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Synthesis and Characterisation of Biolubricants Castor Oil (Ricinus communis L.) Using a Homogeneous Catalyst for Hydraulic Engine Applications

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Abstract

Lubricants are essential products that help reduce surface friction and improve machine efficiency. Lubricating oil consists of 90% base oil and 10% additives. Due to the presence of low molecular weight compounds, mineral-based lubricants exhibit a lower flash point and are not biodegradable, unlike natural oils with equivalent viscosity. Currently, mineral-based lubricants still dominate the global market, yet their environmental drawbacks and reliance on depleting petroleum resources have raised growing concerns. Although several studies have reported the potential of vegetable oils as biolubricants, challenges remain in terms of oxidative stability, viscosity control, and production scalability, which limit their widespread industrial application. The high dependence of the industrial and automotive sectors on lubricants, coupled with the depletion of petroleum reserves, drives the need to seek sustainable alternatives to support sustainable green economic development. This study aims to produce biolubricants from castor oil (Ricinus communis L.) using NaOH catalyst through an esterification method. Esterification was carried out by mixing the oil with alcohol in a molar ratio into a 250 ml three-neck flask, then heating it to 180 °C for 4 hours with 1–2% NaOH catalyst and a methanol-to-oil molar ratio of 1:4. The results showed that the highest values of kinematic viscosity, viscosity index (VI), and density were 28.9 mm²/s, 90.3, and 884.9 kg/m³, respectively. The optimum biolubricant yield was obtained with 2% catalyst (80%). The produced biolubricant met the ISO VG 32 standard, which is widely applied in hydraulic oils, for turning, drilling, and sawing processes. These findings highlight that castor oil-based biolubricants can serve as a sustainable alternative to petroleum-based lubricants; however, further research on long-term stability, wear resistance, and large-scale production remains necessary to bridge the gap towards industrial adoption.

Keywords: biolubricant; esterification; hydraulic; castor oil; NaOH

Abstrak

Pelumas merupakan produk penting yang membantu mengurangi gesekan permukaan dan meningkatkan efisiensi mesin. Minyak pelumas terdiri atas 90% minyak dasar dan 10% aditif. Karena adanya senyawa dengan berat molekul rendah, pelumas berbasis mineral menunjukkan titik nyala yang lebih rendah dan tidak dapat terurai secara hayati, berbeda dengan minyak alami yang memiliki viskositas setara. Saat ini, pelumas berbasis mineral masih mendominasi pasar global, namun kelemahan lingkungannya serta ketergantungan pada sumber daya minyak bumi yang kian menipis menimbulkan kekhawatiran yang semakin meningkat. Meskipun sejumlah penelitian telah melaporkan potensi minyak nabati sebagai biopelumas, tantangan tetap ada terkait stabilitas oksidatif, pengendalian viskositas, dan skalabilitas produksi, yang membatasi penerapannya secara luas dalam industri. Ketergantungan yang tinggi dari sektor industri dan otomotif terhadap pelumas, ditambah dengan menipisnya cadangan minyak bumi, mendorong perlunya mencari alternatif berkelanjutan untuk mendukung pembangunan ekonomi hijau berkelanjutan. Tujuan penelitian ini adalah menghasilkan biopelumas dari minyak jarak (Ricinus communis L.) menggunakan katalis NaOH melalui metode esterifikasi. Proses esterifikasi dilakukan dengan mencampurkan minyak dengan alkohol dalam perbandingan molar ke dalam labu leher tiga berkapasitas 250 ml, kemudian dipanaskan hingga 180 °C selama 4 jam dengan katalis NaOH sebesar 1–2% dan perbandingan molar metanol terhadap minyak 1:4. Hasil penelitian menunjukkan bahwa nilai tertinggi viskositas kinematik, indeks viskositas (VI), dan densitas adalah masing-masing 28,9 mm²/s, 90,3, dan 884,9 kg/m³. Rendemen biopelumas optimum diperoleh pada penggunaan katalis 2% (80%). Biopelumas yang dihasilkan memenuhi standar ISO VG 32, yang banyak diaplikasikan pada oli hidrolik, proses pembubutan, pengeboran, dan penggergajian. Temuan ini menegaskan bahwa biopelumas berbasis minyak jarak berpotensi menjadi alternatif berkelanjutan pengganti pelumas berbasis minyak bumi; namun demikian, penelitian lebih lanjut mengenai stabilitas jangka panjang, ketahanan aus, dan produksi skala besar masih diperlukan untuk menjembatani kesenjangan menuju adopsi industri.

