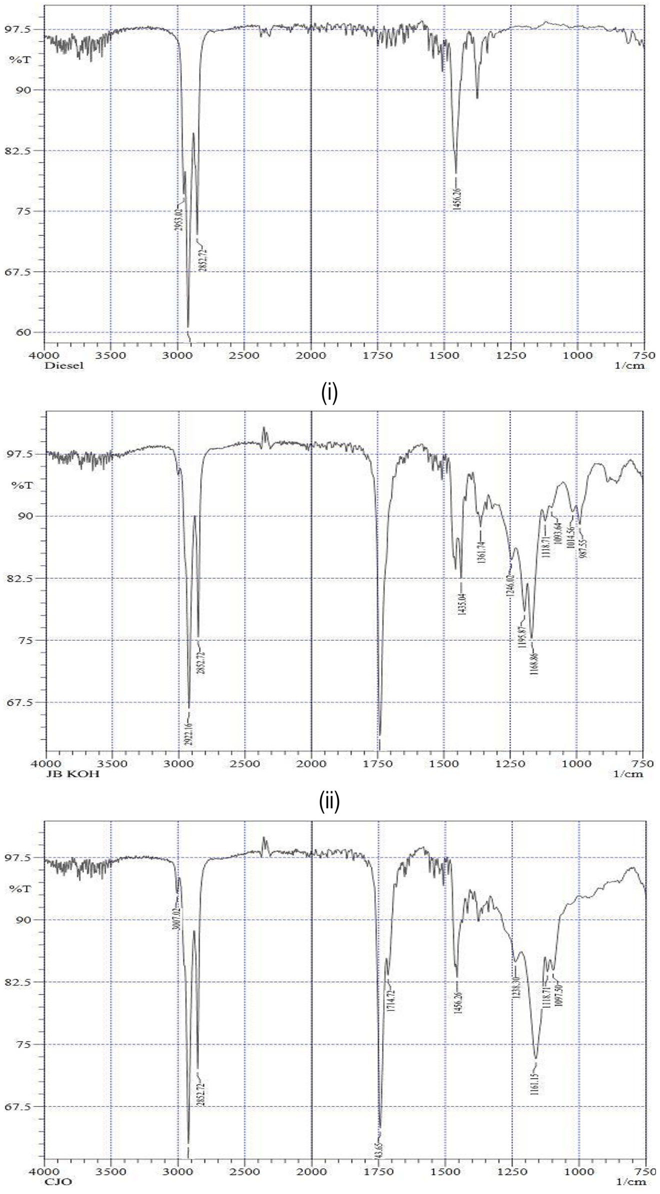
3.7. Analysis of Jatropha Biodiesel Properties

3.7.1 Fourier Transform Infrared Spectrometer (FT-IR) Examination

Figure 10 presents the FT-IR spectra for JB, CJO, and conventional mineral diesel, within the wavenumber range of 750 cm⁻¹ to 4000 cm⁻¹. The FT-IR spectra for JB samples– regardless of the catalyst used (KOH, NaOH, or $CaCO_3$)–exhibit similar patterns.

A notable distinction between the JB and mineral diesel spectrum is the presence of a strong absorption peak at 1741 cm⁻¹ in the JB spectrum, corresponding to the ester carbonyl (C=O) stretching vibration, which is characteristics of methyl esters or aldehyde group (Hanafi et al., 2016). This peak serves as a key identifier of JB or fatty acid methyl esters (FAME) and is absent in mineral diesel, which lacks ester carbonyl functional groups.

Additionally, JB shows distinct absorption bands in the region of approximately 1000 cm⁻¹ to 1320 cm⁻¹, corresponding to carbon-oxygen (C-O) stretching vibrations. These peaks are indicative of ester linkages, further confirming successful transesterification and the formation of biodiesel.



(i)

(ii)

(iii)

Figure 10: FT-IR Spectrum for (i) Mineral Diesel, (ii) Jatropha Biodiesel, (iii) Crude Jatropha Oil.

3.7.2 Calorific Value

Table 2 presents the calorific values of JB, CJO, and mineral diesel, measured using a bomb calorimeter (Model: Parr 6400). Each sample was tested in triplicate to ensure measurement accuracy and reproducibility.

According to the data in Table 2, mineral diesel exhibits the highest calorific value at 44.8025 MJ/kg, followed by CJO at 38.5271 MJ/kg, and JB with the lowest at 35.2275 MJ/kg. The lower calorific value of JB compared to mineral diesel is primarily due to the latter's higher carbon content. Mineral diesel is composed mainly of straight and branced-chain alkanes containing 8–30 carbon atoms, whereas JB consists of long methyl ester chains.

Despite its lower energy density, JB contains oxygen within its molecular structure due to the presence of ester functional groups. This oxygen content enhances combustion efficiency in diesel engine, enabling complete fuel oxidation and partially offsetting the lower calorific value of JB (Mahmudul et al., 2017).

