

Synthesis and Physicochemical Characterization of Castor Oil Methyl Ester

Nirmala Puteri Batari^a, Yulfi Zetra^{*a}, R.Y Perry Burhan^a, Talitha Fitra Firdhausya^a, Yunita Alfiyati Firdausa^a, Rizka Berliana Putri^a

^a Departement of Chemistry, FSAD, Institut Teknologi Sepuluh Nopember, Sukolilo, Surabaya, 60111

INFO ARTIKEL

Received 27 September 2025

Accepted 20 October 2025

Key word:

Biodiesel

Castor Oil

COME

Characterization

Transesterification

ABSTRACT

The increasing consumption of biodiesel has led to the continued development of biodiesel production using oils that do not compete with food, for example castor oil. This study aims to synthesize and characterize castor oil methyl ester (COME) as biodiesel. The FFA of castor oil is 0.66%, so that a transesterification reaction with methanol using a KOH catalyst can be carried out. The reaction was characterized by Thin Layer Chromatography (TLC) and Gas Chromatography-Mass Spectrometry (GCMS). The highest content of COME is methyl ricinoleate at 65.481%. Followed by FFA at 0.4%, a cloud point of -9°C, a pour point of -18°C, and a density at 40°C of 887.2 kg/m³ which is in accordance with SNI. The data serve as an update to complement the quality parameters of castor oil biodiesel.

*e-mail: yzetra@its.ac.id

Introduction

Castor oil (*Ricinus communis*) is a non-edible oil containing 85-90% ricinoleic acid. Ricinoleic acid has hydroxyl groups and double bonds that can be further synthesized to produce more valuable compounds, such as biodiesel [1]. Oil production from castor seeds is the highest than from other oilseeds (40–45%), does not compete with food as it belongs to non edible, and can be grown in marginal land with easy care. this leads to castor oil being optimized for more cost-efficient and more environmentally friendly production of biodiesel [2], [3]. Biodiesel-derived castor oil is more environmentally friendly because it is sulfur-free, aromatic compound-free, and produces cleaner combustion [2].

Biodiesel is a fatty acid methyl ester (FAME). FAME is made through the process of transesterification of triglyceride-containing vegetable oils with alcohols such as methanol,

yielding FAME as the main product and glycerol as the by-product [4]. This reaction is catalyzed by a strong base and a stoichiometric oil : alcohol ratio between 1:6 to 1:9 [5], [6]. In the transesterification reaction, the oil-to-alcohol ratio typically ranges from 1:6 to 1:9 [6].

The demand for biodiesel in Indonesia has grown rapidly, reaching the government's set quota of 16.62 million kiloliters for 2025 [7]. This development is driven by the Decree of the Minister of Energy and Mineral Resources No. 341.K/EK.01/MEM.E/2024 on blending biodiesel with petroleum-based diesel (e.g., B30, B35, B40) to meet various performance and environmental standards. Biodiesel in Indonesia is predominantly composed of fatty acid methyl esters (FAME) derived from palm oil. Such demand must comply with the applicable standards.

Biodiesel standards are regulated under the Quality Standard (Specification) of Biofuel

Type Biodiesel as an Alternative Fuel Marketed Domestically issued by the Ministry of Energy and Mineral Resources of the Republic of Indonesia in 2019. These standards cover acid value as well as physical properties such as cloud point, pour point, and density. The maximum limit for the acid value is 0.5 mgKOH/g, the cloud point of biodiesel must not exceed 18 °C, the pour point must not exceed 15 °C, and the standard density range for biodiesel is 850–890 kg/m³.

FAME derived from palm oil tends to have high cloud and pour points. Research conducted by Joelianingsih et al. (2019), reported that palm oil FAME has a cloud point ranging from 13,2 °C to 17,4 °C. This relatively high cloud point is attributed to the high content of saturated fats (particularly palmitic acid and stearic acid) in palm oil FAME [8]. The pour point of methyl FAME from palm oil ranges between 5,2 °C and 9 °C [9]. Its pour point is significantly higher compared to FAME from more unsaturated oils, thereby limiting its flow performance at low temperatures for use in colder climates [9]. When FAME is at low temperatures, it forms wax crystals that aggregate with each other due to van der Waals forces [10]. Saturated FAME has straight, unbranched chains that can pack closely together. This tight packing enhances London dispersion forces (van der Waals), resulting in stronger intermolecular attractions [11]. Stronger van der Waals interactions in saturated FAME reduce flow properties at low temperatures, as reflected by the increased cloud point and pour point [11].

Previous studies on biodiesel from castor oil have examined in detail the unique chemical structure of ricinoleic acid and the resulting fuel properties. However, key quality parameters of castor oil biodiesel, such as acid value, as well as comprehensive comparisons of cloud point, pour point, and density with literature data, remain limited. Therefore, in this study, an investigation was carried out on the transesterification of castor oil into Castor Oil Methyl Ester (COME), with a focus on reaction mechanisms, Gas Chromatography–Mass Spectrometry (GC–MS) profiles, acid value, and physicochemical properties, in order to provide

deeper insights into its potential as a sustainable biodiesel feedstock.

