International Journal of Emerging Research in Engineering, Science, and Management
Vol. 5 | Issue 1 | pp. 13-31 | Jan-Mar 2026.
www.ijeresm.com | eISSN – 2583-4894
Received: 08 Dec 2025 | Revised: 10 Feb 2026 | Accepted: 14 Feb 2026 | Published: 19 Feb 2026

Development and Evaluation of Automotive Lubricating Oil from *Jatropha curcas* Oil

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Abstract: A *Jatropha curcas*-based bio-lubricant was developed and evaluated for automotive applications through acid esterification, base-catalyzed transesterification, in-situ peracetic acid epoxidation, and multi-additive blending. The molecular transformations were confirmed by GC–MS and FTIR, and physical properties were assessed using ASTM/ISO methods. Performance was further evaluated through a 12,000 km in-service motorcycle engine test and XRF wear analysis. Transesterification decreased kinematic viscosity at 40 °C from 36.6 to 16.7 cSt, and subsequent epoxidation and additive incorporation increased the viscosity to 47.2 cSt (40 °C) and 15.2 cSt (100 °C), meeting ISO VG-46 requirements. The resultant composition (JOA) showed density (888 kg m^{-3}), viscosity index (227), pour point (−20 °C), flash point (230 °C), free fatty acid content (0.1%), and acid value < 0.5 mg KOH g^{-1}. The predominant components of JOA were determined by GC–MS, and ester and epoxide functionalities were confirmed by FTIR. During operation, the viscosity index decreased to 192.9, while maintaining acceptable viscosity retention and thermal stability. XRF analysis indicated controlled wear, with metal concentrations remaining within reported OEM guideline ranges. These results demonstrate the feasibility of using *Jatropha curcas* oil as a sustainable base stock for automotive lubricants.

Keywords: Bio-lubricant, *Jatropha curcas*, Transesterification, Epoxidation, ISO VG-46, Physicochemical properties.

1 INTRODUCTION

Lubricants play a critical role in reducing friction, wear, and energy losses in mechanical systems, particularly in automotive and industrial applications. Conventional mineral oil-based lubricants are derived from non-renewable petroleum resources and are associated with ecological concerns, including toxicity, poor biodegradability, and disposal challenges [1]. These limitations have spurred growing interest in developing sustainable, environmentally friendly bio-lubricants derived from renewable feedstocks [2]. Vegetable oils have received considerable attention as base stocks for bio-lubricant formulation owing to their biodegradability, high lubricity, and favorable viscosity–temperature characteristics [3]. However, their direct use is limited by weak oxidative stability, poor low-temperature performance, and susceptibility to thermal degradation. Consequently, chemical modification methods such as transesterification and epoxidation are frequently employed to improve their physicochemical and tribological properties [4].

Owing to its favorable fatty acid composition, high oil yield, and non-competition with food resources, *Jatropha curcas* oil is regarded as a promising non-edible feedstock for bio-lubricant production [5]. Previous studies have reported improvements in lubrication performance through individual chemical modification steps and additive incorporation [6]. However, many studies remain confined to isolated synthesis procedures or short-term laboratory evaluations, with limited insight into integrated formulation strategies and real engine performance. The present study aims to develop a high-performance bio-lubricant from *Jatropha curcas* oil through a multistep modification process involving esterification, transesterification, epoxidation, and a multi-additive formulation. The study systematically evaluates the influence of chemical functionalization and additive synergy on physicochemical properties, thermal stability, and wear behavior. Unlike many prior studies, the formulated bio-lubricant is evaluated through an extended 12,000 km in-service motorcycle engine test, providing practical insight into durability and performance under real operating conditions.

1.1. Novelty and Contribution of the Study

In most bio-lubricant development studies, transesterification, epoxidation, and additive blending strategies are applied separately. In contrast, this study develops an integrated, application-based formulation strategy and evaluates it under real engine operating conditions. While individual chemical modification steps and laboratory tribological evaluations have been widely reported, this study integrates feedstock selection, multi-step chemical modification, constraint-guided multi-additive formulation, and extended in-service engine evaluation within a coherent framework. Additionally, structure–property–performance relationships are quantitatively analyzed by correlating molecular functionalization (epoxide formation and additive compatibility) with viscosity index enhancement, thermal stability, and wear behavior during the 12,000 km field test. The integration of chemical modification and real-world engine validation offers a contribution beyond incremental chemical processing.

https://doi.org/10.58482/ijeresm.v5i1.2

2 MATERIALS AND METHODOLOGY

2.1. Materials, Samples, and Sample Preparation

Jatropha curcas oil and all reagents were supplied by a chemical supplier in Kumasi, Ghana. The *Jatropha curcas* oil was treated with anhydrous sodium sulfate to remove moisture. The crude oil was stirred with anhydrous sodium sulfate for 2 h, then allowed to stand at ambient temperature for 24 h to facilitate moisture absorption. After filtration to remove the drying agent, the moisture-free oil was obtained and subsequently characterized using FTIR.

2.2. Physicochemical Characterization of *Jatropha curcas* Oil

The physicochemical properties of the moisture-free *Jatropha curcas* oil were determined prior to chemical modification. The tests were carried out in accordance with applicable ASTM standard procedures under controlled laboratory conditions. The oil's density was determined using a pycnometer. Fifty cubic centimeters (50 cm^3) of *Jatropha curcas* oil was filled into a weighed pycnometer. The mass of the oil was obtained by subtracting the mass of the empty pycnometer from that of the filled one. The density was calculated as the mass per unit volume using Eq. 1.

$$\text{Density} = \frac{\text{Mass of the sample}}{\text{Volume of the sample}} \tag{1}$$

Kinematic viscosity was measured using a Cannon–Fenske standard viscometer in accordance with ASTM D445. The viscometer was filled with the oil sample and immersed in a temperature-controlled bath maintained at 40 °C and 100 °C. After allowing sufficient time for the sample to reach the bath temperature, the efflux time was recorded. The kinematic viscosity was obtained by multiplying the viscometer constant by the measured efflux time. The saponification value was determined by refluxing 2 g of *Jatropha curcas* oil with 50 mL of 4% ethanolic potassium hydroxide (KOH) solution at 65 °C. After complete saponification, the excess KOH was back-titrated with 0.5 N hydrochloric acid using phenolphthalein as an indicator. The saponification value was calculated using Eq. 2.

$$\text{Saponification Value} = \frac{\text{Titre value} \times \text{Normality} \times 56.11}{\text{Weight of sample}} \tag{2}$$

The acid value was determined by dissolving 2.5 g of oil in 50 mL of neutralized ethanol and heating the mixture to approximately 65 °C to ensure proper dissolution. The solution was then titrated with 0.1 N sodium hydroxide (NaOH) solution using phenolphthalein as an indicator until a persistent light pink endpoint was observed. The acid value, expressed in mg KOH g^{-1}, was calculated using Eq. 3.

$$\text{Acid Value} = \frac{\text{Titre value} \times \text{Normality} \times 40}{\text{Weight of sample}} \tag{3}$$

The pour point was determined by transferring the oil sample into a test tube fitted with a thermocouple and then gradually cooling it. The temperature at which the oil ceased to flow and subsequently began to flow upon slight warming was recorded as the pour point. The percentage of free fatty acid (% FFA) was determined by titration, similar to the method used for the acid value. A 2.5 g oil sample was mixed with 50 mL of neutralized ethanol and titrated with 0.1 N NaOH until the endpoint was reached. The % FFA was calculated using Eq. 4.

$$\%\text{FFA} = \frac{0.5 \times Titre\ value \times Normalcy \times 40}{Weight\ of\ sample} \tag{4}$$

The average molecular weight of the oil was estimated from the experimentally determined saponification value (SV) and acid value (AV) using Eq. 5.

$$\text{Average Molecular Weight} = \frac{56.11 \times 3 \times 100}{(SV - AV)} \tag{5}$$

where SV is the saponification value (mg KOH g^{-1}), AV is the acid value (mg KOH g^{-1}), and 56.11 represents the molecular weight of potassium hydroxide.

2.3. Synthesis of Bio-Lubricant from *Jatropha curcas* Oil

The bio-lubricant was prepared from *Jatropha curcas* oil through a progressive chemical modification approach. The crude oil was first esterified, then transesterified to produce fatty acid methyl ester (FAME).

Oxidative stability was subsequently enhanced through epoxidation, and selected additives were incorporated to improve lubrication performance and meet automotive requirements. The synthesis steps were carried out under fixed reaction conditions and standardized procedures to ensure consistency of the produced lubricant. Although full batch-to-batch replication was not performed, intermediate and final products exhibited consistent physicochemical behavior across measurements, indicating process stability under the applied conditions.

2.3.1. Esterification of *Jatropha curcas* Oil

A 110 g mass of *Jatropha curcas* oil was weighed and introduced into a 500 mL three-neck round-bottom flask. A 20% (w/w) methanol solution and 5% (w/w) sulfuric acid were added to the flask. The oil–methanol mixture was heated in a water bath at 60 °C with constant stirring at 600 rpm. The free fatty acid content of the esterified oil was determined by titration with 0.1 N NaOH solution.

