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Optimisation of biolubricant synthesis from castor–maggot oil mixture via two-stage transesterification using response surface methodology

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Abstract

This study investigates the optimisation and characterisation of a biolubricant produced from a castor–maggot oil mixture via two-stage transesterification. Response surface methodology using a Box–Behnken design was employed to optimise the oil volume ratio, catalyst concentration, and reaction time. The optimum conditions were a castor oil–maggot oil ratio of 50% (v/v), a catalyst concentration of 1% (w/w), and a reaction time of 2 h, resulting in a biolubricant yield of 71.43%. Ethylene vinyl acetate and ethyl-cellulose were added to enhance stability and performance. The biolubricant exhibited a viscosity index of 101.88, kinematic viscosity at 40°C of 54.57 cSt, and a flash point of 235°C, complying with ISO VG 68 and SNI 7069.9:2016 standards. These performance characteristics demonstrate favourable viscosity–temperature behaviour, adequate thermal safety, and suitability for industrial lubrication systems. The integration of mixed vegetable–insect oil feedstocks with Response Surface Methodology (RSM)–Box–Behnken optimisation, together with the incorporation of performance-enhancing additives, resulted in a biodegradable, non-toxic, and environmentally friendly biolubricant that meets standard requirements and shows strong potential as a sustainable alternative to petroleum-based lubricants for mechanical applications.

Keywords:
Biolubricant, castor oil, maggot oil, transesterification, environmentally friendly.

1 Introduction

Petroleum-based lubricants have been used in automotive and other industries for more than a century [1]. These lubricants, known as mineral oils, are generally derived from crude oil and typically consist of mineral oil base stocks and various additives that enhance their overall performance and efficiency [2]. The use of mineral oils can cause environmental pollution, especially in soil and groundwater [3]. Besides being detrimental to the environment, mineral oils are also hazardous to health because they can trigger allergies, disrupt the nervous and respiratory systems, and potentially cause cancer upon long-term exposure to their vapour [3].

Mineral oil–based lubricants have characteristics such as toxicity, non-biodegradability, and dependence on non-renewable fossil resources, which increasingly conflict with global sustainability goals and stricter environmental regulations [4]. Therefore, there is a critical need to develop more environmentally friendly alternative lubricants to minimise the risks of the lubricants to human health and the environment.

Biolubricants derived from renewable vegetable oils offer a promising solution to conventional petroleum-based lubricants, owing to their low toxicity, environmental friendliness, and ability to reduce dependence on petroleum resources [5], [6]. High biodegradability is an essential characteristic of vegetable oils. A lubricant is considered biodegradable when it can be decomposed by microorganisms or enzymes through aerobic or anaerobic processes [7], [8]. Vegetable oils such as palm, soybean, sunflower, coconut, and olive oils have high potential to be used as raw materials for biolubricants [5], [9]. These types of oils are classified as edible oils, which are easily biodegradable and environmentally friendly [5].

Nevertheless, the issue of escalating food prices due to the use of vegetable oils for fuel and lubricant production has encouraged the exploration of non-edible oils as alternative feedstocks [10]. Castor oil, in particular, has been widely investigated as a prominent non-edible feedstock for the production of biolubricants.

Castor oil is extracted from the seeds of the castor plant, which possesses unique chemical characteristics and excellent lubricating properties [11], [12], [13]. Compared with other vegetable oils, castor oil shows enhanced performance owing to its high viscosity, excellent lubricity, and ricinoleic acid–rich composition that improves polarity and film strength [11]. Its hydroxyl functional group also contributes to increased adhesion, thereby improving the performance of the lubricant under various operating conditions. Its high polarity makes it a more effective solvent for lubricant additives compared with other vegetable or mineral oils. The disadvantage of castor oil is that its viscosity index is lower compared with those of other vegetable oils, making its viscosity sensitive to temperature fluctuations [14].

Maggot oil derived from black soldier fly larvae has garnered much interest due to its potential as a renewable and sustainable feedstock for biolubricant production [15]. In addition to its high biodegradability and low toxicity, maggot oil exhibits favourable lubricating properties, making it a promising alternative to conventional petroleum-based lubricants. The chemical composition of maggot oil is similar to that of coconut oil-based biolubricants, which are dominated by lauric acid. Its high saturated fat content contributes to improved oxidation stability.