Materials and Methods

Materials

Commercial castor oil was obtained from a local supplier in Indonesia, methanol (≥99.0%; Merck), potassium hydroxide (≥99.0%; Merck), distilled water, anhydrous Na₂SO₄ (Merck), phenolphthalein (PP) indicator, propanol (≥99.0%; Merck), universal indicator, silica gel TLC 60 F254, and Whatman No. 42 filter paper.

Methods

Acid Value Test

The acid value was measured twice: first for castor oil before transesterification, and second for COME obtained after transesterification. Approximately ±1.00 g of castor oil was dissolved in 50 mL of isopropanol and 0.8 mL of 1% phenolphthalein (PP) indicator was added. The solution was then titrated with 0.1 N potassium hydroxide (KOH), standardized with oxalic acid, until a faint pink endpoint was reached. The titration was carried out three times, and the volume of KOH was recorded. The volume of KOH was then used to calculate the acid number and FFA values in equations (1) and (2). The acid number in COME was also carried out in the same way.

$$\text{Acid Value} = \frac{V_{\text{titrant}} \times M_{\text{titrant}} \times Mr_{\text{KOH}}}{\text{Sample Weight}} \quad (\text{mgKOH/g}) \quad (1)$$

$$\% \text{Free Fatty Acid (FFA)} \approx \frac{\text{Acid Value}}{2} \quad (2)$$

[12]

Synthesis of Castor Oil Methyl Ester (COME)

Castor oil which has a %FFA below 2-2.5% or below 4-5 mgKOH/g, can be used for COME synthesis [12]. Transesterification of castor oil into COME was adapted from the research of Zetra et al. (2023). Castor oil was heated at 60 °C. KOH solution (1% w/w oil) in methanol with a mole ratio of 1:6 (oil:methanol) was mixed with castor oil when the oil temperature reached 60 °C. The reaction was carried out for two hours at 60 °C and 500 rpm [13]. The reaction was monitored using Thin Layer Chromatography (TLC). The eluent used was n-hexane: diethyl ether: acetic acid (16:6:1) [14]. The separated

components can be identified initially based on the Retention Factor (Rf) value, which indicates how far each component moves on the chromatography plate. Rf can be calculated using equation (3) based on the figure 1.

$$R_f = \frac{a}{b} \quad (3)$$

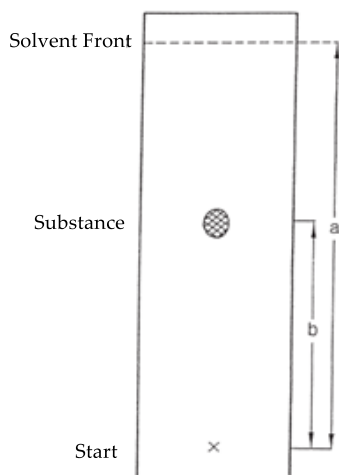


Figure 1. Retention Factor (Rf) of Thin Layer Chromatography (TLC)

After the reaction was complete, the mixture was transferred into a separating funnel and left overnight until two layers separated. Purification was carried out using the Suzihaque (2022) method, where the upper layer was removed and washed with distilled water until the pH was neutral. The remaining water was withdrawn with 10 grams of anhydrous sodium sulfate (Na_2SO_4). The indication that water is completely removed is when the sodium sulfate crystals no longer clump together and remain as free-flowing fine particles.

Analysis of COME Components

The synthesized COME was then analyzed for its composition using Gas Chromatography–Mass Spectrometry (GC–MS) with an Agilent GCMSD5975C equipped with an HP-5MS capillary column (5% phenylmethylpolysiloxane) of dimensions $60 \text{ m} \times 250 \mu\text{m} \times 0.33 \mu\text{m}$, using helium (He) as the carrier gas. The oven operational conditions were set as follows: an initial temperature of 70°C held for 5 minutes, followed by a ramp to 300°C at a rate of $5^\circ\text{C}/\text{min}$, and maintained at 300°C for 19 minutes. The GC–MS data were analyzed using Agilent MSDA software, and the fragmentation patterns were interpreted with reference to literature studies.

Physical Properties Testing of COME

The physical properties of COME analyzed include cloud point, pour point, and density, determined based on ASTM D2500, ASTM D97, and ASTM D4052.

Result and Discussion

Acid Value of Castor Oil

The titration was carried out using castor oil as the titrate and 0.1 N KOH as the titrant, and it was performed three times. The repetition of three trials aimed to estimate errors, thereby making the experimental results more accurate [15]. The results of the repetitions can be seen in Table 1. The acid value is calculated using equation (1) and %FFA is calculated using equation (2). The average acid value of the castor oil used was 1.33 mgKOH/g with a free fatty acid (FFA) content of 0.66% .

Table 1. Acid Value and %FFA of Castor Oil

Repetition	Mass of oil (g)	Volume of KOH (mL)	Acid Value (mgKOH/g) according to Eq. (1)	FFA (%) according to Eq. (2)
1	1,0281	0,24	1,30	0,65
2	1,0106	0,25	1,38	0,69
3	1,0357	0,24	1,29	0,64
Average			1,33	0,66

The principle of the titration is the neutralization of free fatty acids in castor oil by

KOH, which is based on an acid–base reaction. The acid value content in the oil needs to be determined prior to the transesterification

reaction because it can affect the efficiency and yield of the transesterification process [16]. A high acid value can inhibit the transesterification process using strong base catalysts because it tends to promote soap formation. Soap is produced through the saponification reaction, namely the reaction between FFA and a strong base to form soap. Instead of proceeding with transesterification, high FFA levels trigger saponification. Therefore, oils or fats with FFA contents higher than 2–2.5% will encounter difficulties during the transesterification reaction [12]. The saponification reaction is shown in the reaction mechanism in Figure 2.