2.3.2. Transesterification of *Jatropha curcas* Oil

The bio-lubricant was prepared through a two-step transesterification process. In the first step, 100 g of esterified oil was reacted with methanol at a 1:4 molar ratio in the presence of potassium hydroxide (0.5% w/w of oil) as the catalyst. The reaction was carried out at 60 °C with stirring at 600 rpm for 2 h. In the second step, 30 g batches of methyl ester obtained from the first reaction were reacted with ethylene glycol at a 1:2 molar ratio using 0.5 M sodium hydroxide as the catalyst. The reaction was carried out at 120 °C with stirring at 600 rpm for 2.5 h. After completion, the mixture was cooled and transferred to a separating funnel, where gravity separation was used to isolate fatty acid methyl ester (FAME) from glycerol.

2.3.3. Epoxidation of Bio-Lubricant (Fatty Acid Methyl Esters)

Epoxidation using in-situ generated peracetic acid was carried out to enhance the oxidative stability and lubricating properties of the synthesized fatty acid methyl esters (FAME). The oxidizing agent was prepared by mixing 10 mL of glacial acetic acid with 30 mL of hydrogen peroxide and stirring at 40 °C for 30 min to form peracetic acid. The prepared peracid solution was then added to the FAME under stirring at 60 °C for 4 h to induce epoxidation of the unsaturated carbon–carbon double bonds. After the reaction, the mixture was washed and phase-separated to remove residual reactants and by-products, yielding the final epoxidized bio-lubricant.

2.3.4. Incorporation of Additives into the Synthesized Jatropha Bio-Lubricant

The synthesized *Jatropha*-based lubricant was blended in varying volumes (200, 150, 100, and 50 mL) with different concentrations (2, 4, 6, and 8 mL) of six distinct additives: phenolic and amide antioxidants, polyisobutylene (PIB), calcium sulfonate, amide-based inhibitors, molybdenum disulfide, and sulfur–phosphorus compounds. The physicochemical parameters (pour point, viscosity, viscosity index, and density) of the formulated bio-lubricant were subsequently evaluated. Additive concentrations were varied incrementally to observe property trends rather than to perform full factorial optimization, consistent with preliminary formulation screening practice.

2.4. Characterization of Modified Jatropha Oil Samples

The compositional and structural changes during chemical modification were analyzed by characterizing the samples. The products evaluated included synthesized *Jatropha* methyl esters (biodiesel), epoxidized *Jatropha* oil, and the final bio-lubricant formulated with additives.

2.4.1. Fatty Acid Methyl Ester (FAME) Analysis

Gas Chromatography–Mass Spectrometry (GC–MS) was used to evaluate the fatty acid methyl ester (FAME) composition of the oil samples at different stages of modification. Approximately 1 µL of each diluted sample was injected into the GC–MS system. The analyses were performed under consistent operating conditions, and the obtained mass spectra were compared with the NIST library for component identification.

2.4.2. Functional Group Analysis

Functional groups in the synthesized *Jatropha*-based bio-lubricant were identified using Fourier Transform Infrared Spectroscopy (FTIR). The analysis confirmed the presence of characteristic ester and epoxide functional groups, thereby verifying the chemical structure of the modified bio-lubricant.

2.5. Assessment of Bio-Lubricant Performance Samples

The performance of the *Jatropha*-based bio-lubricant was evaluated under real engine operating conditions. The test covered a total distance of 12,000 km using a single engine. Oil samples were collected at 1,000 km intervals and analyzed to monitor changes in key physicochemical parameters. X-ray Fluorescence (XRF) spectroscopy was used to assess the wear-control performance of the developed bio-lubricant.

2.5.1. Performance Testing

The performance of the *Jatropha*-based bio-lubricant was evaluated by operating a motorcycle for 12,000 km under practical test conditions. Oil samples were collected at 1,000 km intervals and analyzed for key physicochemical parameters, including density, kinematic viscosity at 40 °C and 100 °C, viscosity index, pour point, and flash point, using ASTM standard methods. The measured parameters were plotted against distance to observe degradation trends.

2.5.2. Assessment of Wear Protection Efficacy of Synthesized Bio-Lubricant

Metal content analysis was performed using X-ray Fluorescence (XRF) spectroscopy to evaluate the wear protection capability of the synthesized *Jatropha*-based bio-lubricant. Both virgin bio-lubricant samples (new samples with additives) and used bio-lubricant samples (after 12,000 km of engine operation) were analyzed. Prior to analysis, samples were filtered through a 0.45 µm membrane and collected in polypropylene containers. Wear metals such as Fe, Al, Cu, Cr, Mg, Mn, Zn, and Ni were quantified using calibrated XRF procedures. Metal concentrations in used samples were compared with virgin samples and referenced against OEM wear thresholds to assess lubricant performance.

2.5.3. Engine Test Protocol and Operating Conditions

Engine operation testing was conducted using a four-stroke, single-cylinder motorcycle engine commonly used for lightweight transportation in developing regions. The engine was operated under typical mixed urban and highway riding conditions to simulate realistic service environments rather than controlled laboratory bench testing. Engine speed varied within manufacturer-recommended ranges, with natural variations due to rider mass, road gradients, and traffic conditions. Ambient temperatures during operation ranged from 25 °C to 35 °C, typical of tropical climates. The lubricant was charged at the beginning of the test and remained in service without replacement throughout the 12,000 km evaluation period. This extended drain interval was selected to assess lubricant durability under prolonged service conditions. Oil samples were collected at 1,000 km intervals to monitor trends in physicochemical degradation. The test was conducted with a single engine, and no parallel-control oil was evaluated under identical operating conditions.

2.6. Experimental Repeatability and Data Reliability

The physicochemical measurements (density, kinematic viscosity at 40 °C and 100 °C, viscosity index, pour point, flash point, acid value, and free fatty acid content) were determined in accordance with the relevant ASTM and ISO standard methods. All measurements were performed under controlled laboratory conditions and within the repeatability limits specified by the respective standards. Measurement variability was evaluated based on the repeatability and reproducibility criteria defined in the applicable ASTM methods (e.g., ASTM D445, ASTM D2270, ASTM D97). The observed variations were within the acceptable limits specified in these standards, indicating reliable and reproducible measurements. For process development and comparative performance evaluation, the reported values represent the mean of the measured results.

3 RESULTS AND DISCUSSION

Performance evaluation is presented relative to ASTM specifications, OEM guideline limits, and relevant literature benchmarks, while acknowledging the absence of a direct experimental comparison with a commercial reference oil.

3.1. Physicochemical Characterization of the Lubricant Across Successive Chemical Processing Stages

3.1.1. Structure–Processing–Property Relationships across Lubricant Processing Stages

From a materials engineering perspective, the progressive changes in physicochemical properties across the processing stages—raw *Jatropha curcas* oil (JCO), transesterified oil (SJO), epoxidized oil (EJO), and the additive-blended formulation (JOA)—can be explained by systematic modifications in molecular structure, intermolecular interactions, and thermal response at each stage of chemical transformation. Such structure–processing–property relationships are fundamental to the design of lubricant materials, as controlled molecular modification directly influences macroscopic rheological and thermal properties [7].

- **Effect of Transesterification: Transformation of Triglycerides and Molecular Flow:** The crude JCO, comprising triglyceride molecules, consists of long hydrocarbon chains esterified to a glycerol backbone. This bulky molecular structure supports strong van der Waals interactions and molecular entanglement, leading to relatively high viscosity, higher density, and poor low-temperature mobility [8]. Transesterification fragments the glycerol backbone and transforms triglycerides into smaller, more homogeneously distributed fatty acid methyl esters. Such structural simplification causes a loss of molecular weight, chain entanglement, and steric hindrance, resulting in reduced density and a significant decrease at 40 °C and 100 °C. From a transport phenomena point of view, increased molecular mobility, together with diminished intermolecular cohesion post-transesterification, facilitates fluidity, but it also reduces load-bearing and thermal viscosity retention. This explains why the transesterified oil becomes more flowable and does not independently satisfy typical automotive lubrication viscosity requirements. The small increase in viscosity index indicates that, at higher temperatures, structural characteristics that promote elastic or associative responses may be absent, resulting in limited resistance to temperature-induced thinning [9].

