

Sustainable Analysis of *Calophyllum Inophyllum* Oil for Eco-Friendly Green Lubricants as an Alternative to Mineral Oils

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Article Information	ABSTRACT
Article History Received : October 07, 2025 Revised : October 31, 2025 Published : January 02, 2026	<i>Calophyllum Inophyllum</i> (nyamplung) Oil is recognized as a promising non-edible vegetable oil for the development of sustainable green energy lubricants. This study aims to improve the physicochemical characteristics of nyamplung oil through a two-step transesterification followed by esterification using trimethylolpropane (TMP), and to assess its tribological performance. The refined oil exhibited a flash point of 212 °C (ASTM D92) and a pour point of 8 °C (ASTM D97), indicating excellent thermal and flow stability. The kinematic viscosity was 38.3 cSt (ASTM D445) and the density 0.88 g/cm ³ (ASTM D4052), both within industrial lubricant standards. The acid value decreased markedly from 36.5 to 1.62 mg KOH/g, while the iodine value (0.006 g I ₂ /100 g) and peroxide value (0.23 Meq/kg) demonstrated chemical stability. FTIR analysis confirmed the formation of ester functional groups, and GC-MS results showed a balanced distribution of saturated and unsaturated fatty acids. Overall, the modified <i>Calophyllum Inophyllum</i> Oil fulfills key technical criteria for eco-friendly green energy lubricants and shows strong potential as a renewable alternative to conventional mineral-based lubricants in industrial applications. Nevertheless, its crude form presents several drawbacks, including high acid and peroxide values as well as poor oxidative stability.
Keywords: <i>Calophyllum Inophyllum</i> ; <i>Green Energy Lubricant</i> ; <i>Transesterification</i> .	

INTRODUCTION

Lubricants play a crucial role in supporting industrial production processes and improving energy efficiency. Consequently, research has shifted toward renewable and eco-friendly alternatives. Sustainable manufacturing requires replacing petroleum-based lubricants with green options (Alvarez, Barcena, & Gonzalez, 2016), and vegetable oil-based lubricants have emerged as viable candidates due to their biodegradability, renewability, and environmental safety (Pranav, Sneha, & Rani, 2021; Afifah et al., 2019; Sneha, Revikumar, Singh, Thampi, & Rani, 2020).

Non-edible vegetable oils, such as *Calophyllum Inophyllum* Oil (CIO), are particularly attractive because they do not compete with food sources, contain long-chain fatty acids suitable for chemical modification, and are abundantly available in tropical regions (Atabani et al., 2013; Arumugam & Ponnusami, 2019; Venkanna & Venkataramana Reddy, 2009). These oils can be enhanced via transesterification or epoxidation to improve oxidative stability and viscosity (Karmakar, Ghosh, & Sharma, 2017; Xu et al., 2021). The development of such bio-lubricants aligns with sustainable industrial goals by reducing emissions and dependence on petroleum-based lubricants (Alvarez et al., 2016; Pranav et al., 2021)

In contrast, conventional mineral lubricants remain dominant but are non-biodegradable, toxic, and carbon-intensive (Afifah et al., 2019; Atabani et al., 2013). They degrade thermally, shortening machinery life and increasing maintenance costs (Sneha et al., 2020). Therefore, CIO presents a sustainable alternative due to its biodegradability, low toxicity, and high oxidative stability after transesterification (Prasannakumar, Edla, Thampi, Arif, & Santhakumari, 2022; Xu et al., 2021).

However, producing high-quality CIO-based lubricants requires addressing its high free fatty acid (FFA) content through a two-step process involving acid-catalyzed esterification and base-catalyzed transesterification (Prasannakumar et al., 2022). Process optimization—covering temperature, methanol ratio, and catalyst concentration—is essential to ensure optimal viscosity and density. CIO's high oil yield (37–58%) and adaptability to marginal lands (Vigneshwar et al., 2019) further enhance its feasibility.

In addition, CIO supports local industry development and aligns with the UN Sustainable Development Goals on clean energy and sustainable industrialization. Studies on similar oils, such as *Jatropha curcas* and *Hydnocarpus wightianus*, have demonstrated comparable tribological performance (Ewunie, Morken, Lekang, & Yigezu, 2021; Salaji & Jayadas, 2021). Therefore, developing transesterified CIO-based lubricants not only advances renewable energy research but also promotes sustainable, locally driven industrial growth (Arumugam & Ponnusami, 2019; Ting & Chen, 2011).