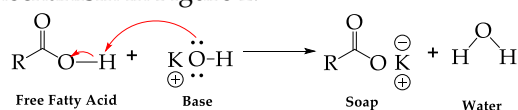


Figure 2. Saponification Reaction Between Free Fatty Acid (FFA) and KOH Base

Transesterification of COME

Castor oil was first heated in a three-neck flask at 60 °C. At this temperature, the reaction achieves high conversion and yield, generally in the range of 83–89% for biodiesel [17]. At low

temperatures, the reaction tends to be incomplete and results in lower yield, while at high temperatures, efficiency may decrease due to increased methanol evaporation and catalyst instability [18].

Potassium hydroxide was first dissolved in methanol before being mixed with the oil. By dissolving potassium hydroxide in methanol beforehand, potassium methoxide is formed, which significantly enhances the catalytic efficiency of the reaction compared to adding solid potassium hydroxide directly into the oil [19]. Strong bases such as potassium hydroxide can deprotonate methanol by removing a proton from methanol and forming potassium methoxide which is nucleophilic and more basic than methanol [20]. The methoxide anion (CH_3O^-) acts as a nucleophile and attacks the carbon atom in the electrophilic carbonyl group of triglycerides, producing a tetrahedral intermediate. This intermediate then releases the diglyceride and forms COME. This also occurs in diglycerides and monoglycerides. Thus, one triglyceride produces three COME and one glycerol [21]. The mechanism reaction can be seen in Figure 3.

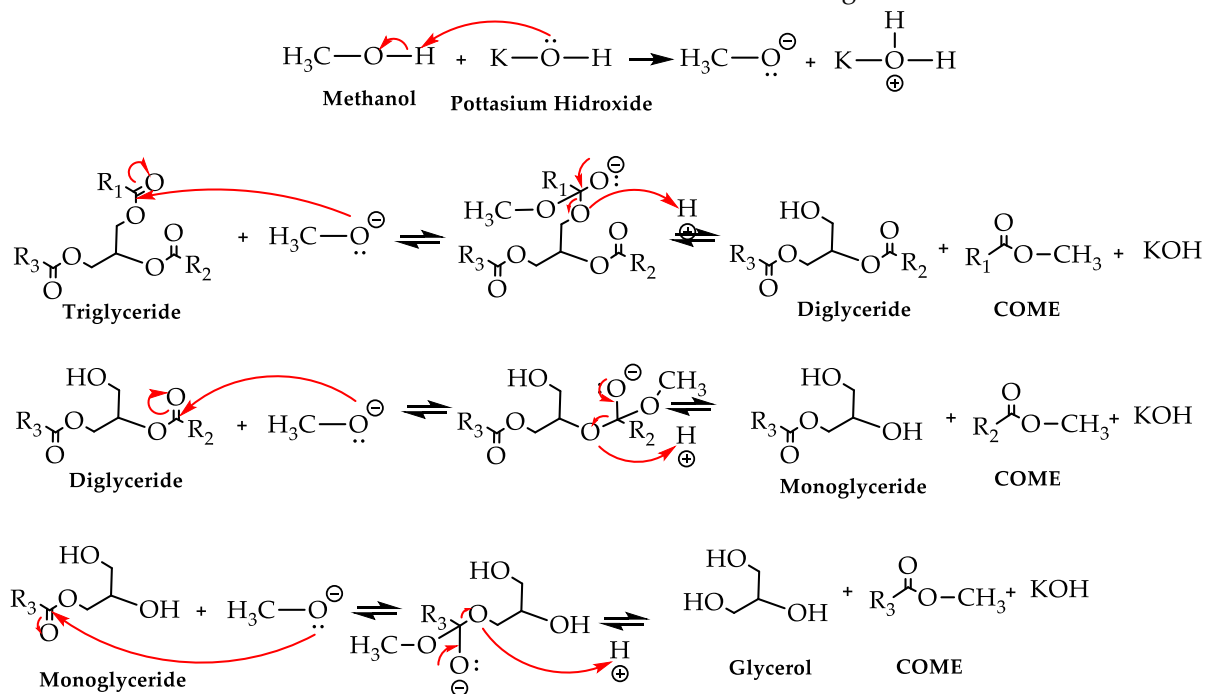


Figure 3. Transesterification Reaction Mechanism of Triglycerides with Methanol Using Potassium Hydroxide as Catalyst

The reaction was monitored using Thin Layer Chromatography (TLC). At 120 minutes (two hours), there were no more traces of the

starting material in the product (Figure 4). The R_f of each substance can be seen in table 2. This is in line with the research of Ramezani et al.

(2010), where the transesterification of castor oil at 60 °C was completed at 120 minutes [22].