- **Effect of Epoxidation: Influence of Polar Functional Groups and the Rigidity of the Structures:** Epoxidation significantly alters the molecular structure by converting unsaturated C=C bonds along the fatty acid chains into oxirane rings. This alteration adds polar oxygen-related functional groups, which enhance dipole–dipole interactions and local chain stiffness [10]. The resulting intermolecular forces are stronger, promoting resistance to molecular sliding and increasing the viscosity and density of the transesterified oil. Structurally, the epoxy rings limit rotational freedom along the fatty acid chains and moderate excessive thermal motion at high temperatures. This structural limitation explains the observed increase in viscosity retention at 100 °C and the substantial increase in viscosity index. Moreover, the epoxidized structure is characterized by lower volatility and greater thermal stability, which is reflected in an elevated flash point [8]. The improved pour point after epoxidation confirms a change in molecular geometry and, more importantly, the disruption of the tendency to pack particles consistently in the crystalline material, which favors solidification at low temperatures [11].
- **Effect of Additive Blending: Microstructural Engineering and Property Optimization:** The additive-blended formulations are thus a microstructural engineering step, rather than merely a compositional adjustment. The epoxidized base oil reacts with viscosity modifiers, pour-point depressants, and stabilizing additives to form transient molecular networks and undergo chemical and physical interactions with the epoxidized base oil. These interactions improve elastic recovery under shear and minimize sensitivity to temperature-induced viscosity loss, enabling the lubricant to meet the ISO VG-46 viscosity classification [12]. From a structure–property perspective, additives occupy free volume in the base oil matrix, adjust intermolecular distance, and generate synergistic interactions that stabilize the lubricant over a wide temperature range [13]. Consequently, the final formulation exhibits a higher viscosity index, a lower pour point, and a higher flash point. The enhanced flash point also indicates lower volatility, lower molecular weight, and greater thermal degradation resistance, which are essential for safe operation in a high-temperature engine [14].
- **Interpretation of Integrated Materials Engineering:** These physicochemical trends are consistent with controlled structural modification at the molecular level. Transesterification maximizes molecular mobility, epoxidation adds polarity and rigidity to enhance mechanical strength and thermal stability, and additive blending tunes intermolecular interactions to meet performance standards tailored to specific applications. The statistically significant differences detected by ANOVA are thus indicative of true processing-induced structural transformations rather than experimental variability [15] and highlight the effectiveness of the multi-stage processing route to customize lubricant behaviour through structure–property control.

3.1.2. Numerical Summary of Physicochemical Property Evolution Across Processing Stages

The physicochemical properties of raw *Jatropha curcas* oil (JCO), transesterified oil (SJO), epoxidized oil (EJO), and the additive-blended formulation (JOA) are summarized in Figs. 1–6. The reported values represent means, with error bars indicating standard deviations from replicate tests, providing a statistical basis for comparison across processing stages. Fig. 1 illustrates the variation in density across successive chemical processing stages. A decrease in density was observed after transesterification, attributable to reduced molecular complexity following conversion of triglycerides to methyl esters. A slight increase in density was observed after epoxidation and additive incorporation, likely due to increased molecular polarity and functional-group interactions. Despite these variations, all density values remained within ASTM-recommended ranges for automotive lubricants, indicating acceptable formulation stability.

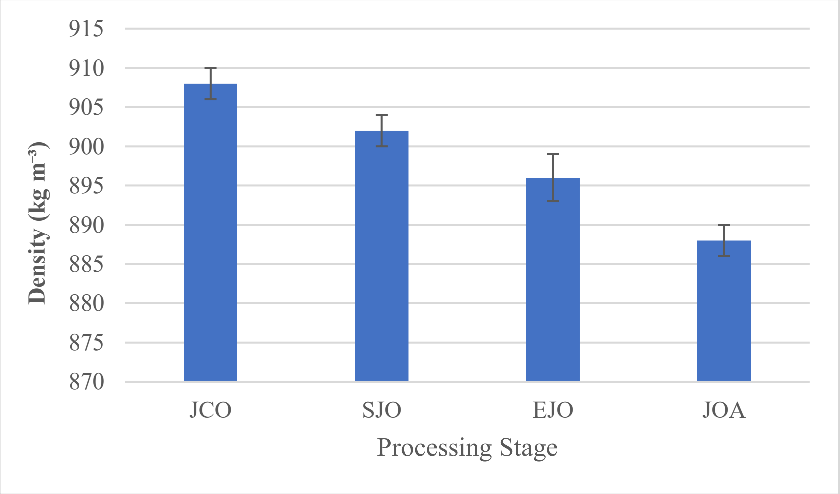

Fig. 1. Density Variation across Processing Stages

Fig. 2 shows that, after transesterification, the kinematic viscosity at 40 °C decreased substantially, indicating that ester formation induced enhanced fluidity. Nevertheless, this viscosity was below the requirement for automotive lubricant applications. Epoxidation led to a marked increase in viscosity because of oxirane ring formation, which enhances intermolecular interactions. The final additive-blended formulation exhibited the highest viscosity, meeting the ISO VG-46 classification, indicating that additive incorporation effectively restored and tuned viscosity to target specifications.

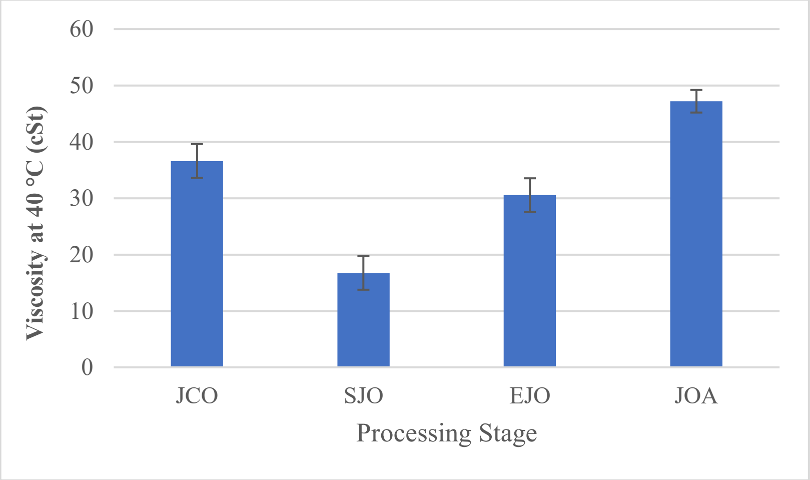

Fig. 2. Kinematic Viscosity at 40 °C

Fig. 3 shows viscosity behavior at elevated temperature (100 °C). Similar trends to those observed at 40 °C were recorded: transesterification reduced viscosity, and epoxidation, followed by additive blending, significantly improved high-temperature viscosity retention. The improved viscosity at 100 °C for the final formulation indicates improved high-temperature viscosity retention and suitability for engine lubrication under operating conditions.

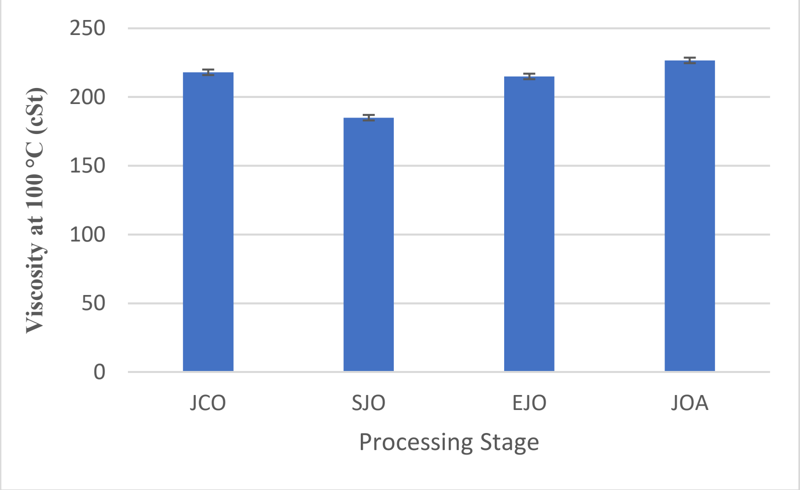

Fig. 3. Kinematic Viscosity at 100 °C

As shown in Fig. 4, the viscosity index (VI) increased progressively with each processing stage. Raw JCO exhibited the lowest VI, whereas transesterification led to a moderate increase. A more pronounced increase was observed after epoxidation, indicating improved viscosity–temperature behavior. The additive-blended formulation exhibited the highest VI, reflecting the combined influence of chemical modification and viscosity index improvers.

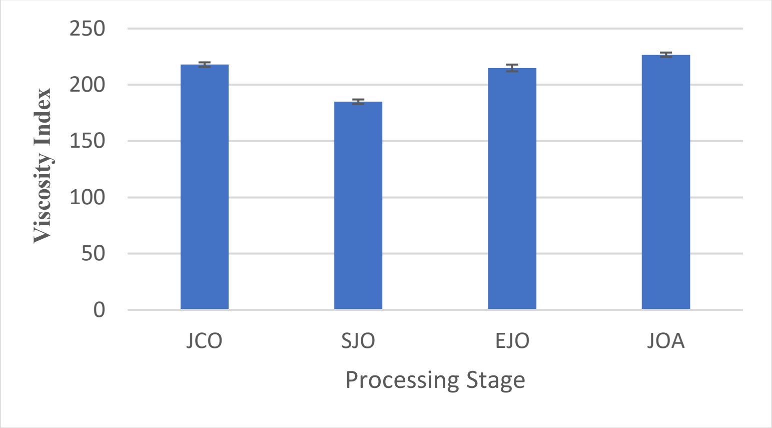

Fig. 4. Viscosity Index

Pour point changes across the stages of the formulation are shown in Fig. 5. Transesterification reduced molecular rigidity, thereby enhancing flow at low temperatures. The lower pour point from epoxidation and additive addition indicates improved cold-flow characteristics, further enhancing the applicability of final formulations for low-temperature engine operation.