RESEARCH METHODS

Materials and Equipment

The research was conducted at the Mechanical Engineering Laboratory of Universitas Islam Raden Rahmat (Unira) Malang, while several samples were tested at the Environmental and Energy Laboratory of Institut Teknologi Sepuluh Nopember (ITS). The main equipment used included a magnetic stirrer with heater, water bath, drying oven, separatory funnel, viscometer, densitometer, and flash and pour point testers, supported by FTIR and GC–MS instruments for compound analysis.

The raw material was crude *Calophyllum Inophyllum* oil extracted from nyamplung seeds from South Malang, while methanol, sulfuric acid, potassium hydroxide, trimethylolpropane (TMP), sodium methoxide, and deionized water were used as supporting chemicals. The process involved three main stages: acid-catalyzed transesterification to reduce free fatty acids, base-catalyzed transesterification to form methyl esters, and final esterification with TMP to enhance oxidative stability and viscosity. The resulting oil was filtered, dried, and analyzed according to ASTM standards, showing improved thermal and lubricating properties suitable for eco-friendly industrial applications.

Chemical Modification Synthesis of CIO

The synthesis consisted of three main stages. The first was acid-catalyzed transesterification to reduce free fatty acids (FFA), where 200 g of oil was reacted with methanol and sulfuric acid at 75°C for 2 h. The second stage involved base-catalyzed transesterification using methanol and KOH at 65 °C for 1–2 h to convert remaining triglycerides into methyl esters and glycerol. The final stage was esterification with trimethylolpropane (TMP) and sodium methoxide

catalyst to improve oxidative and thermal stability. The overall process produced a green lubricant with physicochemical properties comparable to commercial synthetic lubricants.

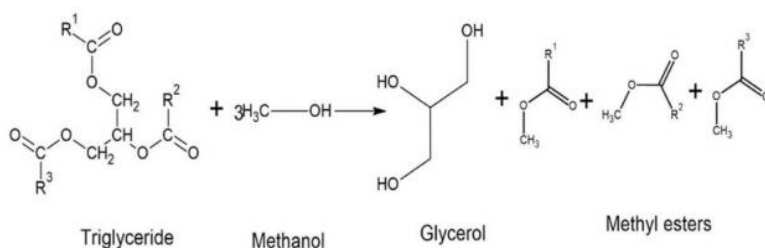


Figure 1. Modified transesterification reaction

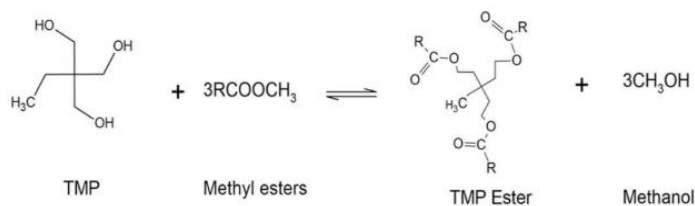


Figure 2. Esterification reaction using TMP

Following the reaction, the produced Green Energy Lubricant underwent physicochemical characterization to assess its quality. Key parameters analyzed included viscosity, density, flash and pour points, acid, iodine, and peroxide values, along with FTIR and GC–MS analyses for functional group and compositional identification. All measurements were conducted in accordance with standard laboratory methods using appropriate analytical instruments such as a viscometer, densitometer, flash point and pour point testers, FTIR spectrometer, and GC–MS system.

Research Process

The research process began with the preparation of materials and equipment, including 200g of *Calophyllum Inophyllum* Oil (CIO) as the main feedstock, methanol, sulfuric acid (H_2SO_4), potassium hydroxide (KOH), trimethylolpropane (TMP), and sodium methoxide (CH_3ONa). All apparatus such as a magnetic stirrer with heater, thermometer, separatory funnel, and drying oven were calibrated to maintain accurate reaction conditions.