Kata kunci: *biopelumas; esterifikasi; Hidrolik; Jarak kepyar; NaOH*

1. Introduction

The global demand for lubricants is estimated to average over 40 million metric tonnes, with an annual growth rate of approximately 2% [1]. Petroleum-based lubricants dominate approximately 95% of the global lubricant market. These petroleum-derived oils consist of a complex mixture of long-chain hydrocarbons, including branched alkanes (paraffins), linear alkanes (waxes), alicyclic compounds (naphthenes), aromatics, olefin chains, and heteroatom concentrations, particularly sulphur, which contribute to their environmentally unfriendly nature [2]. Although mineral lubricating oils possess higher viscosity, one concern regarding mineral oils is the evaporation of low molecular weight components, which leads to thickening of the oil over time (Figure 1). Furthermore, mineral-based lubricants are non-biodegradable and exhibit lower flash points compared to natural oils of equivalent viscosity, due to the presence of low molecular weight compounds [2]. Moreover, approximately 40–50% of lubricants used are not disposed of properly, resulting in adverse effects on ecosystems. Lubricants are also essential products that help reduce surface friction and enhance engine efficiency [3].

Lubricants help to reduce friction and wear between contacting surfaces. They are also employed to dissipate heat and remove foreign particles generated within the working zone [4]. Lubricants are composed of 70–99% base oil and 1–30% additives to enhance performance [3]. Conventional lubricants are primarily derived from petroleum and are widely used across the world [5]. The heavy reliance of the industrial and automotive sectors on mineral-based lubricants whose raw materials are environmentally unfriendly, combined with the rapid depletion of petroleum reserves, has highlighted the need to seek sustainable alternatives to support long-term economic development and a green environment [6].

Figure 1. Conventional lubricants for automotive applications

Biolubricants are considered near-equivalent substitutes for petroleum-based lubricants due to their comparable characteristics. These oils are renewable and exhibit high lubricity, viscosity index, flash point, low volatility, and negligible aromatic and sulphur content [7], They are biodegradable and have no toxic effects on the ecosystem [8]. Bio-based lubricants represent a promising alternative to petroleum-based lubricants, as they offer comparable technical characteristics to conventional lubricants while remaining environmentally friendly [8]. The excessive dependence of the industrial and automotive sectors on petroleum-based lubricants, whose raw materials pose environmental challenges, drives the need for sustainable economic development and a greener environment [3]. The use of biodegradable lubricants reduces the negative environmental impact associated with used oil or accidental spills [8]. Furthermore, bio-based lubricants are classified as non-flammable fluids due to their high flash points (>300 °C)[9].

Figure 2. Castor oil (Ricinus communis) plant tree.

Vegetable oils contain triglycerides as their main component, along with fatty acid chains and other derivatives such as diglycerides, free fatty acids, sterols, tocopherols, and others. The structure of triglycerides exhibits desirable lubricating properties when introduced between contact surfaces. The fatty acid chains also contribute to enhancing the strength of the surface film [2]. Polyhydric alcohol esters (polyol esters) are one of the base materials for biolubricants and can be synthesised from vegetable oils such as rapeseed oil [10], karanja oil [11], Calophyllum inophyllum L [12, 13], cottonseed oil [14], canola oil [15], palm oil [8], soybean oil [16], coconut oil [17], castor oil and jatropha oil [18] [19], sunflower oil [20], rice bran oil and karanja oil [4], Nile tilapia fish fat [21], beef tallow [22], and waste cooking oil [23, 24].