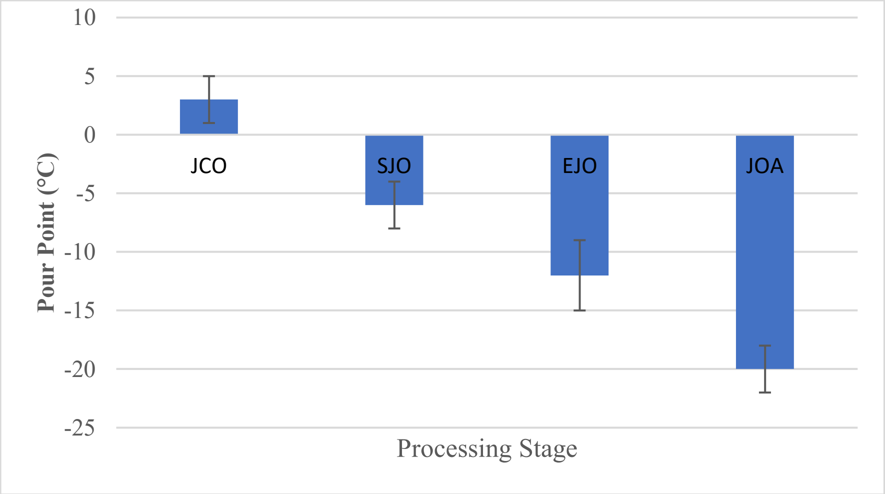

Fig. 5. Pour Point

As shown in Fig. 6, the flash point increased from raw JCO to the final formulation in a sequential manner. Following epoxidation and additive addition, the increment indicates improved thermal stability and decreased volatility. This improvement is particularly relevant to the engine's safe handling and high-temperature performance. Fig. 1-6 shows the standard deviations of replicate measurements as error bars, indicating good repeatability of the experimental data. Physicochemical properties change significantly across processing stages, accounting for variability, indicating that the observed differences are attributable to the processing stage rather than measurement variability. in the differences in physicochemical properties. The one-way ANOVA showed that the processing stage had a statistically significant effect ($p < 0.05$) on viscosity, viscosity index, pour point, and flash point, indicating a significant influence on the measured properties.

All physicochemical measurements were performed in triplicate and reported as mean ± standard deviation. Statistical analysis was performed using one-way analysis of variance (ANOVA) in Microsoft Excel to assess the effect of the processing stage on lubricant properties at the 95% confidence level ($p < 0.05$). The developed *Jatropha*-based bio-lubricant (JOA) was benchmarked against published ASTM specifications, ISO viscosity classification guidelines (ISO VG-46), and representative values reported for commercial mineral and synthetic lubricants. Although a direct parallel experimental comparison with a commercial reference oil was not conducted, literature-based benchmarking provides a standardized basis for evaluating performance and suitability. A summary comparison of the synthesized bio-lubricant properties with typical ISO VG-46 specification ranges is presented in Table 1. The developed formulation meets the viscosity, viscosity index, pour point, and flash point requirements for ISO VG-46 lubricants. Recent literature reports that chemically modified ester-based bio-lubricants derived from non-edible vegetable oils can achieve viscosity indices above 200 and elevated flash points following functional modification [7–9]. Similar findings have been reported for waste-based and seed-based bio-lubricants, where improved viscosity–temperature behavior and thermal stability were observed relative to mineral oil benchmarks.

Based on these comparisons, the developed *Jatropha*-based formulation demonstrates technical feasibility for ISO VG-46 applications under comparable operating conditions.

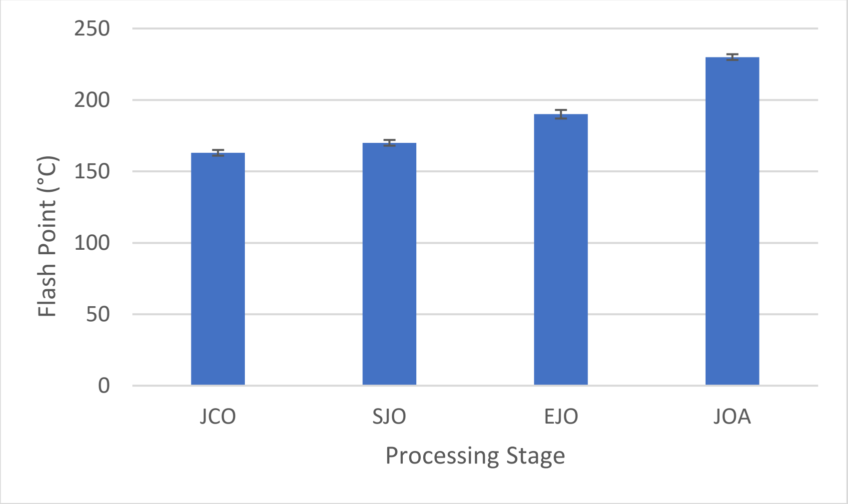

Fig. 6. Flash Point

Table 1. Physicochemical properties of the synthesized Jatropha-based bio-lubricant in comparison with the typical ISO VG-46 lubricant specification ranges

Property	Developed Jatropha Bio-Lubricant (JOA)	Typical ISO VG-46 Mineral Oil*	Typical ISO VG-46 Synthetic Ester*	ISO VG-46 Requirement
Density (kg/m³)	888	860-900	880-920	-
Viscosity @40 °C (cSt)	47.2	41-50	42-48	41.4-50.6
Viscosity @100 °C (cSt)	15.2	6.8-8.6	9-12	≥ 4.1
Viscosity Index	227	90-120	150-220	≥ 90
Pour Point (°C)	-20	-6 to -12	-15 to -25	-
Flash Point (°C)	230	200-220	220-260	≥ 130

3.2. Gas Chromatography–Mass Spectrometry (GC–MS) Analysis

GC–MS analysis was used to determine the compositional changes of *Jatropha curcas* oil resulting from chemical modification. The raw oil consisted primarily of high-molecular-weight triglycerides with low volatility, which were poorly resolved by GC–MS. Following transesterification, fatty acid methyl esters (FAMEs) were formed, enabling effective chromatographic separation and compositional analysis. Compound identification (Table 2) revealed a predominance of C18 methyl esters formed during transesterification. The GC–MS chromatogram of the synthesized methyl esters showed a predominance of C18 components, with methyl oleate (41.7%) and methyl stearate (25.1%) as the major constituents, along with smaller fractions of methyl palmitate and methyl linoleate. This distribution is characteristic of *Jatropha*-derived esters and confirms the effective conversion of triglycerides into lower-molecular-weight methyl esters. From a formulation perspective, the predominance of C18 methyl esters provides a balance between molecular flexibility and thermal stability.

Unsaturated esters improve low-temperature flow behavior, while saturated components support viscosity retention at elevated temperatures. These compositional changes explain the observed decrease in kinematic viscosity following transesterification (36.6 → 16.7 cSt at 40 °C), where heavier triglyceride molecules are replaced by more mobile ester species. Similar reductions in viscosity following FAME formation have been reported for vegetable oil-derived lubricant base stocks. The FAME composition observed in this study aligns with recent findings for transesterified non-edible vegetable oils used in bio-lubricant production, although variations in ester distribution are expected due to differences in feedstock origin, fatty acid profile, catalyst selection, and processing conditions [19–21]. The GC–MS results confirm successful transesterification and provide a compositional basis for the observed improvements in flow characteristics, viscosity–temperature behavior, and compatibility with subsequent additive incorporation. Fig. 7 shows GC–MS chromatograms illustrating the progressive chemical modification of *Jatropha curcas* oil.