The experimental procedure consisted of three major reaction stages:

Acid-catalyzed transesterification - Crude CIO was reacted with 65 mL of methanol and 2 mL of H_2SO_4 at 75 °C for 2 hours to reduce the high free fatty acid (FFA) content. This step converts most FFAs into methyl esters, minimizing soap formation in the subsequent stage.

Base-catalyzed transesterification - The pretreated oil was reacted with 55 mL of methanol and 2 g of KOH at 65 °C for 1–2 hours to convert remaining triglycerides into methyl esters and glycerol. The mixture was then allowed to settle, and the upper ester layer was separated.

Esterification with TMP - The transesterified oil was further reacted with TMP in a 1:4 molar ratio using 1% CH_3ONa as a catalyst. This stage aimed to improve oxidative and thermal stability through the formation of polyol esters, resulting in enhanced lubricant properties.

After the reactions, the product underwent filtration and drying to remove residual catalysts, methanol, and water. The refined oil was then subjected to physicochemical characterization, including measurements of flash point, pour point, viscosity, density, acid value, iodine value, and peroxide value according to ASTM standards. Further FTIR and GC–MS analyses were conducted to confirm ester functional group formation and to identify the fatty acid profile.

Overall, this process sequence ensures that *Calophyllum Inophyllum* Oil is effectively transformed into a high-quality green lubricant with improved thermal stability, reduced acidity, and balanced tribological characteristics suitable for industrial applications.