Several researchers have synthesised vegetable oils into biolubricants using heterogeneous catalysts. Greco-Duarte, et al. [25] employed a two-step (Estolide) method using enzymatic catalysis in the production of biolubricants from castor oil. They reported a viscosity index of 162, oxidation stability of 51 minutes, and a pour point of −42 °C. Furthermore, biolubricants from castor oil can be produced using a heterogeneous catalyst of Fe_3O_4 nanoparticles and ethylene glycol. Ahmad, et al. [19] reported a yield of 94% after two hours at a temperature of 160 °C. The production of biolubricants using heterogeneous catalysts has also been carried out by Hajar and Vahabzadeh [26]. Candida rugosa lipase, covalently immobilised onto functionalised magnetic nanoparticles (MNPs), was used in the synthesis of biolubricants from castor oil. A methyl ester yield of 96.9% was obtained after 24 hours of reaction under optimum conditions.

Table 1. Physicochemical properties of biolubricants from various types of oils.

Feedstock	Density (gr/ml)	kinematic viscosity 40 °C, $mm^2 \cdot s^{-1}$	Viscosity Indeks	Flash point (ºC)	pour point (ºC)	Oxidation stability (h)	Ref
Gmelina arborea	890	47.60	-	298.70	-18.20	-	[28]
Ricinus communis	-	191	119	-	-	24	[29]
Castor oil	-	29.73	107.17	-	-	16.83	[30]
Safflower oil	946	73.39	103	216	-	6.72	[31]
Castor oil	871	35.20	208.1	300	-15	-	[3]
Safflower oil	927	77.70	155	260	-	2.86	[32]
Calophyllum inophyllum L	-	83.46	216.32	243.3		1642.67	[33]
Microalgae	970	74	180	248	-6	-	[27]
Sesame oil	-	35.55	193	196	-21	-	[34]
Waste cooking oil	895	15.5	196	198	-9	-	[35]

The performance of lubricants can be assessed based on various parameters. Viscosity is considered the most important tribological property, as it is directly related to friction reduction and wear resistance. Other parameters, such as oxidative and thermal stability, density, flash point, and pour point, are also significant, as they determine the lubricant's performance in each practical and specific application [27]. The physicochemical characteristics of biolubricants derived from various types of oils are presented in Table 1. Therefore, to reduce waste from petroleum-based lubricating oils, this study synthesises oil from Ricinus communis (castor oil plant) as a biolubricant using a homogeneous NaOH catalyst through the esterification method.

2. Materials and Methodology.

2.1. Materials

In this study, castor oil was sourced from Central Java, while the chemical reagents were purchased from a chemical store in Medan. The production of the biolubricant was carried out at the oleochemical laboratory of Politeknik PTKI Medan. This study utilised several materials, including castor seed oil (Figure 2), ethylene glycol solution, concentrated HCl solution, and NaOH catalyst.

2.2. Research Equipment

The equipment used includes a pycnometer, four-neck reactor, Liebig condenser, stirrer and rotor, oil bath, tachometer, thermometer, Ostwald viscometer, Erlenmeyer flask, separatory funnel, dropper, volumetric flask, and oven.

2.3. Biolubricant Production

The first step involves a saponification process, in which KOH is added at a molar ratio of 1:4 with castor oil and heated at 80 °C for 1 hour. Subsequently, the residual KOH is separated from the obtained soap. A 10N concentrated HCl solution is then added to the castor seed oil at a 1:1 ratio. The mixture is stirred until potassium chloride (KCl) crystals and fatty acids are formed, which takes approximately 20 minutes. The resulting product is transferred into a separatory funnel to separate the KCl crystals from the fatty acids. The KCl crystals settle in the bottom layer, while the fatty acid layer remains on the top of the funnel. A subsequent esterification process is carried out on the fatty acids by adding ethylene glycol at a stirring speed of 200 rpm and a temperature of 180 °C for 4 hours. The final product is washed with warm water to remove impurities and residual catalyst. The production process of biolubricants from castor oil is presented in Figure 3.