Biolubricants derived from coconut oil are well recognised for their excellent oxidation stability. Maggot oil, with a fatty acid composition similar to that of coconut oil, is a promising feedstock for biolubricant production and has comparable performance with coconut oil [16]. The study conducted by Alipour *et al.* demonstrated that the lipid content of black soldier fly, which is rich in saturated fatty acids (72%), shows strong potential for applications such as lubricants [17]. BSF biolubricants exhibit potential thermal stability for moderate-temperature applications and offer a sustainable, environmentally friendly alternative to conventional lubricants by reducing dependence on fossil fuel–based lubricants in industrial applications [18]. Further investigation on maggot oil-based biolubricants is required to verify this. Although castor oil and maggot oil are both promising biolubricant feedstocks, each has inherent limitations when used alone. Castor oil has high viscosity and good film-forming ability but suffers from a low viscosity index and limited thermo-oxidative stability. Maggot oil offers high biodegradability and improved oxidative stability but has relatively low viscosity and load-bearing capacity. Therefore, blending these oils provides a complementary approach to balance their properties, resulting in a biolubricant with improved performance, which represents a relatively novel approach rarely reported in the scientific literature.

This study employs a mixture of castor oil and maggot oil as the feedstock for biolubricant production, with the incorporation of additives such as Ethylene–Vinyl Acetate (EVA) and ethylcellulose to enhance the physicochemical properties of the biolubricant. EVA and ethylcellulose have been reported as effective viscosity modifiers for vegetable oils [9]. The process parameters were optimized using Response Surface Methodology (RSM) with a Box–Behnken Design (BBD).

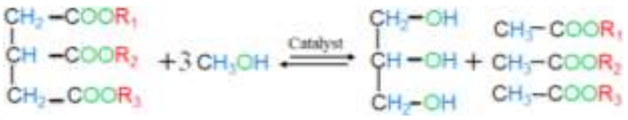
2 Methods

Parameter optimization in this study was carried out using the RSM with a BBD. The BBD was applied to the biolubricant production process by considering three parameters, namely the mixing ratio of castor oil and maggot oil (% v/v), catalyst loading (% wt), and reaction time (h). This study was conducted in three stages: (1) first-stage transesterification (methyl ester synthesis), (2) second-stage transesterification (Trimethylolpropane (TMP) esterification), and (3) characterisation of the resultant biolubricant. In the first stage, methyl ester synthesis was carried out by mixing the raw materials according to the predetermined blending ratios.

The synthesis of Fatty Acid Methyl Esters (FAME) was initiated by blending castor oil and maggot larva oil, with the volume fraction of castor oil varied between 50 and 90% (v/v), while the remainder consisted of maggot oil. The first-stage transesterification was carried out by reacting the vegetable oil mixture with methanol at a molar ratio of 1:6, in the presence of a K_2CO_3 catalyst at a loading of 1 wt% relative to the oil mixture. The reaction was conducted in a three-neck round-bottom flask equipped with a reflux condenser. The mixture was stirred at 360 rpm and the temperature was controlled and maintained at 60°C using a paraffin oil heating medium on a hot plate for 2 h. Subsequently, the mixture was left to settle for 24 h, resulting in the formation of two distinct layers. The upper layer, consisting of FAME, was separated from the lower glycerol layer. Subsequently, the FAME was washed with hot distilled water (50°C) to remove residual methanol, catalyst, and soap. Finally, the sample was purified by drying in an oven at 110°C to eliminate residual moisture.

In the second stage, biolubricant synthesis was performed by reacting the methyl ester with TMP at 130°C under constant stirring at 360 rpm using a K_2CO_3 catalyst, with the catalyst concentration varied from 0.5 to 1.5% (w/w), for a reaction time of 2–5 h. After transesterification, the reaction mixture was filtered to remove residual soap and catalyst, followed by washing of the TMP ester with hot distilled water (50°C) to eliminate remaining impurities. The sample was further dried at 200°C using an oven, and the purified biolubricant obtained from the second-stage transesterification was subsequently analyzed and optimized using RSM in Design-Expert® version 13. The transesterification reactions are given by Eq. (1) and Eq. (2) [19].

$$CH_3CH_2-C(CH_2OH)_2-CH_2OH + 3CH_3COOR \xrightleftharpoons{Catalyst} CH_3CH_2-C(CH_2COOR)_2-CH_2COOR + 3CH_3OH \quad (1)$$



$$\begin{array}{l} CH_2-COOR_1 \\ CH-COOR_2 \\ CH_2-COOR_3 \end{array} + 3CH_3OH \xrightleftharpoons{Catalyst} \begin{array}{l} CH_2-OH \\ CH-OH \\ CH_2-OH \end{array} + \begin{array}{l} CH_3-COOR_1 \\ CH_3-COOR_2 \\ CH_3-COOR_3 \end{array} \quad (2)$$