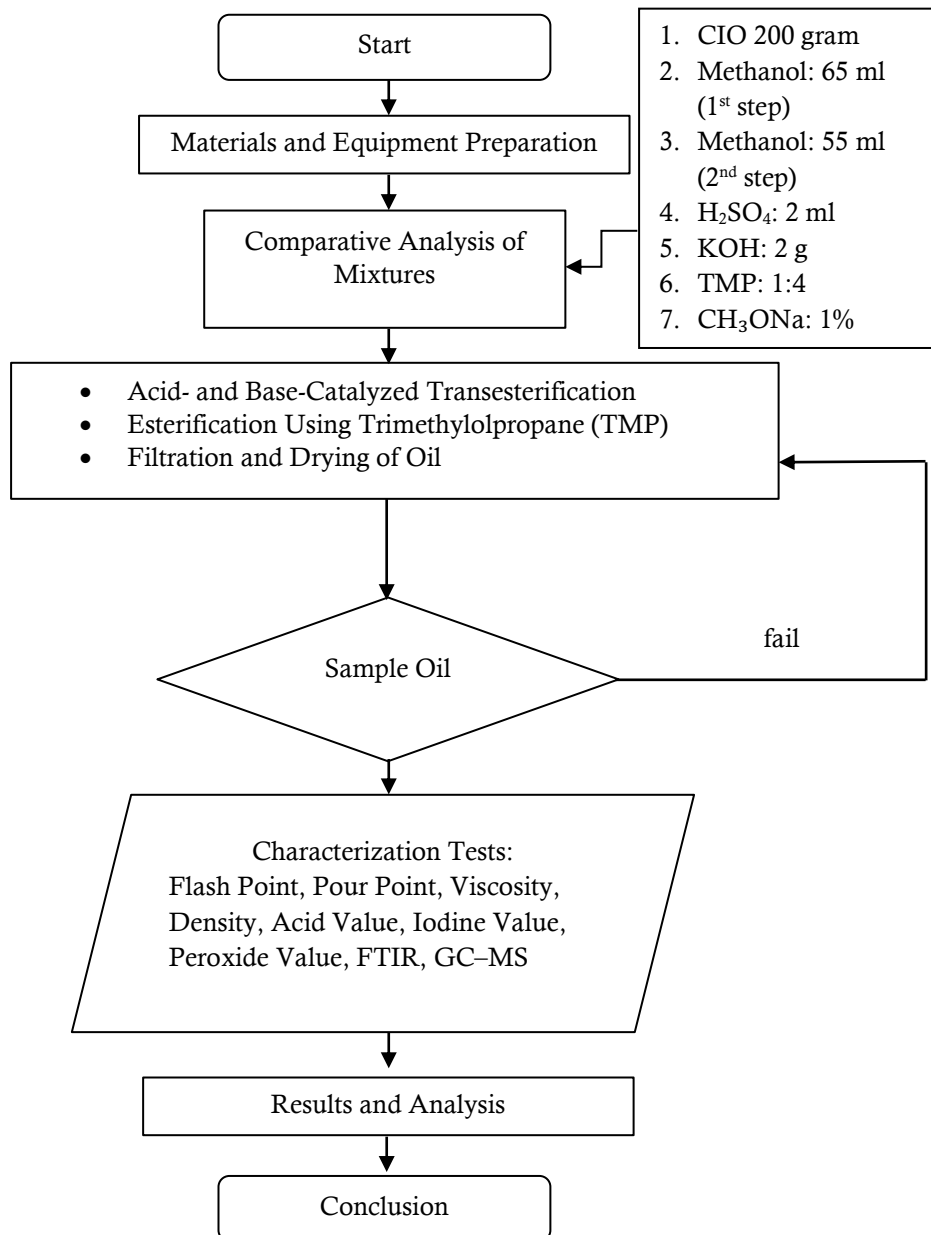


Figure 3. Flowchart of the Research Process

RESULTS AND DISCUSSION

Flash Point of Modified *Calophyllum inophyllum* Oil

The flash point of Transesterified *Calophyllum Inophyllum* Oil (TCIO), determined using the ASTM D92 method, averaged 212 °C based on five replicates, exceeding the minimum requirement of 200 °C for lubricant safety. This high flash point reflects superior thermal resistance and stability under elevated temperatures. The result indicates that TCIO possesses strong oxidative stability due to the presence of ester compounds and long-chain triglycerides, which prevent premature ignition. Similar findings by Prasannakumar et al., (2022) and Thampi, John, Rani, & Arif, (2021) highlight the influence of stable ester bonds and non-volatile compounds on enhancing flash point characteristics in bio-based lubricants. Consequently, TCIO demonstrates excellent safety, low volatility, and long service life, confirming its potential as a green lubricant.

Additionally, its high flash point provides practical advantages in storage and transportation by reducing flammable vapor formation under ambient conditions.

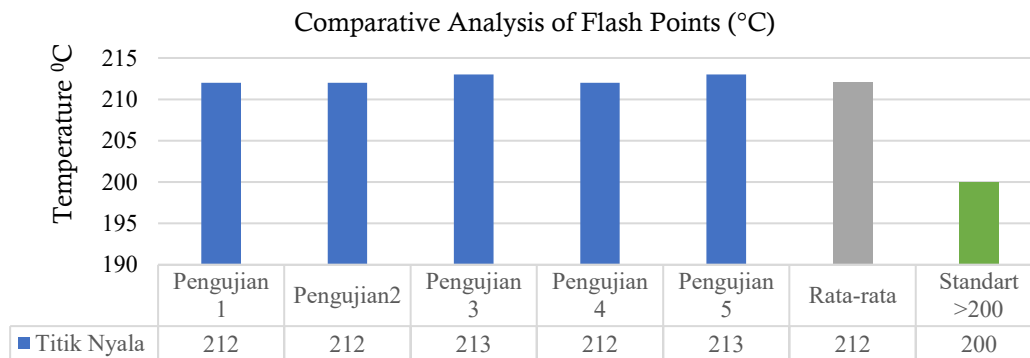


Figure 4. Flash point measurements of transesterified *Calophyllum Inophyllum* Oil

Pour Point Evaluation Results

The pour point of Transesterified *Calophyllum Inophyllum* Oil, measured using ASTM D97, averaged 8°C, which is below the ASTM limit of 10°C, indicating favorable low-temperature fluidity. This value suggests TCIO's suitability for tropical applications, although its performance in colder regions may decline due to crystallization that restricts flow. The relatively high pour point is influenced by the symmetric molecular structure and saturated fatty acid content. Improvements in low-temperature performance can be achieved through chemical modifications such as double esterification and additive incorporation (Karmakar et al., 2017; Zaid, Singh, Kumar, & Gupta, 2019), or through techniques like winterization, blending with synthetic esters, and the use of pour point depressants (Z. Xu et al., 2019; Thampi et al., 2021). Despite these limitations, TCIO remains a viable bio-lubricant for warm climates and holds potential for further optimization in industrial applications.