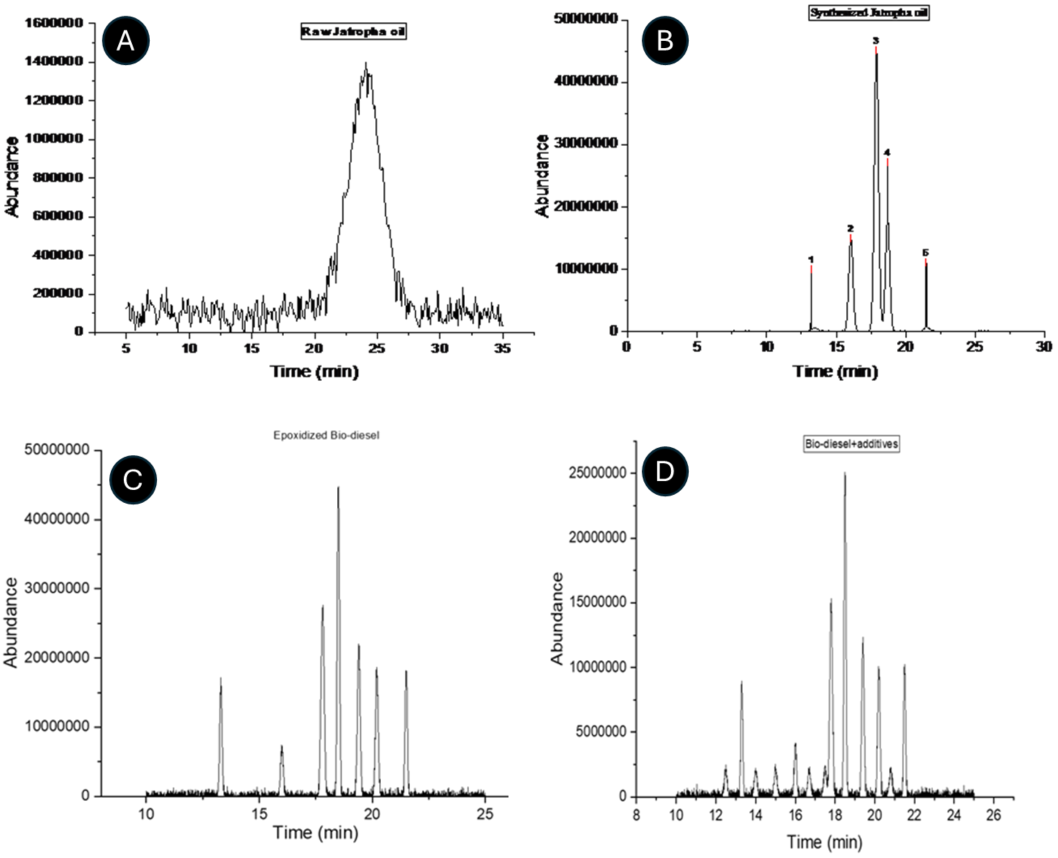

Fig. 7. GC–MS chromatograms illustrating the progressive chemical modification of *Jatropha curcas* oil: (A) unrefined oil, (B) synthesized Jatropha oil (methyl ester), (C) epoxidized synthesized Jatropha oil, and (D) epoxidized Jatropha biodiesel with additives (JOA).

Table 2: Identified Chemical Compounds and their Function in Bio-lubricant

Compound	**Function in Bio-lubricant**
MoS_2 (Molybdenum Disulfide)	Anti-wear, friction reduction
Methyl Palmitate (C16:0)	Base fluid enhances cold-flow
Polyisobutylene (PIB)	Viscosity index improver
Calcium Sulfonate	Detergent, corrosion inhibitor
Methyl Linoleate (C18:2)	Improves biodegradability and flow
Amide-based Inhibitors	Corrosion and oxidation protection
Phenolic & Amide Antioxidants	Thermal stability, oxidative resistance
Methyl Oleate (C18:1)	Lubricity, thermal stability
Methyl Stearate (C18:0)	Viscosity and lubricating film strength
Epoxidized Methyl Oleate (EMO)	Anti-wear, oxidative resistance
Epoxidized Methyl Linoleate (EMLO)	Improves low-temp and anti-oxidation
Sulfur-Phosphorus compounds	EP additive (extreme pressure)
Methyl Arachidate (C20:0)	Viscosity booster, thermal protection

3.3. Fourier Transform Infrared (FTIR) Analysis

Fourier Transform Infrared (FTIR) spectroscopy was employed to monitor the evolution of functional groups across successive stages of chemical modification of *Jatropha curcas* oil. The FTIR spectra of the synthesized methyl ester, epoxidized ester with additives, and the final bio-lubricant formulation are presented in Fig. 8(a–c), while the principal absorption bands and corresponding functional groups are summarized in Table 3. The spectrum of synthesized *Jatropha* methyl ester showed a strong ester carbonyl (C=O) stretching band near 1740 cm^{-1}, confirming successful transesterification. The reduction in hydroxyl-associated bands is consistent with triglyceride conversion to methyl esters, as reported for chemically modified vegetable oils [22]. Such FTIR-observed changes are generally associated with reduced intermolecular hydrogen bonding, which may contribute to improved flow behavior.

Epoxidation of the methyl ester is indicated by the appearance of characteristic oxirane ring absorptions near 1160 and 965 cm^{-1}, along with a reduction in bands associated with unsaturation. Comparative studies of epoxidized natural oils have reported similar functional group changes, with increased molecular polarity in FTIR spectra associated with improved lubricity and viscosity–temperature behavior. Following additive incorporation, the FTIR spectrum of the final formulation retained the characteristic ester and epoxide functional groups, suggesting chemical compatibility during blending. The absence of new degradation-associated peaks indicates no significant chemical degradation during formulation, consistent with additive compatibility [23]. These results support a structure–property relationship between chemical functionalization and the observed improvements in lubricant performance.

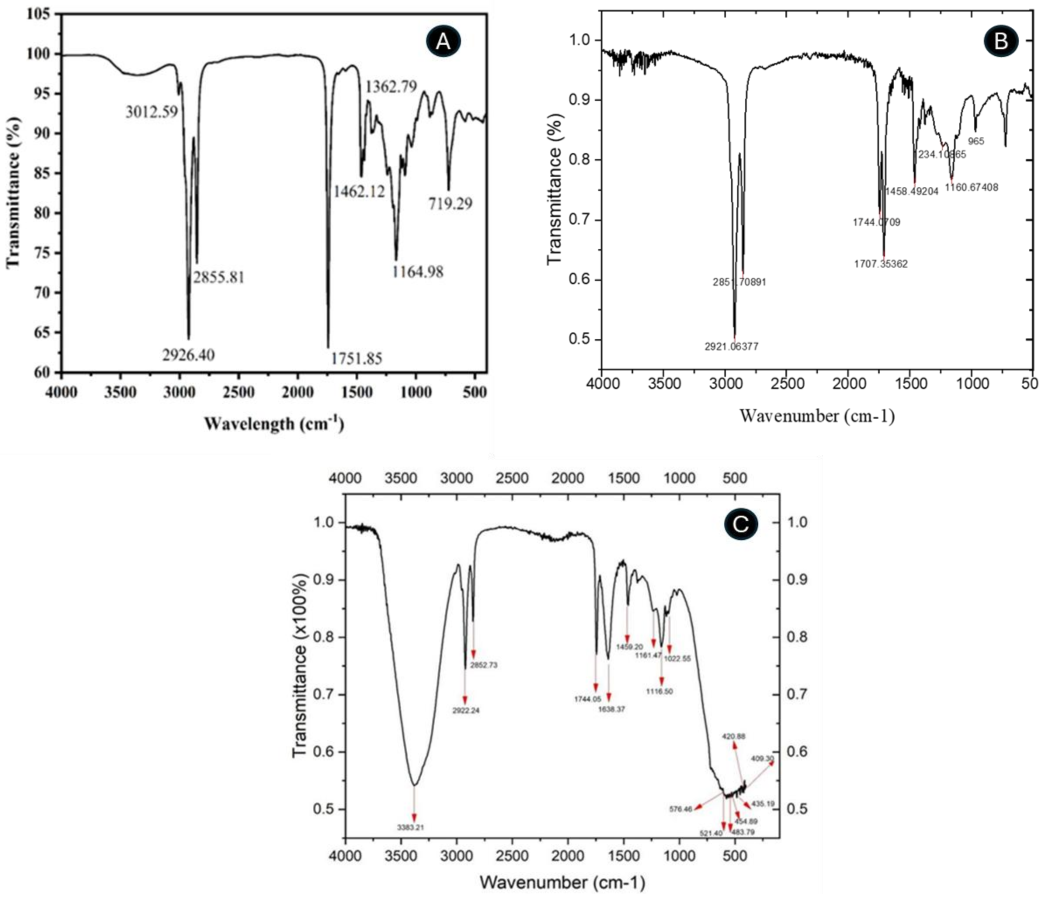

Fig. 8. FTIR spectra illustrate functional group evolution during chemical modification of *Jatropha curcas* oil. (a) bio-lubricant obtained from *Jatropha* oil, (b) synthesized *Jatropha* oil-based bio-lubricant (methyl ester), and (c) epoxidized *Jatropha* biodiesel with additives (JOA).

Table 3. Principal FTIR absorption bands and corresponding functional group assignments at different chemical modification stages of *Jatropha curcas* oil.

Wavenumber (cm^{-1})	**Assigned Functional Group**
2921.06	C–H asymmetric stretch of –CH_2– (long aliphatic chains)
2851.70	C–H symmetric stretch of –CH_2– chains
1744.07	Strong C=O stretch of ester carbonyl (–COO–), indicating methyl esters
1707.35	Minor free acid or conjugated carbonyl (unreacted FFA or oxidation)
1653.49	C=C stretching vibration (residual unsaturation in FAME chains)
1458.49	CH_2 scissoring or bending vibrations (aliphatic backbone)
1375 (typical)	CH_3 symmetric bending (–CH_3 group)
1160.67 and 965	Epoxide C–O–C asymmetric stretch and oxirane ring deformation

3.4. Additive Effects and Final Bio-Lubricant Formulation

The additive concentrations used in this study were selected through a sequential formulation approach consistent with preliminary industrial lubricant development practices.

Individual additives were introduced at incremental low-to-medium concentrations to evaluate their influence on key physicochemical properties, including kinematic viscosity, viscosity index, pour point, and density, with the objective of meeting ISO VG-46 requirements. The final formulation adopted an equal-fraction approach (3.33% per additive; total additive content of 20%), considering three practical constraints: (i) total additive loading should remain within typical limits for ester-based engine lubricants; (ii) excessive viscosity thickening and unfavorable additive interactions should be avoided; and (iii) a balanced performance profile should be maintained across friction modification, oxidation resistance, detergency, corrosion inhibition, and extreme-pressure protection. The incremental additive screening results (Tables 4–9) show progressive changes in viscosity, viscosity index, and pour point within the investigated concentration ranges. While property improvements were observed with increasing additive levels, the magnitude of improvement diminished at higher concentrations, particularly for viscosity and density control. Therefore, the selected formulation represents a practical balance between performance enhancement and formulation stability.