EVA and ethylcellulose additives were incorporated into the biolubricant exhibiting optimal physicochemical properties, namely the highest flash point, viscosity, and viscosity index, as well as the lowest pour point. The purpose of the additives was to improve the physicochemical properties of the biolubricants. The additives were blended with the biolubricant under constant stirring at 150 rpm and 130°C for 1 h. The samples were then cooled to room temperature and prepared for further analysis. The concentrations of ethylcellulose and EVA additives used in this stage ranged from 0.5 to 2 wt% relative to the biolubricant. The resultant biolubricants were subsequently characterised and compared with the ISO VG 68 and Indonesian National Standard (SNI) 7069.9:2016 standards. The response variables measured in this study were the biolubricant yield, viscosity index, density, flash point, pour point. The biolubricant yield was determined using Eq. (3) [6].

$$\text{Yield} = \frac{\text{Weight of biolubricant}}{\text{Weight of vegetable oil}} \times 100 \qquad (3)$$

3 Results and discussion

The optimisation parameters investigated in this study comprised of the castor oil-to-maggot oil volume ratio (%(v/v)), catalyst concentration (%(w/w)), and reaction time (h). These parameters were evaluated to determine the optimal conditions that would maximise the yield and viscosity index of the synthesised biolubricant. The results of the optimisation process obtained using RSM with Box–Behnken experimental design are summarised in Table 1. Based on the results, it is evident that the castor oil-to-maggot oil volume ratio, catalyst concentration, and reaction time influenced both the yield and viscosity index of the resultant biolubricant. This finding is in agreement with the results of Campos, *et al.* [12], who observed an increase in yield by optimising the reaction conditions of the esterification, epoxidation, and ring-opening processes of castor oil fatty acids using RSM. They successfully achieved a high biolubricant yield (>93%) and sufficient viscosity index in the synthesis of castor oil-based biolubricant.

Based on the results shown in Table 1, the maximum biolubricant yield (99.86%) was achieved in Run 3 at a castor oil-to-maggot oil ratio of 90% (v/v), catalyst concentration of 0.5% (w/w), and reaction time of 3.5 h. However, under these conditions, the viscosity index was relatively low (71.62). A similar trend was observed in Run 9, which also employed a high castor oil ratio (90% v/v) and resulted in a high yield (99.84%) but a reduced viscosity index (75.52). These observations indicate a statistically meaningful negative interaction between the castor oil-to-maggot oil ratio and viscosity index, where increasing castor oil content enhances conversion efficiency but adversely affects the rheological performance of the final product.

In contrast, the highest viscosity index (101.88) was recorded in Run 6 at a lower castor oil-to-maggot oil ratio of 50% (v/v), catalyst concentration of 1.0% (w/w), and reaction time of 2.0 h, although the yield decreased to 71.43%. This suggests that increasing the proportion of maggot oil contributes to improved molecular interactions and chain flexibility, which enhance the viscosity index but limits overall conversion efficiency. The repeated centre-point experiments (Runs 1, 4, 10, 15, and 17) exhibited relatively consistent response values, supporting the statistical reliability of the experimental design and indicating low experimental error.

Furthermore, interaction effects between catalyst concentration and reaction time were evident. Moderate catalyst loadings (around 1.0% w/w) combined with shorter reaction times favoured viscosity index enhancement, whereas lower catalyst concentrations coupled with longer reaction times improved yield. This behaviour suggests that excessive reaction severity may promote side reactions or molecular degradation, negatively impacting viscosity performance despite high conversion.

The observed trade-off between biolubricant yield and viscosity index can be attributed to differences in feedstock composition and reaction severity. Higher castor oil-to-maggot oil ratios favour higher yields due to the abundance of reactive hydroxyl-containing fatty acids in castor oil, which promote conversion efficiency.