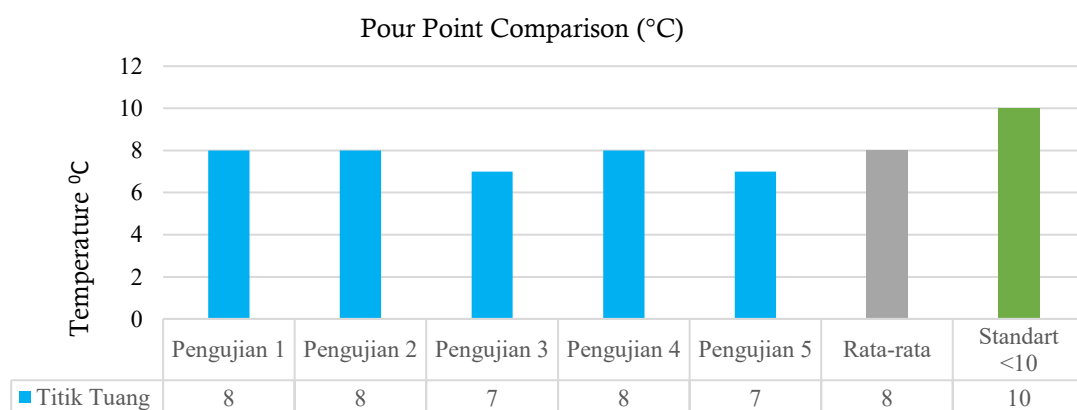


Figure 5. Comparison of Pour Point Values of TCIO over Five Consecutive Tests

Viscosity Test Results

The kinematic viscosity of Transesterified *Calophyllum Inophyllum* Oil at 40 °C averaged 38.30 cSt, within the ASTM D445 range of 30–50 cSt, indicating its suitability as a medium-temperature lubricant. This viscosity level aligns with ISO VG grades 46–68, commonly used in industrial machinery (Thampi et al., 2021). The relatively high viscosity is attributed to the presence of long-chain triglycerides and saturated fatty acids, such as stearic and palmitic acids, which maintain film thickness and stability under thermal stress (Z. Xu et al., 2019; Ting & Chen, 2011). Such stability minimizes evaporation, reduces friction, and prolongs lubricant service life.

(Prasannakumar et al., 2022; Nurulita et al., 2024). Moreover, the viscous nature of TCIO supports the formation of a strong lubricating film between metal surfaces, effectively reducing wear (Mangopang & Prasetyawati, 2015). These characteristics affirm TCIO's potential as an environmentally friendly green lubricant for mechanical applications.

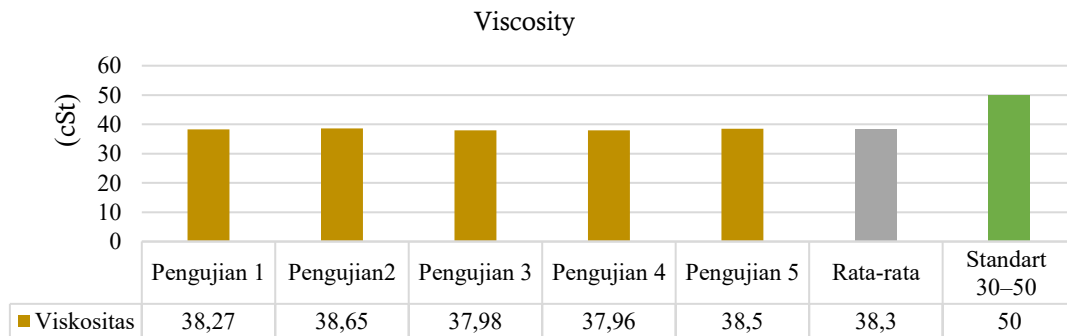


Figure 6. Viscosity Profile of Transesterification-CIO across Five Consecutive Tests

Density Test Results

The density of Transesterified *Calophyllum Inophyllum* Oil averaged 0.88 g/cm^3 at 20°C , which falls within the ASTM D4052 standard range of $0.70\text{--}0.95 \text{ g/cm}^3$. This value indicates an appropriate mass density for lubrication applications, ensuring effective flow and film formation on metal surfaces. The relatively high density is attributed to the presence of long-chain fatty acids and triglycerides, such as stearic and linoleic acids, which enhance stability against variations in pressure and temperature (Nurulita et al., 2024). Additionally, the compact ester and triglyceride structures contribute to lower volatility and longer service life (Z. Xu et al., 2019; Prasannakumar et al., 2022), while adequate density supports the formation of a uniform hydrodynamic film and improved resistance to extreme operating conditions (Ting & Chen, 2011; Thamphi et al., 2021).