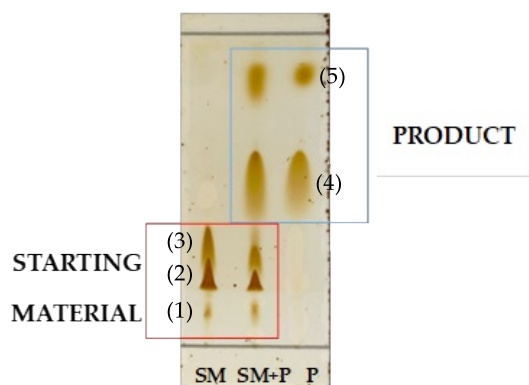


Figure 4. Spots on TLC. MA = Starting Material; MA + P = Starting Material plus Product; P = Product.

Table 2. Rf for Each Substance According to TLC

Substance	a (cm)	b (cm)	Rf
(1)	4	0,3	13,33
(2)	4	0,8	5,00
(3)	4	1,3	3,07
(4)	4	2,3	1,74
(5)	4	3,5	1,14

Components of COME

Table 3. Methyl Ester Components in COME and Their Abundances

Peak	Methyl Ester	Molecule Mass	Abundance (%)
A	Palmitate	270	12,440
B	Heptadecanoate	284	0,342
C	Linoleate	294	0,342
D	Oleate	296	6,260
E	Stearate	298	12,601
F	Ricinoleate	312	65,481
H	Arachidate	326	0,885

Of the eight peaks observed, three were the most prominent. Peak A, at a retention time of 29.720 minutes, with an area of 99,870,059 and a relative abundance of 12.440%, was identified as

Thin Layer Chromatography (TLC) was used to verify the formation of the product and to ensure that the starting material had completely reacted, as shown in Figure 4. Subsequently, the obtained product was analyzed using Gas Chromatography–Mass Spectrometry (GC–MS) to identify its components and determine the relative abundance of each component. The Total Ion Chromatogram (TIC) results are presented in Figure 5.

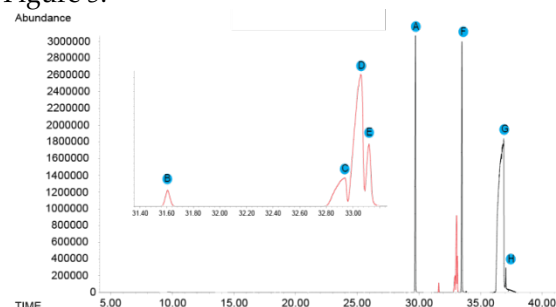


Figure 5. Total Ion Chromatogram (TIC)

Gas chromatography produced a Total Ion Chromatogram (TIC) as shown in Figure 5, where peaks and retention times were detected. The mass spectrometer (MS) then provided additional information on the molecular masses and characteristic fragments [23]. From the analysis results, the identified COME components and their abundances are summarized in Table 3.

methyl palmitate. Peak F, at a retention time of 33.491 minutes, with an area of 101,157,638 and a relative abundance of 12.601%, was identified as methyl stearate. Peak G, at a retention time of 36.822 minutes, with an area of 513,761,977 and

a relative abundance of 65.481%, was identified as methyl ricinoleate. The mass spectra of methyl palmitate, methyl stearate, and methyl ricinoleate are shown in Figure 6.

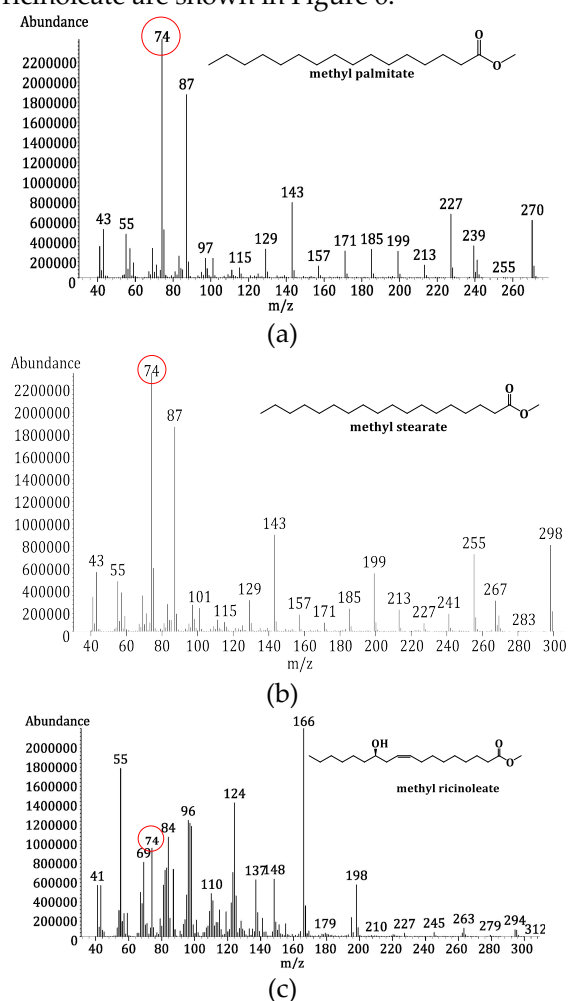


Figure 6. Mass Spectra (MS) of (a) Methyl Palmitate, (b) Methyl Stearate, and (c) Methyl Ricinoleate.