Table 1. Optimisation of the reaction conditions for biolubricant synthesis from castor–maggot oil mixture

Run	Factor			Response	
	A: Castor oil-to-maggot oil volume ratio	B: Catalyst concentration	C: Reaction time	Yield (%)	Viscosity index
	%(v/v)	%(w/w)	H		
1	70	1.0	3.5	93.86	85.25
2	70	1.5	2.0	72.99	86.45
3	90	0.5	3.5	99.86	71.62
4	70	1.0	3.5	95.88	85.38
5	50	1.5	3.5	91.99	100.45
6	50	1.0	2.0	71.43	101.88
7	70	1.5	5.0	87.20	84.83
8	90	1.5	3.5	81.27	77.41
9	90	1.0	2.0	99.84	75.52
10	70	1.0	3.5	90.72	86.22
11	50	0.5	3.5	88.85	99.99
12	90	1.0	5.0	90.04	75.13
13	70	0.5	5.0	91.41	89.41
14	70	0.5	2.0	98.95	83.04
15	70	1.0	3.5	91.47	84.17
16	50	1.0	5.0	82.81	83.21
17	70	1.0	3.5	77.94	85.26

However, excessive castor oil content leads to the formation of more rigid ester structures and increased molecular uniformity, which can reduce chain flexibility and consequently lower the viscosity index. In contrast, higher proportions of maggot oil introduce a broader fatty acid distribution and greater molecular diversity, enhancing intermolecular mobility and improving viscosity index, albeit at the expense of conversion efficiency. Additionally, increased catalyst concentration and prolonged reaction time intensify reaction severity, which may promote side reactions or partial molecular degradation, further reducing viscosity index despite improved yield. These findings highlight the importance of balancing reaction conditions to achieve optimal physicochemical and rheological performance.

Overall, the RSM results demonstrate that the optimisation of waste-derived biolubricant synthesis involves a multi-objective balance between yield and viscosity index. The interaction effects between the castor oil-to-maggot oil ratio, catalyst concentration, and reaction time play a critical role in defining this balance, highlighting the importance of RSM in identifying statistically meaningful operating windows rather than relying on single-factor optimisation.

3.1 Composition of the biolubricant

Gas Chromatography–Mass Spectrometry (GC–MS) analysis was carried out to determine the chemical composition of the biolubricant produced from transesterification of the castor–maggot oil mixture. The GC–MS results provide essential information regarding the type of FAMEs formed, which serve as an indicator of the success of the transesterification reaction and the quality of the resultant biolubricant. In general, the GC–MS analysis serves as a basis for evaluating the conversion of triglycerides in the castor and maggot oils into methyl ester, as well as to understand the chemical composition that influences the performance of the synthesised biolubricant. The GC–MS chromatogram is shown in Fig. 1.