Table 2: Result of Bomb Calorimeter Analysis.

Specimen	Trial 1 (MJ/kg)	Trial 2 (MJ/kg)	Trial 3 (MJ/kg)	Average (MJ/kg)
Diesel	44.8652	44.5689	44.9734	44.8025
CJO	38.2437	38.3588	38.9787	38.5271
JB	34.6777	35.3315	35.6842	35.2275

3.7.3 Density

Table 3 presents the results of the density analysis conducted using an Anton Paar Portable Density Meter (Model: DM 35). According to the data, CJO exhibited the highest density among the three samples, followed by JB and mineral diesel. The measured density values were 915 kg/m³, for CJO, 915 kg/m³ for JB, and 841 kg/m³ for mineral diesel are 898 kg/m³.

Density is a critical parameter in biodiesel production, as it directly influences engine performance by affecting the air-fuel ratio. In diesel engines, fuel density determines the mass of fuel injected into the combustion chamber per unit volume. A higher-density fuel contains more mass in the same volume, potentially altering combustion characteristics and power output.

The JB produced in this study demonstrated a density of 898 kg/m³, which falls within the acceptable range of 860–900 kg/m³ specified by ASTM D-6751 for biodiesel fuels (Mofijur et al., 2012). Therefore, the density of JB suggests that its performance in diesel engines is expected to be comparable to that of conventional mineral diesel

Table 3: Density of diesel, CJO & JB.

Specimen	Density (kg/m³)
Diesel	841
CJO	915
JB	898

3.7.4 Flash Point

Table 4 presents the flash point results obtained using the Seta Multiflash Automatic Flash Point (Model: 34000-0). Each measurement was performed using a sample volume of 70-80 mL.

According to the data in Table 4, the flash point of JB is 165 °C, which is higher than that of mineral diesel. The flash point is defined as the lowest temperature at which vapors of a combustible liquid can ignite in the presence of air.

A higher flash point indicates improved safety during storage, transportation, and handling. Therefore, the relatively high flash point of JB suggests that it poses a lower fire hazard compared to mineral diesel, making it a safer and potentially more cost-effective alternative in fuel logistics and supply chains.

Table 4: Flash Point of Diesel, CJO & JB.

Specimen	Flash Point (°C)
Diesel	75
CJO	190
JB	165

3.7.5 Diesel Engine Performance with Jatropha Biodiesel Blends

For this study, blends of JB and mineral diesel were prepared in the ratios of B0, B10, B20, B30, B40, and B50, and tested in a single-cylinder diesel engine. Each test was conducted using 20 mL of the respective fuel blend under a constant load of 120 N. To ensure accuracy and reproducibility, the experiments were repeated four times for each blend.

One key parameter assessed was fuel consumption rate, which reflects the quantity of fuel consumed to operate the engine over time. A lower fuel consumption rate indicates higher fuel efficiency. As shown in Figure 11, all JB blends exhibit higher fuel consumption rates than pure diesel (B0), primarily due to lower calorific value of JB, which requires greater fuel volume to generate equivalent energy output (Buyukkaya et al., 2010). Among the JB blends, B20 demonstrated the lowest fuel consumption rate, although still slightly higher than B0. This suggests that B20 is the most fuel-efficient among the biodiesel blends tested.

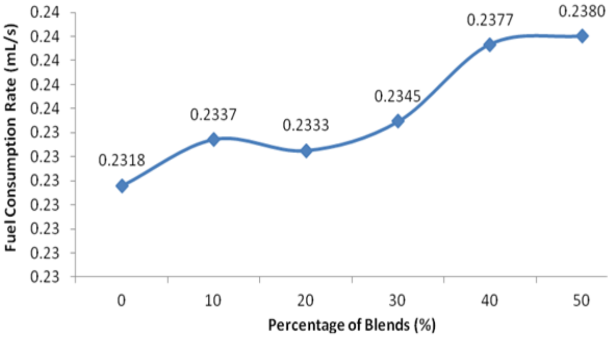


Figure 11: Fuel Consumption Rate of JB Blends.

Figure 12 illustrates the specific fuel consumptions (SFC) for each blend. SFC, defined as the amount of fuel consumed per unit of power output (mL/kW), was observed to increase gradually from B0 to B50. The highest SFC was recorded for B50 at 18.1967 mL/kW. Mineral diesel exhibited the lowest SFC due to its superior energy content. However, the overall variation in SFC across all blends was minimal, with a difference of only 0.822 mL/kW between the highest and lowest values.

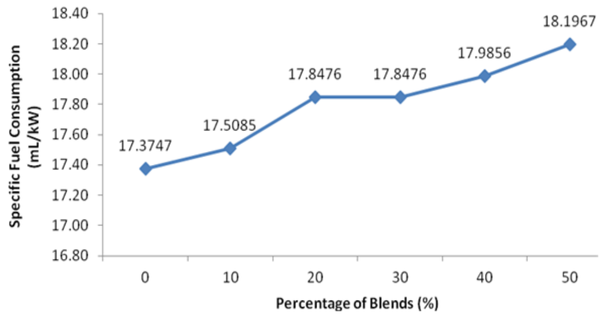


Figure 12: Specific Fuel Consumption of JB Blends.