Table 4. Effect of Polyisobutylene (PIB) concentration on physicochemical properties of synthesized *Jatropha* bio-lubricant

Base Oil (ml)	**Additive – PIB (ml)**	**Properties of the Lubricant Mixture**				
		Pour Point (°C)	**Viscosity @40°C (cSt)**	**Viscosity @100°C (cSt)**	**Viscosity Index**	**Density (g/cm³)**
200	2	-19	40	8.5	150	0.86
200	4	-21	42	8.8	155	0.865
200	6	-23	44	9.1	160	0.87
200	8	-25	46	9.4	165	0.875
150	2	-17	44	9.0	140	0.87
150	4	-19	46	9.3	145	0.875
150	6	-21	48	9.6	150	0.88
150	8	-23	50	9.9	155	0.885
100	2	-15	48	9.5	135	0.88
100	4	-17	50	9.8	140	0.885
100	6	-19	52	10.1	145	0.89
100	8	-21	54	10.4	150	0.895
50	2	-13	52	10.0	125	0.89
50	4	-15	54	10.3	130	0.895
50	6	-17	56	10.6	135	0.90
50	8	-19	58	10.9	140	0.905
125	5	-17.88	49	9.7	145	0.883

Table 5. Average physicochemical Property Data of Molybdenum Disulfide (MoS_2) Addition to Synthesized *Jatropha* Bio-lubricant

Base Oil (ml)	**Additive – MoS_2 (ml)**	**Properties of the Lubricant Mixture**				
		Pour Point (°C)	**Viscosity @40°C (cSt)**	**Viscosity @100°C (cSt)**	**Viscosity Index**	**Density (g/cm³)**
200	2	-20	45	9.0	140	0.87
200	4	-22	46	9.2	142	0.875
200	6	-24	48	9.5	145	0.88
200	8	-26	50	9.8	148	0.885
150	2	-18	50	9.5	135	0.88
150	4	-20	52	9.8	138	0.885
150	6	-22	54	10.0	140	0.89
150	8	-24	56	10.3	143	0.895
100	2	-16	55	10.0	130	0.89
100	4	-18	57	10.3	133	0.895
100	6	-20	59	10.5	135	0.90
100	8	-22	61	10.8	138	0.905
50	2	-14	60	10.5	125	0.90
50	4	-16	62	10.8	128	0.905
50	6	-18	64	11.0	130	0.91
50	8	-20	66	11.3	133	0.915
125	5	-17.78	55.31	10.14	136.44	0.893

The formulation strategy used an empirical screening approach commonly adopted in early-stage bio-lubricant development, in which additive effects are evaluated sequentially before advanced multivariate optimization. Although factorial or response-surface methodologies may provide more refined interaction analysis, the present approach establishes a representative and practically applicable baseline for performance evaluation and subsequent optimization studies.

Table 6. Average physicochemical Property Data of Calcium Sulfonate Addition to Synthesized *Jatropha* Bio-lubricant

Base Oil (ml)	**Additive – Calcium Sulfonate (ml)**	**Properties of the Lubricant Mixture**				
		Pour Point (°C)	**Viscosity @40°C (cSt)**	**Viscosity @100°C (cSt)**	**Viscosity Index**	**Density (g/cm³)**
200	2	-18	48	9.3	145	0.875
200	4	-20	50	9.6	150	0.88
200	6	-22	52	9.9	155	0.885
200	8	-24	54	10.2	160	0.89
150	2	-16	52	9.8	140	0.885
150	4	-18	54	10.1	145	0.89
150	6	-20	56	10.4	150	0.895
150	8	-22	58	10.7	155	0.90
100	2	-14	56	10.3	130	0.895
100	4	-16	58	10.6	135	0.90
100	6	-18	60	10.9	140	0.905
100	8	-20	62	11.2	145	0.91
50	2	-12	60	10.8	120	0.905

Table 7. Average physicochemical Property Data of Amine-Based Inhibitors Addition to Synthesized *Jatropha* Bio-lubricant

Base Oil (ml)	**Additive – Amide-Based Inhibitors (ml)**	**Properties of the Lubricant Mixture**				
		Pour Point (°C)	**Viscosity @40°C (cSt)**	**Viscosity @100°C (cSt)**	**Viscosity Index**	**Density (g/cm³)**
200	2	-19	47	9.2	148	0.87
200	4	-21	49	9.5	150	0.875
200	6	-23	51	9.8	153	0.88
200	8	-25	53	10.1	156	0.885
150	2	-17	51	9.7	138	0.88
150	4	-19	53	10.0	141	0.885
150	6	-21	55	10.3	144	0.89
150	8	-23	57	10.6	147	0.895
100	2	-15	55	10.1	133	0.89
100	4	-17	57	10.4	136	0.895
100	6	-19	59	10.7	139	0.90
100	8	-21	61	11.0	142	0.905
50	2	-13	60	10.6	123	0.90
50	4	-15	62	10.9	126	0.905
50	6	-17	64	11.2	129	0.91
50	8	-19	66	11.5	132	0.915
125	5	-17.88	56.25	10.35	139.81	0.893

The final additive concentrations (3.33% per additive) were selected based on a quantitative interpretation of the screening data presented in Tables 4–9. The justification is based solely on the experimental screening data presented in Tables 4–9. Preliminary additive screening was conducted to establish a feasible concentration range for each functional additive. Additives were evaluated at volumes of 2, 4, 6, and 8 mL added to base oil volumes of 50, 100, 150, and 200 mL (Tables 4–9). For consistent ratio evaluation, a fixed base oil volume of 200 mL was adopted for formulation analysis, as this corresponds to the base oil quantity used in the final formulation.

Table 8. Average physicochemical Property Data of Phenol & Amine Antioxidants Addition to Synthesized *Jatropha* Bio-lubricant

Base Oil (ml)	Additive – Phenolic & Amide Antioxidants (ml)	Properties of the Lubricant Mixture				
		Pour Point (°C)	Viscosity @40°C (cSt)	Viscosity @100°C (cSt)	Viscosity Index	Density (g/cm³)
200	2	-20	46	9.1	147	0.87
200	4	-22	48	9.4	150	0.875
200	6	-24	50	9.7	153	0.88
200	8	-26	52	10.0	156	0.885
150	2	-18	50	9.6	137	0.88
150	4	-20	52	9.9	140	0.885
150	6	-22	54	10.2	143	0.89
150	8	-24	56	10.5	146	0.895
100	2	-16	54	10.0	130	0.89
100	4	-18	56	10.3	133	0.895
100	6	-20	58	10.6	136	0.90
100	8	-22	60	10.9	139	0.905
50	2	-14	58	10.5	122	0.90

Table 9. Average physicochemical Property Data of Sulfur-Phosphorus Compounds Addition to Synthesized *Jatropha* Bio-lubricant

Base Oil (ml)	Additive – Sulfur-Phosphorus Compounds (ml)	Properties of the Lubricant Mixture				
		Pour Point (°C)	Viscosity @40°C (cSt)	Viscosity @100°C (cSt)	Viscosity Index	Density (g/cm³)
200	2	-21	44	8.8	149	0.865
200	4	-23	46	9.1	152	0.87
200	6	-25	48	9.4	155	0.875
200	8	-27	50	9.7	158	0.88
150	2	-19	48	9.3	138	0.875
150	4	-21	50	9.6	141	0.88
150	6	-23	52	9.9	144	0.885
150	8	-25	54	10.2	147	0.89
100	2	-17	52	9.8	128	0.88
100	4	-19	54	10.1	131	0.885
100	6	-21	56	10.4	134	0.89
100	8	-23	58	10.7	137	0.895
50	2	-15	56	10.3	120	0.89
50	4	-17	58	10.6	123	0.895
50	6	-19	60	10.9	126	0.90
50	8	-21	62	11.2	129	0.905
125	5	-19.76	53	10	138.25	0.885

The volumetric additive concentration was calculated using Eq. 6.

$$C(\%) = \frac{V_{\text{additive}}}{V_{\text{base oil}}} \times 100 \tag{6}$$

For a 200 mL base oil volume, the screened additive levels correspond to:

- 2 mL → 1% (v/v)
- 4 mL → 2% (v/v)
- 6 mL → 3% (v/v)
- 8 mL → 4% (v/v)

These results define a practical working concentration range of approximately 1–4% (v/v) per additive. Within this range, the viscosity index increased progressively, the pour point improved, and the kinematic viscosity rose in a controlled manner. No evidence of phase instability, density reduction, or additive incompatibility was observed. Inspection of Tables 4–9 indicates that the most pronounced improvements in viscosity index and pour point occurred toward the upper end of the screened range (6–8 mL per 200 mL base oil; 3–4%). Beyond this region, incremental gains became less proportional relative to viscosity increase, suggesting the need to limit additive loading to preserve formulation balance and avoid excessive thickening.