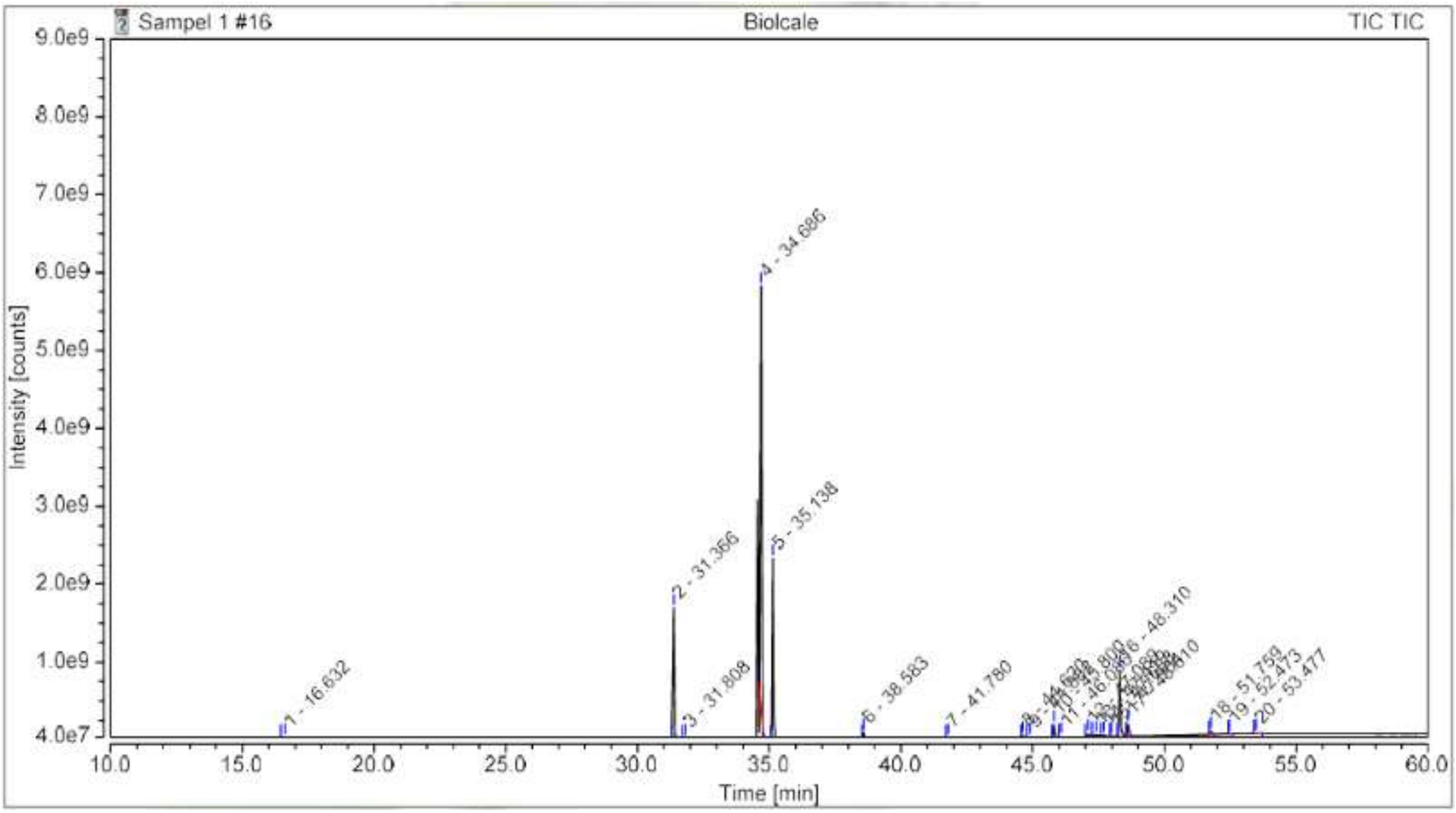


Fig. 1. GC-MS chromatogram of the biolubricant produced from the castor–maggot oil mixture.

The detailed composition of the main chemical compounds identified in the biolubricant is presented in Table 2.

Table 2. Composition of the biolubricant produced from the castor–maggot oil mixture

Compound	Composition (%)
9-Octadecenoic acid (Z)-, methyl ester (methyl oleate)	41.91
Methyl stearate	19.63
Hexadecanoic acid, methyl ester (methyl palmitate)	15.48
9-Octadecenoic acid (Z)-, 2-hydroxy-1-(hydroxymethyl) ethyl ester	11.01
Others (minor, <2%)	11.97

Based on the results of GC-MS analysis of the biolubricant obtained from transesterification of the castor–maggot oil mixture, the biolubricant was mainly composed of long-chain fatty acid methyl esters, which play an important role in determining the characteristics of the biolubricant. This observation was consistent with the findings of Obanla**,** *et al.* [20], who demonstrated that the hydroxyl structure in castor oil contributed to good lubrication and viscosity stability.

Methyl oleate (9-octadecenoic acid, methyl ester) constitutes the largest fraction (41.91%) of the biolubricant. The high proportion of this monounsaturated C18 ester is especially beneficial for lubrication performance. The presence of a single double bond introduces molecular flexibility, allowing the lubricant molecules to align and shear easily under applied stress. This molecular behaviour contributes to stable viscosity, low friction coefficients, and improved energy efficiency during operation. Moreover, methyl oleate is widely recognised for providing a balance between fluidity at moderate temperatures and sufficient film strength under load.

Saturated fatty acid methyl esters, namely methyl stearate (C18:0, 19.63%) and methyl palmitate (C16:0, 15.48%), play a complementary role in enhancing the thermal and oxidative stability of the biolubricant. Their fully saturated hydrocarbon chains are less susceptible to oxidative degradation, which is critical for maintaining lubricant integrity during prolonged exposure to elevated temperatures. The presence of these saturated components therefore mitigates the inherent oxidation vulnerability associated with unsaturated esters, improving service life and reducing the formation of degradation products.

Importantly, the GC–MS analysis also identifies a significant fraction (11.01%) of hydroxy-functional esters, specifically 9-octadecenoic acid (Z)-, 2-hydroxy-1-(hydroxymethyl)ethyl ester. Hydroxyl-containing molecules introduce polarity into the lubricant system, which enhances adsorption onto metallic surfaces through dipole–dipole interactions and hydrogen bonding. This increased surface affinity promotes the formation of a more robust and persistent lubricating film, particularly under boundary lubrication conditions where surface interactions dominate. Such behaviour is consistent with the well-documented lubricity advantages of castor-oil-derived compounds, where hydroxyl groups are known to improve film strength and wear protection.

Overall, the GC–MS results demonstrate that the transesterification of the castor–maggot oil mixture produces a chemically balanced biolubricant composed of unsaturated esters for fluidity and friction reduction, saturated esters for thermal and oxidative stability, and hydroxy-functional esters for enhanced surface adhesion and film durability. This synergistic combination of molecular features explains the suitability of the synthesised biolubricant for lubrication applications and confirms that its chemical composition is directly aligned with desirable lubrication performance characteristics rather than being merely compositional in nature.