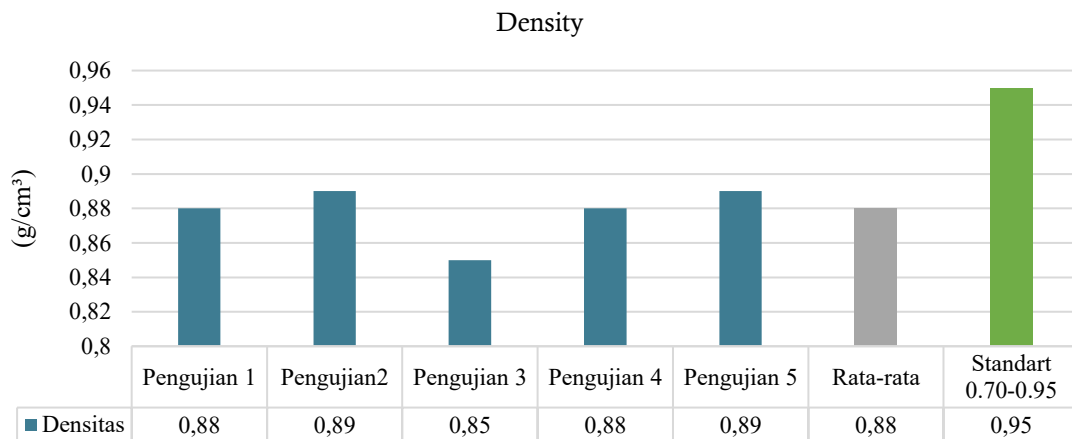


Figure 7. Comparison of Density Values of Transesterification-CIO across Five Consecutive Tests

Acid Value Test Results

The acid value of Transesterified *Calophyllum Inophyllum* Oil averaged 1.62 mg KOH/g , which is slightly above the ASTM D664 limit of $<1.0 \text{ mg KOH/g}$ but significantly lower than that of raw CIO (36.50 mg KOH/g), indicating that transesterification effectively reduces free fatty acid (FFA) content (Prasannakumar et al., 2022). The acid value represents FFA levels resulting from triglyceride degradation, where higher values indicate reduced chemical stability and increased oxidation tendency (Ting & Chen, 2011; (Mangopang & Prasetyawati, 2015). The remaining FFA may originate from oxidation or hydrolysis during extraction and storage, particularly in unsaturated fatty acids such as linoleic and oleic acids (Nurulita et al., 2024). To further improve stability, pretreatment methods such as degumming and esterification are recommended (Z. Xu et

al., 2019). Elevated FFA levels can promote peroxide formation, deposit accumulation, and thermal degradation, thereby reducing lubricant durability (Prasannakumar et al., 2022).