In the final formulation, six functional additives—polyisobutylene (PIB), molybdenum disulfide (MoS_2), calcium sulfonate, amide-based corrosion inhibitors, phenolic/amine antioxidants, and sulfur–phosphorus compounds were combined. To prevent excessive viscosity thickening, minimize potential additive antagonism, and maintain functional balance, total additive loading was capped at 20% of the formulation, with the remaining 80% comprising the base oil. The total additive package was distributed equally among the six components:

$$\text{Each additive } (\%) = \frac{20}{6} = 3.33\%$$

This yields a final composition of 80% base oil and 3.33% per additive. To maintain consistency with the screening experiments, the total blend volume was derived from the selected 80% base oil fraction. A base oil volume of 200 mL corresponds to a total blend volume (V_T) of 250 mL:

$$0.80 \times V_T = 200 \Rightarrow V_T = 250 \text{ mL} \quad (7)$$

Thus, the combined additive package represents 20% of the final blend (50 mL). When distributed equally among six additives, the individual additive volume becomes:

$$\frac{50}{6} = 8.33 \text{ mL}$$

Expressed as a percentage of the total blend:

$$\frac{8.33}{250} \times 100 = 3.33\% \quad (8)$$

The final additive concentration of 3.33% per additive was therefore derived directly from the experimentally identified high-performance region during single-additive screening. This value remains within the validated 3–4% concentration range, satisfies ISO VG-46 viscosity requirements, and reduces the likelihood of excessive viscosity increase or adverse additive interactions. The formulation approach represents a constraint-guided empirical strategy appropriate for early-stage lubricant development, providing a practical basis for subsequent multivariate optimization using formal design-of-experiments methodologies.

Table 10. Final bio-lubricant formulation based on constraint-guided additive optimization

Component	**Function**	**Percentage (%)**	**Notes**
Jatropha-Based Synthetic Base Oil	Base Lubricant	80%	The main lubricating medium provides the bulk of the formulation.
Molybdenum Disulfide (MoS_2)	Friction Modifier	3.33%	Reduces friction and boundary wear, particularly under boundary lubrication conditions.
Polyisobutylene (PIB)	Viscosity Index Improver	3.33%	Enhances viscosity stability across a wide temperature range.
Calcium Sulfonate	Detergent/Corrosion Inhibitor	3.33%	Provides cleaning properties and protects against corrosion.
Amide-Based Inhibitors	Corrosion Inhibitor	3.33%	Offers additional corrosion protection, especially in harsh environments.
Phenolic and Amide Antioxidants	Oxidation Inhibitors	3.33%	Prevents oxidation, extending the lubricant's life.
Sulfur-Phosphorus Compounds	Extreme Pressure Additive	3.33%	Protects against wear and tear in high-pressure conditions.

The final lubricant performance results from the combined interaction between the epoxidized ester base oil and the multi-additive system. Polyisobutylene (PIB) functions as a viscosity index improver by expanding with temperature and moderating viscosity loss. Calcium sulfonate contributes to detergency and helps stabilize surface films. Molybdenum disulfide and sulfur–phosphorus compounds primarily operate under boundary and extreme-pressure conditions, forming protective tribofilms that reduce direct metal-to-metal contact.

International Journal of Emerging Research in Engineering, Science, and Management
Vol. 5 | Issue 1 | pp. 13-31 | Jan-Mar 2026.
www.ijeresm.com | eISSN – 2583-4894
Received: 08 Dec 2025 | Revised: 10 Feb 2026 | Accepted: 14 Feb 2026 | Published: 19 Feb 2026

The epoxide functional groups in the base oil increase molecular polarity, which may enhance additive adsorption and surface interaction. This combined effect corresponds with the observed increase in viscosity at 40 °C (30.5 → 47.2 cSt) and the elevated viscosity index (227) after additive incorporation. Similar cooperative interactions between functionalized ester base oils and additive systems have been reported in ester-based lubricants designed to meet ISO VG-grade specifications [27–30]. The integrated behavior of individual additives and their combined effects guided the selection of the final formulation.

3.5. Engine Performance and In-Service Oil Condition Monitoring

The developed *Jatropha*-based bio-lubricant was evaluated through a 12,000 km in-service motorcycle engine test to assess viscosity retention, physicochemical stability, and wear-related indicators under practical operating conditions. The evolution of key physicochemical parameters with mileage is presented in Fig. 9(A–F). As shown in Fig. 9(E–F), kinematic viscosity at both 40 °C and 100 °C decreased progressively with increasing mileage. This reduction is consistent with shear-induced degradation and the gradual depletion of additives during continuous engine operation. Despite the observed numerical decrease, viscosity values remained within the acceptable ISO VG-46 operating range throughout the test period, indicating satisfactory in-service viscosity retention.

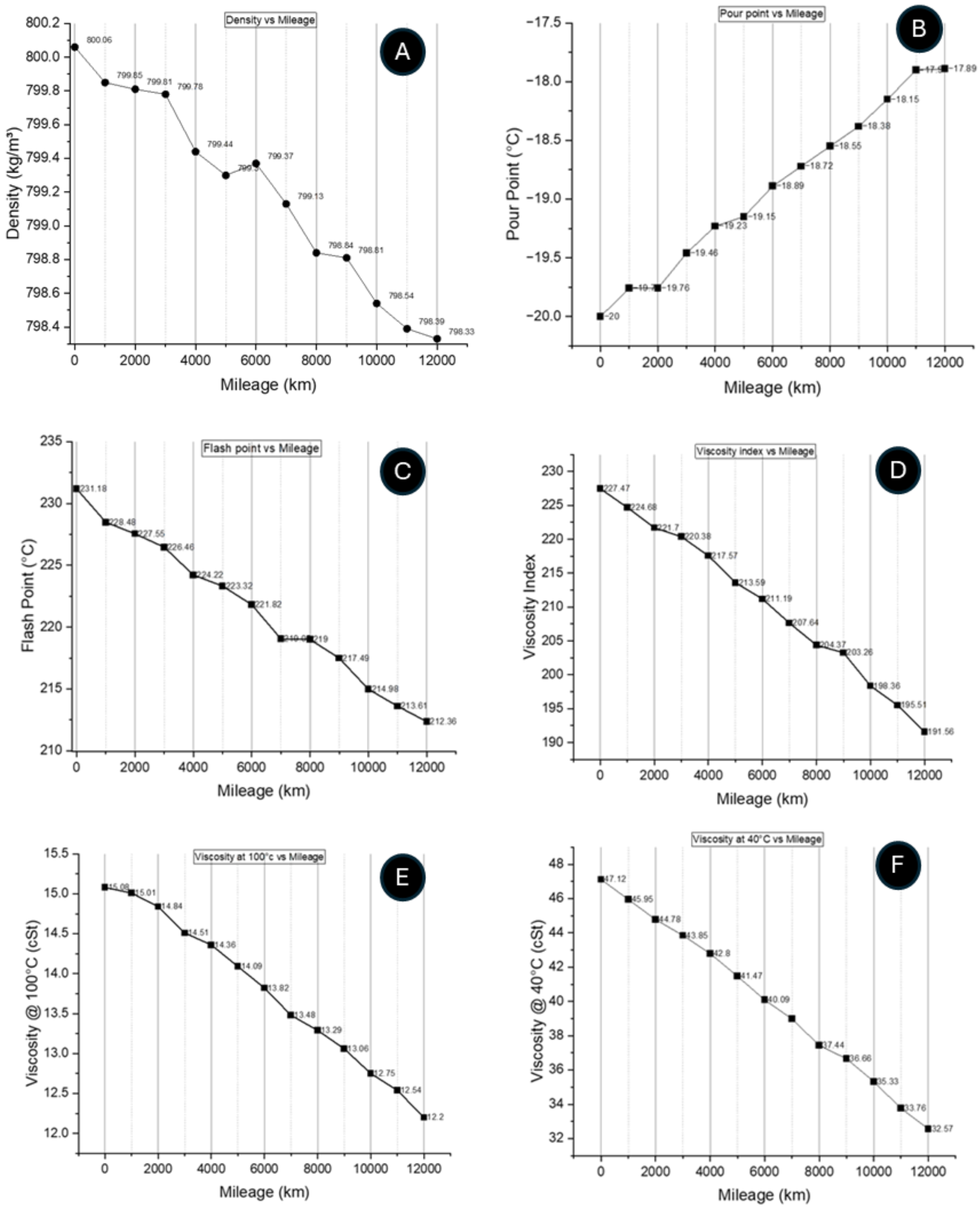

Fig. 9. Variation of key physicochemical properties with mileage during the 12,000 km engine test for the Jatropha-based bio-lubricant: (A) density, (B) flash point, (C) pour point, (D) viscosity index, (E) kinematic viscosity at 100 °C, and (F) kinematic viscosity at 40 °C.