3.2 Functional groups of the biolubricant

Fourier Transform Infrared (FTIR) spectroscopy was conducted to identify the functional groups present in the biolubricant produced from the castor–maggot oil mixture. This characterisation method was used to clarify the transesterification reaction and the formation of ester compounds as the main components of the biolubricant. The FTIR spectrum of the biolubricant is presented in Fig. 2.

The FTIR spectrum of the biolubricant synthesised from the castor–maggot oil mixture (Fig. 2) confirms the successful formation of ester-based lubricant molecules and provides insight into their molecular performance. The strong absorption bands observed at 2923 and 2854 cm^{-1} correspond to asymmetric and symmetric stretching vibrations of aliphatic C–H groups, indicating the presence of long hydrocarbon chains. These chains are essential for effective lubricity, as they facilitate the formation of a stable boundary film on metal surfaces, thereby reducing friction and wear during sliding contact. The prominent absorption peak at 1743 cm^{-1} is attributed to the C=O stretching vibration of ester functional groups (–COOR), confirming successful transesterification of triglycerides into fatty acid methyl esters.

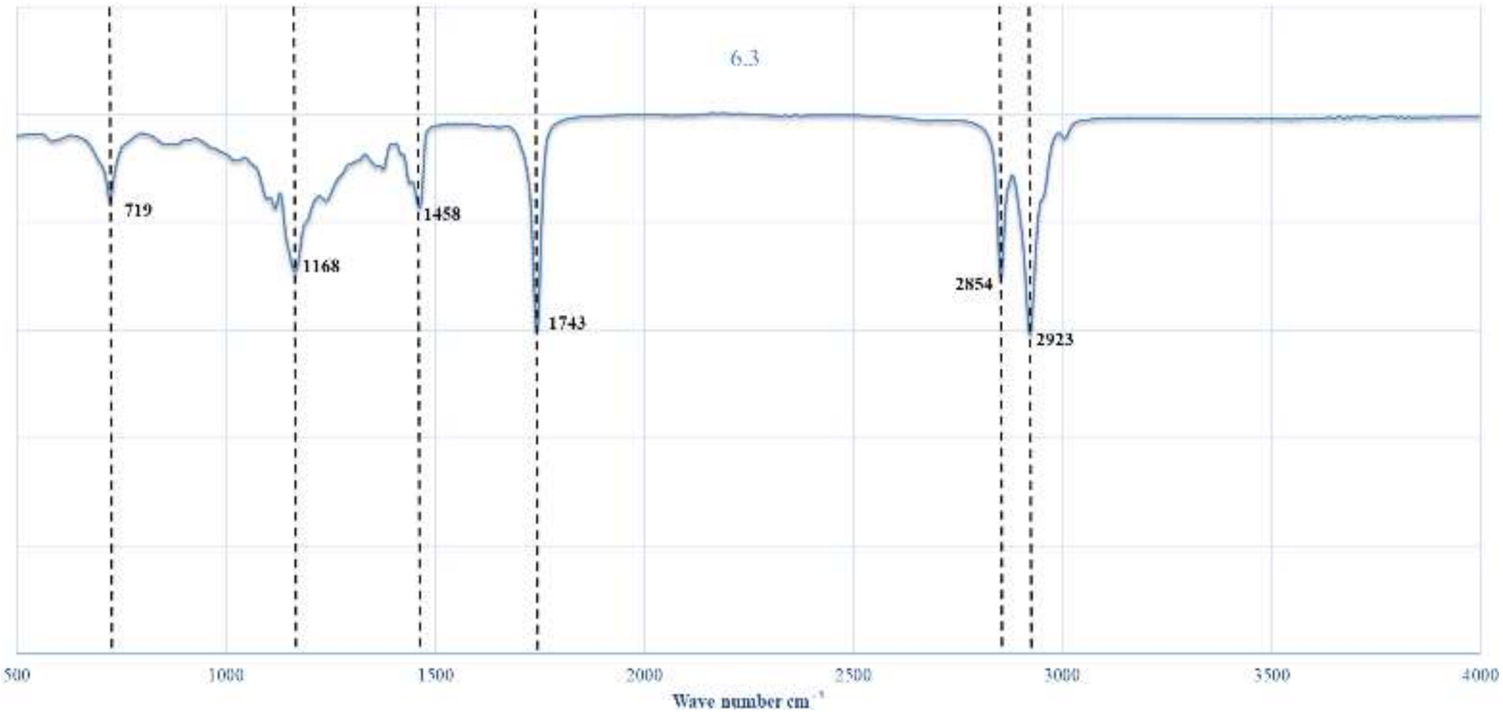


Fig. 2. FTIR spectrum of the biolubricant produced from the castor–maggot oil mixture.