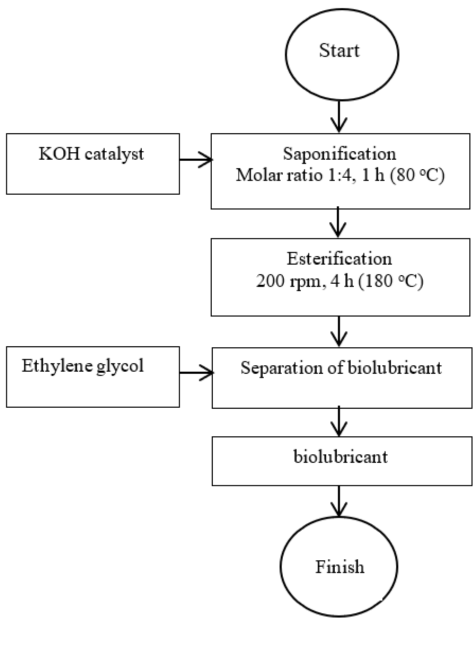

Figure 3. Flow diagram of the production process of biolubricant from castor oil

3. Results and Discussion

The results of the synthesis of castor oil into biolubricant using different amounts of NaOH catalyst are presented in Figure 4. The variation in catalyst concentration (1% and 2%) generally did not significantly affect the biolubricant yield, with yields of 78% and 80% respectively. These results are slightly higher than those reported by Nogales-Delgado, et al. [31] for safflower-based biolubricants, which ranged from 76% to 78%.

Figure 4. Biolubricant derived from castor oil.

3.1. Kinematic Viscosity of Biolubricant

Viscosity is considered the most important tribological property, as it is directly related to friction reduction and wear resistance [27]. Kinematic viscosity describes the degree of internal resistance of a fluid to flow, or the magnitude of shear resistance the fluid possesses. Viscosity values at 40 °C and 100 °C have been classified and standardised for each grade, facilitating the selection of the appropriate viscosity grade according to specific application requirements.

Figure 5 presents the results of the kinematic viscosity test for both samples with different catalyst concentrations, namely 1% and 2%. The sample with 2% catalyst exhibited the highest kinematic viscosity value of 28.9 mm^2/s. This value was then compared with the ISO VG 32 standard, indicating that the kinematic viscosity of the sample with 2% KOH catalyst exceeded the standard value of 28.8 mm^2/s. This result is comparable to the findings of Rios, et al. [36], which reported a value of 28.25 mm^2/s.

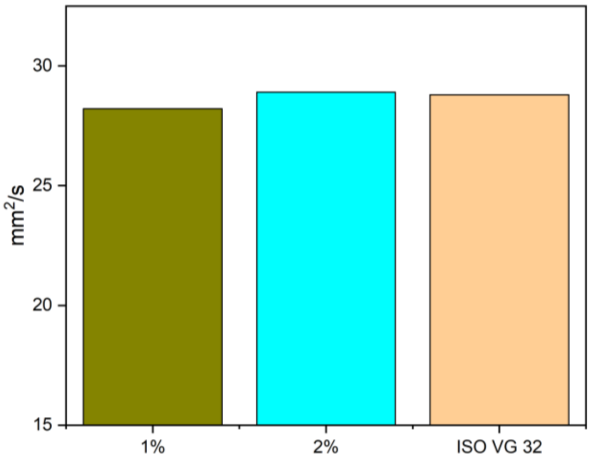

Figure 5. Kinematic viscosity of biolubricant.

A similar study was conducted by [37] in which esters were produced from Ricinus communis L. seed oil using NaOH as a catalyst for biolubricant synthesis. The results of pour point, flash point, and viscosity tests indicated that the NaOH-based methyl ester met the criteria for use as a lubricant. This was evidenced by a low pour point (–6 °C), a high flash point (246 °C), and an optimal viscosity of 39.2 cps, all of which conform to the ISO VG 32 standard. The kinematic viscosity of biolubricants with varying NaOH catalyst concentrations (1% and 2%) also demonstrated values comparable to the ISO VG 32 standard, which is commonly applied to hydraulic oils. This standard is frequently used for hydraulic fluids operating at elevated temperatures in machinery and equipment such as turning tools, drilling machines, and saws [38].

Biolubricants with excessively low viscosity will flow too easily between metal components, thereby failing to achieve their primary lubricating function except in light-duty applications such as hydraulic or automotive transmission oils. Conversely, biolubricants with excessively high viscosity (overly thick) may experience difficulty in flowing, thus failing to effectively lubricate most metal parts. Therefore, a good biolubricant must possess an optimal level of viscosity, tailored to the type of lubricant and its specific application requirements [39].