While gas chromatography provides information on retention time and peak intensity, mass spectrometry adds information about molecular mass. This mass data can be used to identify, quantify, and determine the structure and chemical properties of a compounds [23]. Electrons are fired at molecules to produce positively charged fragments. These fragments are unique to each compound and are known as "fingerprints." Therefore, these fragments can be used to identify a compound [23]. The same case in fatty

acid methyl ester, there is a fragment that is characteristic of fatty acid methyl ester, namely a fragment with a molecular ion of m/z 74 [24]. COME is a fatty acid methyl ester, so COME also has a molecular ion fragment m/z 74 (Figure 5). The peak of the m/z 74 molecular ion fragment was obtained from McLafferty rearrangement. McLafferty rearrangement is the transfer process of γ -hydrogen atom into double-bonded atom through β -bond cleavage in a six-membered transition stage [25]. The McLafferty rearrangement of COME can be seen in Figure 7.

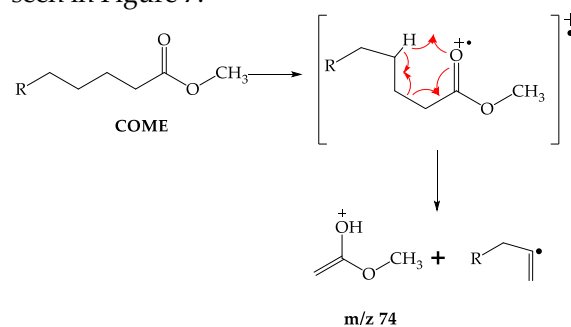


Figure 7. The McLafferty Rearrangement of COME

Physicochemical Properties of COME

Biodiesel's demand in Indonesia tends to be high. The biodiesel market volume surged from 3.7 million kiloliters in 2018 to 13 million kiloliters in 2023, with a compound annual growth rate (CAGR) of 28.2%. During the same period, the market value rose from IDR 40.7 trillion to IDR 139.7 trillion. This market is projected to continue expanding, with estimated revenues reaching USD 2.8 billion in 2025 and USD 7.1 billion in 2031 [26]. This high demand must be accompanied with high quality of biodiesel ora FAME.

The quality of produced FAME was analysed and evaluated based on its physicochemical properties, such as free fatty acid (FFA) content, cloud point, pour point, and the density of COME. The results then compared with the SNI (Indonesian National Standard) for biodiesel and other studies, as presented in Table 4.

Table 4. Physicochemical Properties of COME in This Study Compared with SNI and Other Studies

Physicochemical Properties				
FFA (%)	Cloud Point (°C)	Pour Point (°C)	Density at 40 °C (kg/m ³)	References
0,5	Max, 18	Max, 15	850–890	SNI
0,4	-9	-18	887,2	This Study
-	-15	-	909,8	(Todaka, 2014) [27]
0,3	-	-	920	(Roy et al., 2020) [28]
0,32	-	-	819	(Mamuye and Reshad, 2022) [29]
0,73	-	-20	925,6	(Canoira et al., 2009) [30]

In this study, the %FFA in COME was 0.4%, which means that after transesterification, the %FFA decreased by 0.26%. This is in line with research by Roy et al. (2020) and Mamuye et al. (2022), where castor oil after transesterification became 0.3% and 0.32% [28], [29]. The %FFA in COME meets the %FFA requirements of the Indonesian National Standard (SNI).

The percentage of FFA needs to be considered in biodiesel production because FFA affects the quality, safety, and suitability of biodiesel for diesel engines. The standard of %FFA should not more than 0.5% (SNI, ASTM). The presence of FFA in biodiesel indicates that the oil has not been fully transesterified [31]. Biodiesel containing high levels of FFA is prone to causing engine corrosion, oxidative degradation, and can form soap and cause clogging in filters and injectors. In addition, the presence of FFA causes changes in combustion characteristics, such as exhaust gas temperature, carbon residue, and increases the heating value of biodiesel [31], [32], [33].

The cloud point and pour point of COME were -9 °C and -18 °C, respectively. This is consistent with the findings of Todaka (2014) and Canoira et al. (2010), which reported that the cloud point and pour point of castor oil FAME were below 0 °C. The hydroxyl group in methyl ricinoleate plays an important role in the resulting cloud and pour points. The presence of a polar group, in this case the hydroxyl group, limits the degree of co-crystallization between FAME molecules [34]. Co-crystallization can be limited because the

hydroxyl group hinders van der Waals interactions between FAME molecules.

The density of COME at 40 °C was 887.2 kg/m³, which is still within the limits set by the SNI standard. Other studies, as shown in Table 5, reported the density of castor oil FAME in the range of 819–925.6 kg/m³. A higher number of double bonds (unsaturation) slightly increases density, as the presence of double bonds introduces bends in the chains that allow the molecules to pack somewhat more closely [35]. In this case, the degree of unsaturation in COME is relatively high, as indicated by the abundance of methyl ricinoleate containing a double bond at 65.481%. Consequently, the density of COME tends to be higher, yet it still falls within the SNI specification limits.

Density affects atomization, spray formation in the injectors, and combustion efficiency. The range 850–890 kg/m³ matches diesel engine specifications so biodiesel behaves similarly to petroleum diesel in flow, injection, and burning processes [36]. Low density (below standard) can cause fuel burns too fast or less completely, leading to lower engine efficiency and higher emissions and reduce fuel's lubricating properties, potentially increasing wear on engine components [36]. High density (above standard) can cause dirty smoke, carbon deposits, and engine knocking, injector and filter blockage, increased emissions, and formation of deposits in engines and exhaust systems, harder to pump and may gel, especially at lower temperatures, and sometimes indicates incomplete washing, leading to water in biodiesel, which is harmful to engines [37], [38]. Density of FAME from

palm oil typically range from 860-890 kg/m³ [39], [40]. Density of FAME from soybean oil generally between 882-890 kg/m³ [41]. Density of FAME from coconut oil range from 860-870 kg/m³ [42], [43].