Ester groups enhance lubricant polarity and promote strong adsorption onto metallic surfaces, improving load-carrying capacity and boundary lubrication performance. Additionally, the presence of unsaturated bonds, reflected by absorptions in the region around 1458 cm^{-1}, contributes to molecular flexibility, which is associated with improved viscosity–temperature behaviour and a higher viscosity index.

The absorption band at 1168 cm^{-1} corresponds to C–O stretching vibrations, further verifying ester bond formation and indicating chemical stability of the lubricant structure. Meanwhile, the peak at approximately 723 cm^{-1} is assigned to the bending vibrations of long-chain methylene groups, which are characteristic of extended alkyl chains and play a critical role in maintaining cohesive lubricating films at the tribological interface.

The combined presence of polar functional groups derived from castor oil (notably hydroxyl-containing ricinoleic acid) and saturated fatty acid chains from maggot oil results in a balanced molecular architecture. This balance enhances viscosity index, lubricity, and oxidative stability while avoiding excessive rigidity. Overall, the FTIR results demonstrate that the molecular functionalities present in the synthesised biolubricant are directly linked to its physicochemical and tribological performance, consistent with ester-based biolubricants reported in previous studies [21], [22], [23].

3.3 Physicochemical properties and compliance with ISO VG 68 and SNI 7069.9:2016 standards

The physicochemical properties of the biolubricant produced from the castor–maggot oil mixture indicate the potential of the biolubricant as an environmentally friendly lubricant, were evaluated and compared with both international (ISO VG 68) and Indonesian (SNI 7069.9:2016) standards for industrial lubricants to assess its suitability for practical applications. The ISO VG 68 standard serves as an international reference for classifying lubricants based on the kinematic viscosity at 40°C, ensuring compatibility and optimal performance in various mechanical and industrial systems. The ISO VG 68 standard serves as a primary reference in formulating biolubricants that fulfil technical requirements and thermal stability. Moreover, this standard facilitates optimizing the reaction conditions in order to produce biolubricants that meet the desired specifications of the lubrication system. Viscosity is a key parameter that determines a lubricant's quality, representing the fluid's resistance to flow and its ability to form a protective film between interacting metal surfaces [7]. Table 3 shows a comparison of the physicochemical properties of the biolubricant produced from the castor–maggot oil mixture and those specified in the ISO VG 68 standard.

Based on Table 3, the measured density of the biolubricant was 0.925 g/cm^3 at 15°C, slightly higher than the ISO VG 68 and SNI 7069.9:2016 standard ranges (0.88–0.90 g/cm^3). This higher density reflects the predominance of long-chain fatty acid esters typical of ester-based biolubricants, which enhance load-bearing and film-forming properties.

The kinematic viscosity values of 54.57 cSt at 40°C and 7.61 cSt at 100°C show that the synthesised biolubricant is within the operational range of industrial ISO VG 68 oils (68 cSt at 40°C; 6.9 cSt at 100°C). Although the 40°C viscosity is slightly lower than the nominal ISO value, it remains adequate for medium-to-heavy-load lubrication systems, ensuring effective film formation and flow behaviour. The viscosity index of 101.88 meets and slightly exceeds both ISO and SNI minimum requirements (90–100), indicating that the change in viscosity of the biolubricant with temperature is relatively small, allowing the biolubricant to maintain good lubricity over a wide operating temperature range, comparable to commercial ISO VG 68 lubricants. These results are consistent with those of Hussein, *et al.* [24], who reported that biolubricants produced from transesterified waste cooking oil optimised with Aspen Plus process simulation had a kinematic viscosity of 68.1 and 8.4 at 40 and 100°C, respectively, and a viscosity index of more than 100, which were comparable to the physicochemical properties stipulated in the ISO VG 68 standard. Therefore, the results obtained in this study demonstrate that the castor–maggot oil mixture produces a biolubricant with kinematic viscosities comparable to the ISO VG 68 standard, which gives it a competitive edge compared with other vegetable waste-based feedstocks.

Table 3. Comparison of the physicochemical properties of the biolubricant produced from the castor–maggot oil mixture and those stipulated in the ISO VG 68 standard.