Biolubricants are generally based on vegetable oils, which consist of various types of fatty acids. The viscosity level is influenced by the content of saturated and unsaturated fatty acids in the material. Saturated fatty acids tend to provide higher viscosity due to their straight chains, which facilitate stronger intermolecular interactions. In contrast, unsaturated fatty acids, particularly those with double bonds, result in lower viscosity, as their bent molecular structure reduces compactness [40]. Moreover, the longer the carbon chain of a fatty acid, the higher its viscosity, due to the increased van der Waals forces between molecules [41].

3.2. Viscosity Index of Biolubricant

The viscosity index describes the degree to which a lubricant's viscosity changes with temperature. A high viscosity index indicates that the viscosity undergoes only minimal variation with temperature fluctuations. For machinery and equipment operating across a range of temperatures, lubricants with a high viscosity index are recommended [27]. High-performance biolubricants must possess a high viscosity index, as a higher index corresponds to reduced temperature effects on the biolubricant's performance [29]. The viscosity index (VI) of a biolubricant is a parameter that reflects the extent of viscosity variation with temperature. The higher the viscosity index, the lower the viscosity change as temperature varies. It is typically estimated from viscosity values measured at 40 °C and 100 °C. A good lubricant should exhibit a high viscosity index [42]. As a result, chemical synthesis has led to the development of lubricants from organic and renewable sources with properties comparable to mineral-based lubricants, offering the additional advantage of biodegradability. In general, fluids become thinner as temperature increases and thicker as temperature decreases. A fluid's ability to maintain its viscosity despite temperature changes is referred to as its viscosity index. Lubricants with a high viscosity index are more desirable as they demonstrate strong resistance to viscosity changes caused by temperature fluctuations.

Lubricants with a high viscosity index are regarded as high-quality lubricants, as they are capable of delivering optimal lubrication performance across a wide temperature range. This ensures that the lubricant effectively fulfils its function in reducing wear. The results of the biolubricant viscosity index test, as shown in Figure 5, indicate that the sample with 2% NaOH exhibited the highest viscosity index, namely 90.3, while the sample with 1% NaOH recorded a value of 89.9. When compared with the ISO VG 32 standard, which specifies a viscosity index parameter of 90, the sample with 2% catalyst meets the required standard. These results, however, are lower than those reported by Rios, et al. [36], who obtained a value of 104, and Oliveira, et al. [29], who reported 119. A viscosity index of around 100 is generally considered an indicator of a biolubricant's resistance to viscosity changes due to temperature. In comparison with other biolubricants or commercial lubricants, the values obtained in this study fall within the average range, aligning with those found in the literature for biolubricants and other organic esters [31]. Figure 6 illustrates the viscosity index values of biolubricants with varying NaOH catalyst concentrations, demonstrating comparability with the ISO VG 32 standard. This ISO VG 32 standard is commonly applied to hydraulic oils, particularly for supporting high-pressure hydraulic fluid operations in machinery components and equipment such as turning tools, drilling machines, and saws [38].