Brake horsepower (BHP), which represents the engine's effective power output, was also evaluated. As shown in Figure 13, BHP generally declined with increasing JB content in the blend. However, an exception was observed at B20, which produced the highest BHP among all biodiesel blends at 28.3456 kW. Although this marginally lower than the BHP for pure diesel (B0), recorded at 28.3534 kW, the difference is negligible (0.0078 kW), indicating that B20 offers near-equivalent engine power.

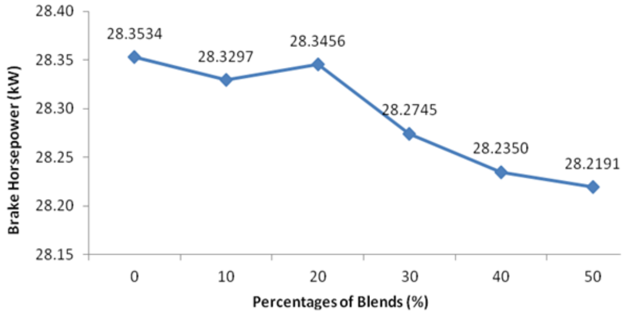


Figure 13: Brake Horsepower of JB Blends.

Mechanical efficiency, which reflects the proportion of input energy successfully converted into mechanical work, was analyzed and is presented in Figure 14. B20 exhibited the highest mechanical efficiency among JB blends, achieving 49.04%, which is nearly identical to the efficiency of mineral diesel (49.05%). Beyond B20, mechanical efficiency declined with increasing JB proportion. These findings support the conclusion that B20 is the optimal blend, offering a balanced performance in terms of fuel economy, power output, and efficiency.

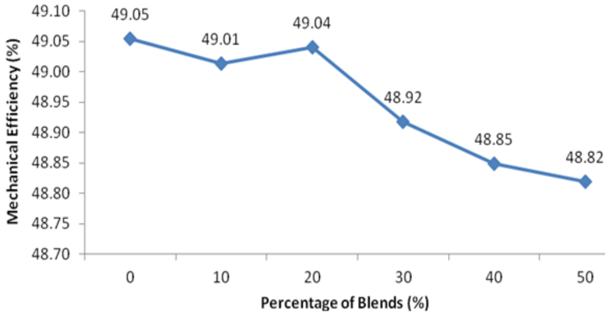


Figure 14: Mechanical Efficiency of Diesel Engine Across Different JB Blends.

4. CONCLUSION

Transesterification remains as the most effective and widely adopted method for biodiesel production. This study evaluated both one-step and two-step transesterification method for converting CJO into JB. The results confirmed that the two-step transesterification method is more suitable for CJO, primarily due to its high initial FFA content. Effective JB conversion requires reducing the FFA content below 4%, which is achieved through an acid-catalyzed esterification pre-treatment step, significantly improving biodiesel yield in the subsequent base-catalyzed transesterification.

The optimal process conditions identified for acid esterification (Step 1) include a catalyst-to-oil ratio of 0.02:1, a methanol-to-oil ratio of 1:1, and a reaction time of one hour. In the base transesterification step (Step 2), the best results were obtained using NaOH as the catalyst at a catalyst-to-oil ratio of 0.03:1, a methanol-to-oil ratio of 5:1, and reaction time of two hours. Additionally, using an orbital shaker proved more effective than a magnetic stirrer, yielding better mixing and reaction efficiency. Under these optimized conditions, the maximum JB yield achieved was 84%.

FT-IR spectral analysis revealed a distinct absorption peak at 1741 cm^{-1} in the JB, corresponding to the ester carbonyl bond (C=O), which is absent in mineral diesel. This confirms successful transesterification and differentiates JB from fossil-based diesel.

In terms of fuel properties, JB exhibited a calorific value of 35.2275 MJ/kg–lower than mineral diesel and CJO due to its molecular composition. However, the presence of oxygenated compounds in JB enhances combustion effiency. JB demonstrated a density of 898 kg/m³, which falls within ASTM D6751 standards and is intermediate between the densities of CJO and mineral diesel. Additionally, JB showed a significantly higher flash point (165°C), indicating superior safety in storage and handling.

Engine performance test conducted with JB blends (B0 to B50) identified B20 as the optimal blend. It delivered the lowest fuel consumption rate, the highest brake horsepower (28.3456 kW) among biodiesel blends, and a mechanical efficiency of 49.04% closely matching mineral diesel. Although SFC increased with higher JB content, the performance of B20 was nearly equivalent to that mineral diesel (B0), confirming its suitability for real-world diesel engine applications.

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