Property	Density at 15°C (g/cm^3)	Kinematic viscosity at 40°C (cSt)	Kinematic viscosity at 100°C (cSt)	Viscosity index	Pour point (°C)	Flash point (°C)
ISO VG 68 standard	0.88 - 0.90	68	6.9	90 - 100	(-15) - (-30)	226
Biolubricant produced in this study	0.925	54.57	7.61	101.88	2 - 4	235

The pour point of the biolubricant (2–4°C) complies with the ISO VG 68 and SNI 7069.9:2016 requirements for industrial lubricants used in moderate climates (≤ −15°C). The relatively higher pour point is attributed to long-chain saturated fatty acids and strong ester intermolecular interactions, which limit molecular mobility at low temperatures, but it remains adequate for reliable flow and circulation in moderate-climate industrial applications.

Meanwhile, the biolubricant had a high flash point (235°C), which is higher than the minimum flash point specified in the ISO VG 68 standard. This suggests that the biolubricant is resistant to volatilisation and combustion at high temperatures, ensuring safe application in both industrial and automotive systems that demand high thermal resistance. The flash point of the biolubricant was significantly lower than those obtained by Bahadi, *et al.* [25], who reported a flash point of 320–360°C for palm kernel fatty acid-based biolubricants. Nevertheless, the biolubricant produced from the castor–maggot oil mixture remains safe for high-temperature industrial and automotive lubrication systems owing to its high flash point.

The oxidation stability test yielded a duration of 6 h, which is consistent with the behaviour of other ester-based biolubricants reported in prior studies. Although this value is lower than that of mineral-based oils (typically >500 h), it remains acceptable under ISO and SNI criteria for biodegradable lubricants, where moderate oxidative stability is expected due to the natural fatty acid composition.

Overall, the physicochemical properties of the synthesised biolubricant comply well with the general requirements outlined in ISO and SNI standards for ester-based industrial lubricants. These results confirm that the castor–maggot oil biolubricant possesses suitable density, low-temperature flowability, thermal safety, and oxidative resistance, supporting its potential application as an environmentally friendly alternative to conventional petroleum-based lubricants.

The physicochemical profile of the castor–maggot oil biolubricant suggests its suitability for several specific mechanical and industrial systems. With a kinematic viscosity of 54.57 cSt at 40°C and 7.61 cSt at 100°C, corresponding to the ISO VG 68 grade, this lubricant is well suited for hydraulic and gear systems that operate under moderate-to-heavy load conditions. In such systems such as hydraulic presses, industrial gearboxes, and bearing housings, the viscosity ensures adequate film thickness to prevent metal-to-metal contact, minimizing wear and friction losses.

Its high viscosity index (101.88) indicates minimal viscosity change with temperature, which makes the lubricant ideal for machines with fluctuating operating temperatures, including pumps, compressors, and mechatronic actuators. These systems require stable viscosity to maintain consistent lubrication and motion control. The flash point of 235°C exceeds the minimum thermal stability requirements for internal combustion engines and industrial compressors, demonstrating its capacity to withstand elevated temperatures without volatilization or decomposition.

The pour point of 2–4°C indicates good flow characteristics at low ambient temperatures, making it appropriate for machinery operating in tropical and moderate climates, such as automotive gear units, agricultural machinery, and robotic systems. Moreover, its biodegradability and non-toxicity make it particularly advantageous for environmentally sensitive applications, including food processing machinery, marine equipment, and renewable-energy systems (e.g., wind turbine gearboxes), where accidental leaks could pose ecological risks.

4 Conclusions

This study demonstrated the synthesis of a biolubricant from a castor–maggot oil mixture via a two-stage transesterification process. The produced biolubricant fulfilled the requirements of ISO VG 68 and SNI 7069.9:2016, confirming its applicability for lubrication purposes. A synergistic interaction between castor oil and maggot oil contributed to improved physicochemical properties, particularly viscosity behaviour and thermal stability. To systematically achieve and further enhance these properties, an integrated approach combining mixed vegetable–insect oil feedstocks with RSM–Box–Behnken optimisation and performance-enhancing additives was applied. This approach enabled efficient identification of optimal synthesis conditions and yielded a TMP-ester-based biolubricant that meets industrial lubricant standards. This study is limited to laboratory-scale synthesis and physicochemical evaluation. The developed biolubricant shows strong potential as a biodegradable, non-toxic, and environmentally friendly alternative to petroleum-based lubricants. Future work should focus on tribological performance assessment, long-term oxidative stability, additive compatibility, and scale-up feasibility.

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