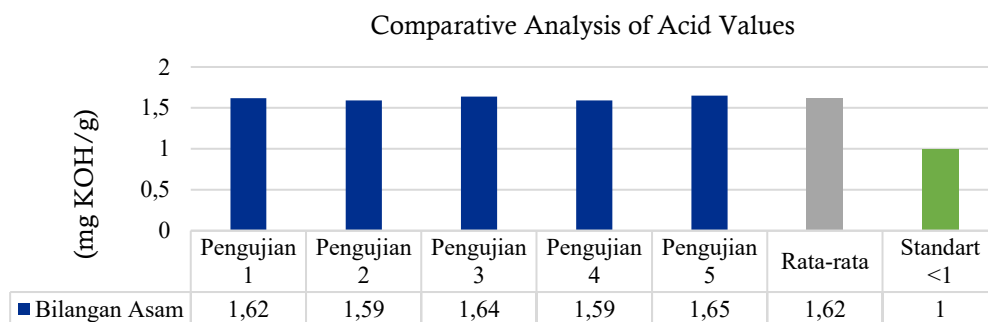


Figure 8. Acid Value of Transesterification-CIO across Five Consecutive Tests

Iodine Value Test Results

The iodine value of Transesterified *Calophyllum Inophyllum* Oil averaged 0.0060 g I₂/100 g, which is well below the AOCS limit of <100 g I₂/100 g, indicating a low degree of unsaturation and high oxidative stability. The reduction in double bonds due to transesterification enhances resistance to oxidation and polymerization (Ting & Chen, 2011; Mangopang & Prasetyawati, 2015). The moderate unsaturation level, mainly attributed to oleic and linoleic acids, contributes to molecular flexibility and improved film formation on metal surfaces while maintaining structural stability under tropical conditions (Nurulita et al., 2024; Prasannakumar et al., 2022). This semi-unsaturated profile aligns with the desirable characteristics of green lubricants that balance flexibility and oxidative resistance (Z. Xu et al., 2019).

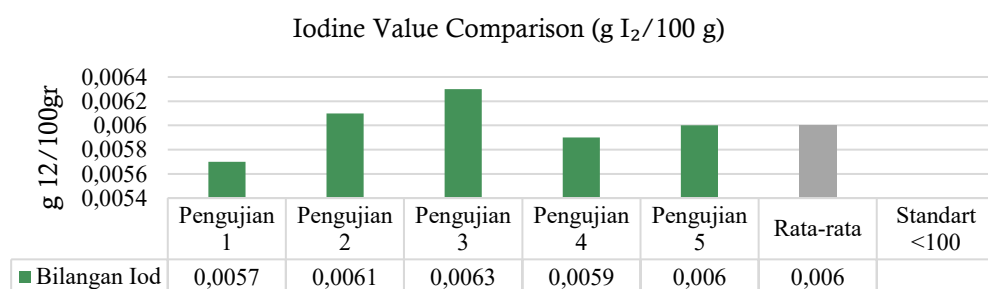


Figure 9. Comparison of Iodine Values Between Transesterified Oil and CIO Across Five Tests

Peroxide Value Analysis

The peroxide value of Transesterified *Calophyllum Inophyllum* Oil averaged 0.23 Meq/kg, significantly below the IFOS/FAO limit of 5.0 Meq/kg, indicating high oxidative stability. This low value reflects the effective elimination of oxidation sites within the triglyceride structure, thereby reducing hydroperoxide formation during initial oxidation (Prasannakumar et al., 2022; Z. Xu et al., 2019). The improved oxidative resistance demonstrates the successful modification of TCIO in minimizing free radical formation and peroxide accumulation (Nurulita et al., 2024). Consequently, the low peroxide content enhances lubricant durability and operational safety, meeting the essential criteria for long-term stability in vegetable-based lubricants (Mangopang dan Prasetyawati, 2015).

Results of FTIR Spectroscopic Analysis

Fourier Transform Infrared (FTIR) Spectroscopy was employed to identify functional groups and compare chemical structures before and after transesterification. The FTIR spectrum of Transesterified *Calophyllum Inophyllum* Oil displayed two dominant peaks at 1437 cm⁻¹ and 1740 cm⁻¹, corresponding to CH₃-O and ester (C=O) groups, respectively. The consistent spectra obtained from five replicates confirm the successful formation of new ester compounds and

indicate that no significant thermal degradation occurred during the reaction. These findings are consistent with Prasannakumar et al., (2022), who reported similar FTIR evidence confirming the generation of new functional groups during transesterification.