This study just analyzed for four parameters. Which is acid value, cloud point, pour point, and density. Therefore, future studies are recommended to include other parameters such as viscosity, flash point, cetane number, so on to strengthen the validity and completeness of the research findings.

Conclusions

This study discusses the synthesis and characterization of castor oil methyl ester (COME) as a biodiesel feedstock to address the growing demand for biodiesel in Indonesia. Castor oil with an FFA content of 0.66% was converted into methyl esters via transesterification using methanol and KOH as a catalyst (molar ratio 1:6). TLC and GC-MS analyses showed that the main component was methyl ricinoleate, comprising 65.481% of the product. COME exhibited an FFA of 0.4%, a cloud point of -9 °C, a pour point of -18 °C, and a density of 887.2 kg/m³ at 40 °C. All physicochemical parameters complied with the SNI biodiesel standards, indicating that COME has the potential to be used as biodiesel in cold climates and as a blend component in B40 and B50 formulations, and possibly as B100 in the future.

References

- [1] D. Rajan, A. Benesh, and K. M. Nampoothiri, "Biomanufacturing of ricinoleic acid from castor oil using immobilized lipase of *Pseudomonas guariconensis* as biocatalyst," *Biocatal. Agric. Biotechnol.*, vol. 58, no. February, p. 103184, 2024, doi: 10.1016/j.bcab.2024.103184.
- [2] V. R. Patel, G. G. Dumancas, L. C. K. Viswanath, R. Maples, and B. J. J. Subong, "Castor oil: Properties, uses, and optimization of processing parameters in commercial production," *Lipid Insights*, vol. 9, no. 1, pp. 1-12, 2016, doi: 10.4137/LPIS.40233.
- [3] A. Yasyifa, R. Atin, A. Istiani, and H. Anggorowati, "Enhancing Biodiesel Yield from Castor Seed Oil through Co-Solvent-Assisted Transesterification Using n-Hexane," vol. 22, no. 2, pp. 106-112, 2025.
- [4] A. Gautam, "Chemical Engineering and Processing - Process Intensification Optimization and Control of Continuous Biodiesel Production Processes: A Review," *Chem. Eng. Process. - Process Intensif.*, vol. 213, no. April, p. 110323, 2025, doi: 10.1016/j.cep.2025.110323.
- [5] A. Firmansyah, Y. Zetra, R. Y. P. Burhan, D. Prasetyoko, and N. Jamarun, "Synthesis of 2-Hydroxyethyl Esters from Castor Oil as Lubrication Bio-Additive Candidates for Low-Sulfur Fossil Diesel," *Indones. J. Chem.*, vol. 22, no. 3, pp. 845-856, 2022, doi: 10.22146/ijc.73038.
- [6] N. Sajjad *et al.*, "Biodiesel Production from Alkali-Catalyzed Transesterification of Tamarindus indica Seed Oil and Optimization of Process Conditions," *Molecules*, vol. 27, no. 10, pp. 1-15, 2022, doi: 10.3390/molecules27103230.
- [7] UkrAgroConsult, "Indonesia's B50 biofuel mandate could boost palm oil demand by 3m tonnes." Accessed: Aug. 26, 2025. [Online]. Available: <https://ukragroconsult.com/en/news/indonesias-b50-biofuel-mandate-could-boost-palm-oil-demand-by-3m-tonnes/#:~:text=Of the 15.62 million kiloliters allocated>
- [8] J. Joelianingsih, M. Christwardana, and I. S. Purwaningsih, "Prediction of Palm Based Biodiesel Properties Through the Preparation of Empirical Equation," *Int. J. Oil Palm*, vol. 2, no. 1, pp. 12-23, 2019, doi: 10.35876/ijop.v2i1.25.
- [9] S. B. Anistiawan, A. Hasan, and E. Dewi, "Pembuatan Bio - Pelumas dari Fatty Acid Methly Ester (FAME) yang Berbahan Baku Crude Palm Oil (CPO)," *J. Pendidik. dan Teknol. Indones.*, vol. 2, no. 7, pp. 341-347, 2022, doi: 10.52436/1.jpti.199.
- [10] T. Yang *et al.*, "Influence of polar groups