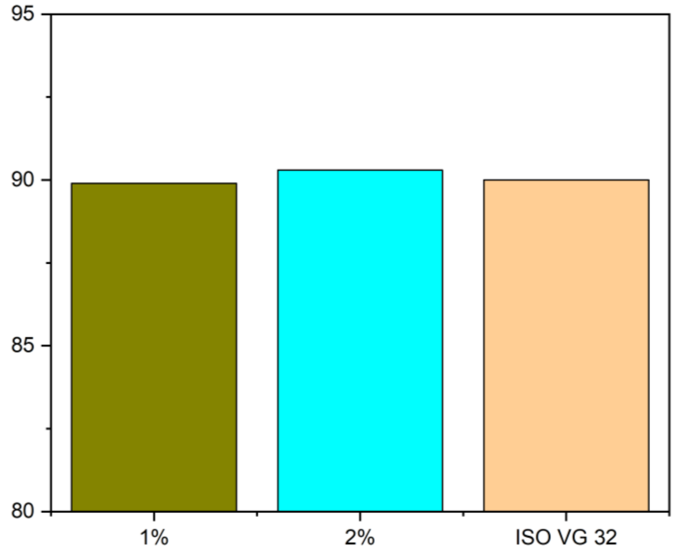

Figure 6. Viscosity Index (VI) of biolubricant

Also conducted a similar study by producing biolubricants from castor oil (Ricinus communis) using NaOH as a catalyst and successfully achieved a viscosity index (VI) of 94.3. A higher viscosity index indicates that viscosity changes less with temperature, meaning the oil is less likely to thin at elevated temperatures. Therefore, engine systems operating at high temperatures require biolubricants with high VI values [44]. Biolubricants require a high viscosity index to maintain an adequate lubricating film and to ensure effective lubrication of tribological pairs under varying working conditions. As lubricants must operate at different temperatures, a high viscosity index ensures viscosity stability. Vegetable oils possess higher viscosity indices due to their higher molecular weight compared to mineral oils, making them suitable for lubrication purposes [45].

3.3. Density of Biolubricants

Density is one of the fundamental properties of matter, representing the mass of a material per unit volume. This physical property plays an important role in understanding both the structural and the physical chemical characteristics of a material. In biolubricants, density is influenced by various factors, such as the number and arrangement of atoms or molecules, as well as the temperature and pressure conditions to which the material is exposed. Additionally, density aids in distinguishing between different types of materials and affects their properties and applications across various fields.

Density testing was carried out on two samples with varying catalyst concentrations, as shown in Figure 7. Both samples yielded values that conformed to the ISO VG 32 standard. The sample with 1% NaOH catalyst showed a density of 885.2 kg/m^3, while the sample with 2% NaOH exhibited a slightly lower density of 884.9 kg/m^3. These values are comparable to the ISO VG 32 standard density of 869.7 kg/m^3, which is commonly used in hydraulic oils and various machinery such as turning machines, drilling equipment, and sawing tools [38]. Amdebrhan, et al. [43], [46] conducted a similar study and reported the density of castor oil to be 888.92 kg/m^3. When compared with the EN 14214 standard for methyl esters, which ranges between 860 and 900 kg/m^3, these results fall within the acceptable range.

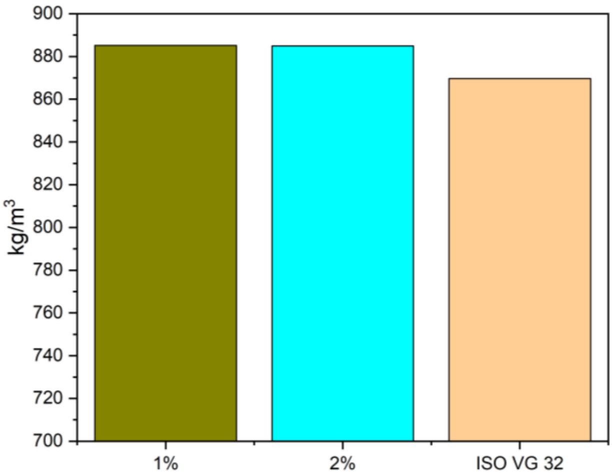

Figure 7. Density of biolubricant

The fatty acids that form triglycerides in biolubricants possess varying structures and molecular masses. The higher the proportion of fatty acids with large molecular weights and compact structures, the greater the tendency for the density of the biolubricant to increase. Saturated fatty acids typically result in higher densities due to their straight and tightly packed structures. In contrast, unsaturated fatty acids, particularly those with multiple double bonds, lead to lower densities, as their molecules are more loosely packed and irregular shape [47]. Reactions such as epoxidation, esterification, and transesterification can introduce functional groups that alter the molecular mass and volume, thereby affecting the density.