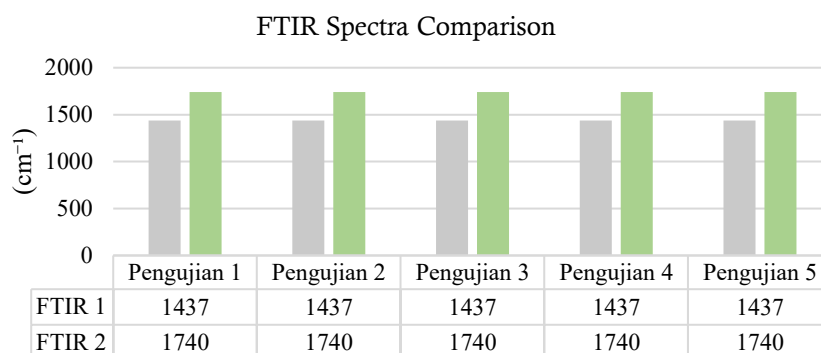


Figure 11. FTIR Spectrum of Transesterified CIO Across Five Tests

GC-MS

Gas Chromatography–Mass Spectrometry (GC–MS) analysis identified the major fatty acid components of Transesterified *Calophyllum inophyllum* Oil (TCIO) as palmitic (C16:0), stearic (C18:0), oleic (C18:1), linoleic (C18:2), and linolenic (C18:3) acids, with a minor presence of arachidic acid (C20:0). This composition demonstrates a balanced proportion of saturated and unsaturated long-chain fatty acids that enhance the oil's physicochemical properties. The presence of oleic and linoleic acids contributes to molecular flexibility and spreading behavior, while palmitic and stearic acids improve thermal stability. These results align with Prasannakumar et al., (2022) and Nurulita et al., (2024), who noted that semi-unsaturated structures support lubricant performance and film stability, as well as Thampi et al., (2021) and Zaid et al., (2019), who emphasized that an optimal balance of fatty acid composition enhances oxidative resistance and sustainability in bio-based lubricants.

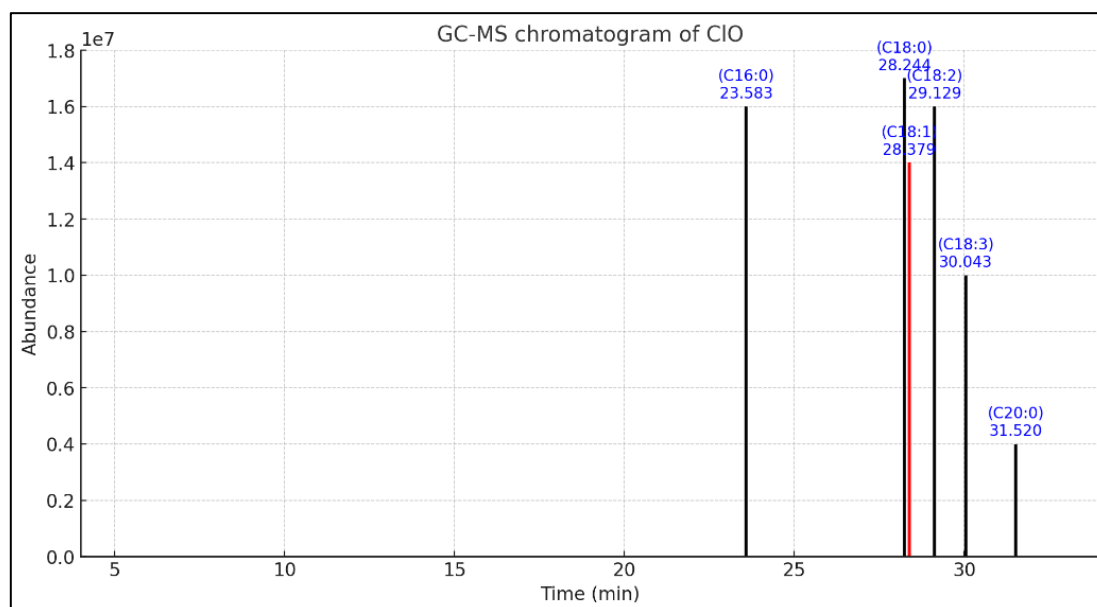


Figure 12. GC-MS Analysis Results

CONCLUSION

Based on the objectives and experimental results, the modification of *Calophyllum inophyllum* oil through transesterification and esterification successfully enhanced its

physicochemical and tribological properties. The produced oil exhibited a high flash point, acceptable viscosity and density, and low acid and peroxide values, indicating improved thermal and oxidative stability. FTIR and GC–MS analyses confirmed the formation of ester groups and a balanced composition of saturated and unsaturated fatty acids, which support stable lubrication performance.

The main advantages of this research are the utilization of a renewable, non-edible oil source and the achievement of lubricant properties that meet several industrial standards, demonstrating strong potential as an eco-friendly alternative to mineral oils. However, limitations such as the relatively high pour point and moderate oxidation resistance suggest that further optimization particularly for low-temperature or long-term industrial applications is still required.

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