- on the depressive effects of polymethacrylate polymers as cold flow improvers for diesel fuel," *Fuel*, vol. 290, no. January, p. 120035, 2021, doi: 10.1016/j.fuel.2020.120035.
- [11] R. O. Dunn, "Correlating the cloud point of biodiesel with its fatty acid methyl ester composition: Multiple regression analyses and the weighted saturation factor (wSF)," *Fuel*, vol. 300, no. May, p. 120820, 2021, doi: 10.1016/j.fuel.2021.120820.
- [12] M. U. H. Suzihaque, N. Syazwina, H. Alwi, U. K. Ibrahim, S. Abdullah, and N. Haron, "A sustainability study of the processing of kitchen waste as a potential source of biofuel: Biodiesel production from waste cooking oil (WCO)," *Mater. Today Proc.*, vol. 63, pp. S484–S489, 2022, doi: 10.1016/j.matpr.2022.04.526.
- [13] Y. Zetra, R. A. Basit Hariyanto, R. A. Firmansyah, R. Y. P. Burhan, and Pusparatu, "Lubricity Performance of Ethylene Glycol Ester from Soybean Oil as a Lubricity Enhancer Bio-Additive for Low-Sulfur Diesel Fuel," *Malaysian J. Fundam. Appl. Sci.*, vol. 19, no. 4, pp. 481–493, 2023, doi: 10.11113/mjfas.v19n4.2843.
- [14] R. K. Elango, K. Sathiasivan, C. Muthukumaran, V. Thangavelu, M. Rajesh, and K. Tamilarasan, "Transesterification of castor oil for biodiesel production: Process optimization and characterization," *Microchem. J.*, vol. 145, no. October 2018, pp. 1162–1168, 2019, doi: 10.1016/j.microc.2018.12.039.
- [15] D. L. Vaux, F. Fidler, and G. Cumming, "Replicates and repeats-what is the difference and is it significant? A brief discussion of statistics and experimental design," *EMBO Rep.*, vol. 13, no. 4, pp. 291–296, 2012, doi: 10.1038/embor.2012.36.
- [16] G. P. Maniam, H. S. Lim, and N. Mat Hussin, "Effect of Free Fatty Acid on Transesterification of Waste Cooking Oil," *Curr. Sci. Technol.*, vol. 3, no. 1, pp. 57–63, 2023, doi: 10.15282/cst.v3i1.10290.
- [17] O. I.A and E. T. Akhihero, "Effect of Temperature on the transesterification of Animal Fat," *J. Energy Technol. Environ.*, vol. 3, no. 4, pp. 74–82, 2021, doi: <https://doi.org/10.37933/nipes.e/3.4.2021.9>.
- [18] M. Z. Attallah, Y. Agustina, S. Effendy, Y. Bow, and I. Yunanto, "Temperature Effect on the Transesterification Process of Used Cooking Oil with a CaO-MgO Catalyst in the Biodiesel Production," vol. 2, no. 2, pp. 57–61, 2024.
- [19] Y. Yoeswono, T. Triyono, and I. Tahir, "Kinetics of Palm Oil Transesterification in Methanol With Potassium Hydroxide As a Catalyst," *Indones. J. Chem.*, vol. 8, no. 2, pp. 219–225, 2010, doi: 10.22146/ijc.21625.
- [20] Hendriyana, H. Susanto, and Subagjo, "Thermodynamics and kinetics study of CH₃OK preparation from KOH and CH₃OH," *ARPN J. Eng. Appl. Sci.*, vol. 11, no. 16, pp. 9946–9950, 2016.
- [21] M. Tubino, J. G. Rocha, and G. F. Bauerfeldt, "Biodiesel synthesis: A study of the triglyceride methanolysis reaction with alkaline catalysts," *Catal. Commun.*, vol. 75, pp. 6–12, 2016, doi: 10.1016/j.catcom.2015.10.033.
- [22] K. Ramezani, S. Rowshanzamir, and M. H. Eikani, "Castor oil transesterification reaction: A kinetic study and optimization of parameters," *Energy*, vol. 35, no. 10, pp. 4142–4148, 2010, doi: 10.1016/j.energy.2010.06.034.
- [23] H.-J. Hübschmann, *Handbook of GC/MS: Fundamentals and Applications, Second Edition*, 2nd ed., vol. 53, no. 3. Bremen, Germany: WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim, 2009. doi: 10.1016/s0144-8617(02)00204-7.
- [24] K. Tahya, C. Y. Tahya, and H. Kainama, "Transesterifikasi Minyak Ikan Perak (Mene maculata) Dengan Katalis CaO Dari Cangkang Telur Ayam," *Indones. J. Chem. Res.*, vol. 7, no. 1, pp. 69–76, 2019, doi: 10.30598/ijcr.2019.7-can.
- [25] M. Takayama, "Metastable McLafferty rearrangement reaction in the electron impact ionization of stearic acid methyl