FTIR Analysis

The FTIR (Fourier Transform Infrared Spectroscopy) spectra analysis compares crude castor oil and the resulting biolubricant (Figure 8). A common peak observed in both samples at 3464 cm^{-1} (O–H stretching) indicates the presence of hydroxyl (O–H) groups, characteristic of alcohols or carboxylic acids, which are components of free fatty acids. This finding is consistent with previous studies [28, 30], both spectra reveal the presence of polar groups in the crude oil and the biolubricant. Additionally, the peak at 2856 cm^{-1} (C–H symmetric stretching) signifies the presence of methyl or methylene groups ($–CH_2–$), typically found in long aliphatic chains originating from triglycerides or vegetable oils. The peak at 1464 cm^{-1} (C–H bending) indicates deformation of methyl or methylene groups ($–CH_3$ / $–CH_2–$). Similarly, the peak at 589 cm^{-1} (possibly C–H bending or fingerprint region) falls within the fingerprint region, which is often difficult to assign specifically but is distinctive for certain molecular structures.

The characteristic peak typically found in crude oil (black line) at 2676 cm^{-1} most likely indicates the presence of –CHO (aldehyde) groups or an overtone vibration of C=O, suggesting contamination or degradation. The peak at 1640 cm^{-1} indicates the presence of C=C double bonds or vibrations associated with bound water.

The characteristic of carbonyl groups (either esters or free fatty acids) appears at the 1739 cm^{-1} peak (C=O stretching), which is typical of raw vegetable oils. Peaks at 883 and 722 cm^{-1} are commonly associated with out-of-plane C–H bending, indicating the presence of aromatic or alkene structures. A distinctive peak observed in the biolubricant (red line) at 2681 cm^{-1} suggests modification of aldehyde groups or specific C–H vibrations formed during the lubricant synthesis process. The 1744 cm^{-1} peak (C=O stretching) still indicates the presence of ester groups, although the shift in peak position from the crude oil (1739 cm^{-1} to 1744 cm^{-1}) may suggest the formation of new esters via transesterification. The biolubricant shows a peak at 1744 cm^{-1}, which is associated with the stretching vibration of the ester C=O bond [30].

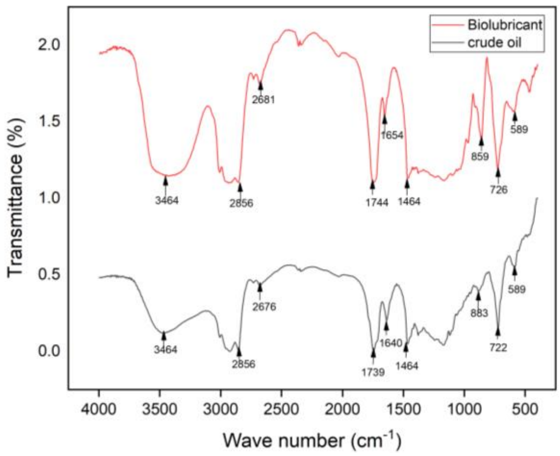

Figure 8. FTIR analysis of crude oil and biolubricant.

The peak at 1654 cm⁻¹ corresponds to C=C double bond or amide vibrations, potentially indicating structural modifications resulting from the reaction. Furthermore, strong absorption bands at 859 and 726 cm⁻¹ are characteristic of well-ordered aliphatic molecular structures or possibly small cyclic structures formed during the process. These bands indicate C–H bending vibrations from aliphatic carbon chains (CH_3 and CH_2) in tri-esters. Similar absorption patterns have been reported by Hadiza, et al. [28].

4. Conclusions

Based on the findings of this study, castor oil has proven to be a promising raw material for the production of biolubricants, as it can be effectively synthesised using a heterogeneous NaOH catalyst. Among the tested formulations, the best physicochemical properties were achieved in the sample with 2% NaOH catalyst, yielding a viscosity index (VI) of 90.3, a kinematic viscosity of 28.9 mm²/s, and a density of 884.9 kg/m³. Furthermore, the produced biolubricant successfully met the ISO VG 32 standard, indicating its potential for application in hydraulic machine oils. Looking forward, future research is recommended to focus on enhancing the oxidative stability, tribological performance, and long-term durability of castor oil-based biolubricants. Additionally, investigations into scaling up the production process, as well as evaluating the environmental and economic feasibility, would be essential steps to support wider industrial adoption and to strengthen the role of biolubricants in promoting sustainable green technology.

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