- ester," *Int. J. Mass Spectrom. Ion Process.*, vol. 144, no. 3, pp. 199–204, 1995, doi: 10.1016/0168-1176(95)04169-L.
- [26] M. Y. Rachmadiano, "From Fossil to Future: Indonesian's Biodiesel Market Tripled in 5 Years." Accessed: Aug. 26, 2025. [Online]. Available: <https://centralinsight.com/indonesias-biodiesel-market-tripled-in-five-years/>
- [27] M. Todaka, "Reduction of the Cloud Point of Biodiesel by Combination of Various Factors," *Int. J. Chem. Eng. Appl.*, vol. 5, no. 6, pp. 479–482, 2014, doi: 10.7763/ijcea.2014.v5.432.
- [28] T. Roy, S. Sahani, and Y. C. Sharma, "Green synthesis of biodiesel from Ricinus communis oil (castor seed oil) using potassium promoted lanthanum oxide catalyst: kinetic, thermodynamic and environmental studies," *Fuel*, vol. 274, no. April, p. 117644, 2020, doi: 10.1016/j.fuel.2020.117644.
- [29] L. F. Mamuye and A. S. Reshad, "Reactive Extraction for Fatty Acid Methyl Ester Production from Castor Seeds Using a Heterogeneous Base Catalyst: Process Parameter Optimization and Characterization," *ACS Omega*, vol. 7, no. 45, pp. 41559–41574, 2022, doi: 10.1021/acsomega.2c05423.
- [30] L. Canoira, J. García Galeán, R. Alcántara, M. Lapuerta, and R. García-Contreras, "Fatty acid methyl esters (FAMES) from castor oil: Production process assessment and synergistic effects in its properties," *Renew. Energy*, vol. 35, no. 1, pp. 208–217, 2010, doi: 10.1016/j.renene.2009.05.006.
- [31] M. Sarno and M. Iuliano, "Biodiesel production from waste cooking oil," *Green Process. Synth.*, vol. 8, no. 1, pp. 828–836, 2019, doi: 10.1515/gps-2019-0053.
- [32] C. Y. Lin and Y. W. Lin, "Engine Performance of High-Acid Oil-Biodiesel through Supercritical Transesterification," *ACS Omega*, 2023, doi: 10.1021/acsomega.3c06997.
- [33] Y. T. Wang, Z. Fang, and X. X. Yang, "Biodiesel production from high acid value oils with a highly active and stable bifunctional magnetic acid," *Appl. Energy*, vol. 204, pp. 702–714, 2017, doi: 10.1016/j.apenergy.2017.07.060.
- [34] P. Sivakumar, A. Sircar, B. Deka, A. Silviya Anumegalai, P. Suresh Moorthi, and N. Yasvanthrajan, "Flow improvers for assured flow of crude oil in midstream pipeline - A review," *J. Pet. Sci. Eng.*, vol. 164, pp. 24–30, 2018, doi: 10.1016/j.petrol.2018.01.022.
- [35] M. J. Pratas, S. Freitas, M. B. Oliveira, S. C. Monteiro, A. S. Lima, and J. A. P. Coutinho, "Densities and viscosities of fatty acid methyl and ethyl esters," *J. Chem. Eng. Data*, vol. 55, no. 9, pp. 3983–3990, 2010, doi: 10.1021/je100042c.
- [36] H. Hindarso, Aylianawati, and M. E. Sianto, "Biodiesel production from the microalgae nannochloropsis by microwave using CaO and MgO catalysts," *Int. J. Renew. Energy Dev.*, vol. 4, no. 1, pp. 72–76, 2015, doi: 10.14710/ijred.4.1.72-76.
- [37] U. L. Azzahro and W. Broto, "Utilization of Waste Shells as Cao Catalyst in Biodiesel Production from Used Cooking Oil," *Acta Chim. Asiana*, vol. 5, no. 1, pp. 147–152, 2022, doi: 10.29303/aca.v5i1.69.
- [38] G. Fikria and C. Rustana, "Analysis of the Physical Characteristics of Biodiesel Products Made From Used Cooking Oil," *J. Neutrino*, vol. 14, no. 2, pp. 63–69, 2022, doi: 10.18860/neu.v14i2.14131.
- [39] E. Daryono and L. Mustiadi, "One-phase Transesterification of Palm Oil in to Biodiesel with Co-solvent Methyl Esters: The Effect of Adding Co-solvent to Kinetic Energy and Dipole Moment," *Reaktor*, vol. 22, no. 1, pp. 7–13, 2022, doi: 10.14710/reaktor.22.1.7-13.
- [40] Hendriyana, Hendriyana, Fajar Subagja, and Disti Ayu Hania, "Pembuatan Fatty Acid Methyl Ester (FAME) dari Crude Palm Oil (CPO) Off Grade dengan Metode Esterifikasi dan Transesterifikasi," *J. Tek. Media Pengemb. Ilmu dan Apl. Tek.*, vol. 23, no. 2, pp. 159–165, 2025, doi: 10.55893/jt.vol23no2.699.
- [41] S. Jekayinfa, A. Adebayo, M. A.

- Sulaiman, and V. Ayoola, "Prediction of Density and Viscosity of Biodiesel Fuel From Fatty Acid Methyl Ester (Fame) Composition," *Arid Zo. J. Eng. Technol. Enviroment*, vol. 15, no. 3, pp. 519–534, 2019, [Online]. Available: www.azojete.com.ng
- [42] M. I. Sofyan, M. Ma'ruf, M. A. E. Hafizah, and A. Manaf, "Synthesis of Coconut Methyl Ester Using Organic Catalytic Agents," *Maj. Ilm. Pengkaj. Ind.*, vol. 15, no. 3, pp. 161–167, 2023, doi: 10.29122/mipi.v15i3.5058.
- [43] A. Abideen Adeyinka, O. Samuel Akin, A. Oluwadare, E. Olubayode, and O. Gbenga Micheal, "Lipid Extraction and Fatty Acid Methyl Ester (Fames) Production from Coconut," *Int. J. Acad. Multidiscip. Res.*, vol. 4, no. 6, pp. 92–104, 2020, [Online]. Available: www.ijeais.org/ijamr



2025 by the authors. Licensee Fullerene Journal Of Chem.
This article is an open access article distributed under the
terms and conditions of the Creative Commons Attribution
(CC BY) license
(<http://creativecommons.org/licenses/by/4.0/>).