Fig. 9(D) shows a gradual decline in viscosity index (VI) with mileage. This trend is consistent with the effects of mechanical and thermal stresses on viscosity-modifying components during prolonged operation. Nevertheless, the VI values remained comparable to those reported for ester-based lubricants under similar service conditions, suggesting sustained viscosity–temperature performance. Flash point values (Fig. 9(B)) exhibited only minor variation during the test period, indicating limited fuel dilution and reasonable thermal stability under the applied operating conditions. Similarly, the pour point (Fig. 9(C)) remained stable throughout the 12,000 km evaluation, suggesting that low-temperature flow characteristics were not significantly affected by service aging.

Density variation with mileage (Fig. 9(A)) was minimal. This stability suggests limited contamination or excessive oxidative thickening during service, consistent with the formulated lubricant's acceptable structural stability. The in-service evaluation indicates that the formulated *Jatropha*-based bio-lubricant maintained stable physicochemical properties over 12,000 km of operation. The test was conducted using a single engine without a parallel commercial reference oil; therefore, conclusions are based on compliance with ISO specifications and comparison with literature-reported ester-based lubricant behavior under extended service conditions.

3.6. Wear Metal Analysis by ASTM D5185 (XRF)

Wear protection performance of the formulated lubricant was evaluated by elemental wear-metal analysis of virgin and used oil samples, following ASTM D5185, using X-ray fluorescence (XRF) spectroscopy. This method quantifies trace wear metals and additive-derived elements in lubricating oils and is widely applied for condition monitoring and tribological assessment. Wear metal concentrations (ppm) for virgin oil, post-service oil (12,000 km), service-induced difference (Δ), and OEM excessive wear limits are summarized in Table 11 and illustrated in Fig. 10.

Table 11. Wear metal concentrations in the synthesized bio-lubricant compared with OEM guideline limits

Metals	**Virgin Oil (ppm) before**	**Used Oil (ppm) after**	**Change (ppm)**	**(OEM) Excessive Wear Limit (ppm)**
Iron (Fe)	6.9 ± 2	96.6 ±2	+89.7	>100-150
Aluminum (Al)	1687.5±3	1690±2	+2.5	>15–30
Copper (Cu)	3.05 ±2	25 ± 2	+21.95	>30
Chromium (Cr)	3.1 ± 1	11.1 ±1	+8	>10–15
Magnesium (Mg)	685 ± 2	690± 2	+5	>50–100
Manganese (Mn)	3.05 ± 2	20.6 ±2	+17.55	>10–20
Zinc (Zn)	129.05±1	132.5±2	+3.45	>2000-2500
Nickel (Ni)	1.1 ± 2	1.785±1	+0.685	>5–10

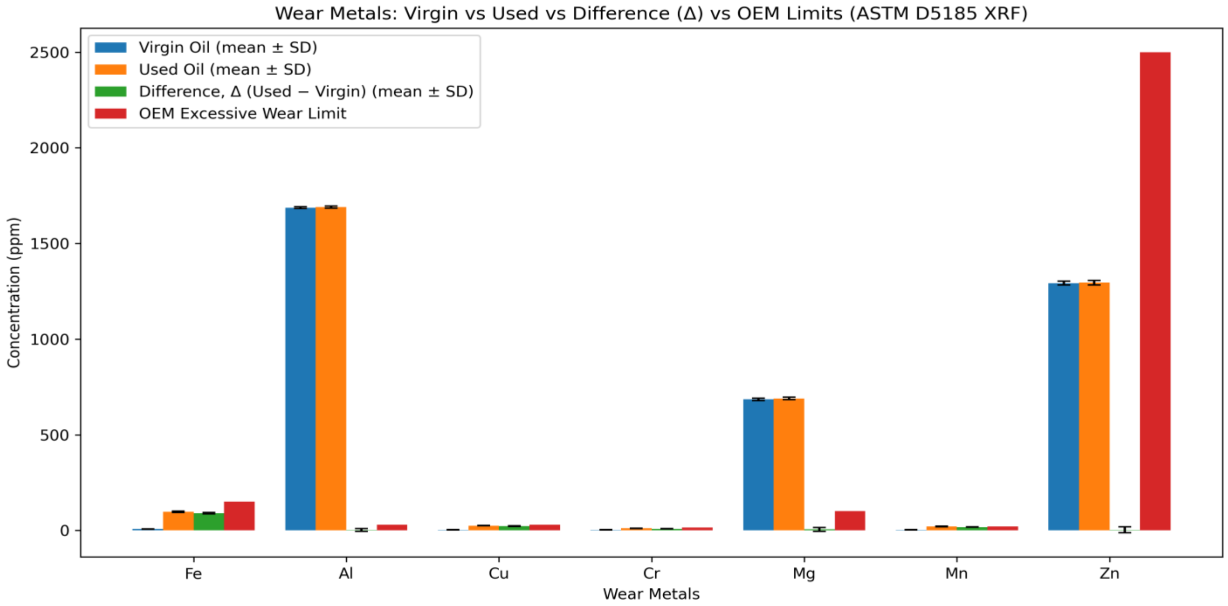

Fig. 10. Wear distribution showing virgin oil, used oil, service-induced difference (Δ), and OEM excessive wear limits determined by ASTM D5185 (XRF).

The grouped bar chart in Fig. 10 enables direct comparison between baseline elemental levels, post-service concentrations, and OEM excessive wear thresholds. For all monitored elements (Fe, Al, Cu, Cr, Mg, Mn, Zn, and Ni), post-service concentrations remained below OEM excessive wear limits. Iron (Fe) increased from 6.9 ppm to 96.6 ppm (+89.7 ppm) after service. Although numerically substantial, this value remains below the OEM excessive wear threshold (100–150 ppm), indicating normal ferrous wear consistent with extended engine operation. Copper (Cu), chromium (Cr), and manganese (Mn) exhibited moderate increases that align with typical bearing, alloy steel, and piston ring wear under steady-state boundary lubrication. Aluminum (Al) showed only a marginal increase, suggesting limited piston or bearing distress during operation.

Magnesium (Mg) and zinc (Zn), primarily associated with additive chemistry, remained relatively stable. The limited change in zinc concentration suggests moderate additive consumption and continued boundary film protection during service. Nickel (Ni) remained at low levels throughout testing, indicating no abnormal alloy wear. Compliance margins relative to OEM excessive wear limits confirm that none of the monitored elements approached critical thresholds. The observed wear patterns are consistent with controlled, steady-state adhesive wear rather than abrasive scuffing or corrosive damage. All measurements were conducted in replicate, and results are reported as mean ± standard deviation. The relatively low standard deviations observed for both virgin and used oil samples indicate good analytical reproducibility and consistent wear behavior. The lack of large variability supports the conclusion that the measured increases reflect actual service-induced wear rather than analytical fluctuations.

According to ASTM D5185 interpretation guidelines, gradual increases in Fe, Cu, and Al are expected during normal engine service. Diagnostic concern typically arises only when wear metal concentrations exceed OEM alarm limits or exhibit exponential growth. In the present study, all wear metals remained within normal-to-moderate severity ranges throughout the 12,000 km evaluation period. Note that the engine test was conducted on a single engine without a parallel commercial reference oil. Therefore, conclusions are based on compliance with OEM guideline limits and ASTM D5185 interpretation criteria rather than direct comparative benchmarking. Within these constraints, the results indicate that the formulated *Jatropha*-based bio-lubricant provided controlled wear behavior under practical operating conditions.

4 CONCLUSION

A bio-lubricant based on *Jatropha curcas* oil was successfully developed through sequential chemical modification involving esterification, transesterification, epoxidation, and multi-additive incorporation. The integrated processing and formulation strategy improved key physicochemical properties, including viscosity–temperature behavior, low-temperature flow characteristics, and thermal stability, consistent with ISO VG-46 requirements. Structural characterization using GC–MS and FTIR confirmed effective conversion of triglycerides to fatty acid methyl esters and subsequent epoxidation, providing a molecular basis for the observed improvements in viscosity index and additive compatibility. Incremental additive screening, followed by a constraint-guided formulation approach, enabled the development of a balanced multi-additive system that improved viscosity control and oxidative resistance without compromising formulation stability.

During the 12,000 km in-service engine evaluation, the lubricant demonstrated stable viscosity retention, acceptable thermal behavior, and wear metal concentrations within defined OEM guideline limits. The observed trends were consistent with reported literature on the performance of ester-based lubricants under comparable operating conditions. The study was conducted using a single-engine evaluation without parallel testing against a commercial reference oil; therefore, conclusions are based on compliance with ISO specifications, ASTM interpretation criteria, and literature benchmarking. Within these constraints, the findings support the technical feasibility of utilizing non-edible *Jatropha curcas* oil as a base stock for ISO VG-46 bio-lubricant applications. Future work should focus on assessing batch-to-batch reproducibility, multivariate additive optimization using formal design-of-experiments methodologies, and direct comparative testing against commercial ISO VG-46 lubricants to further validate long-term performance.

FUNDING INFORMATION

This research was supported by the Organisation for Women in Science for the Developing World (OWSD) under Grant No. 4500501094. Additional funding was provided by DAAD, with support from the German Federal Ministry for Economic Cooperation and Development (BMZ), through the WE-AFRICA Project (No. 57708984). Further support was received from the Afriger-SDC DAAD Project.

ETHICS STATEMENT

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

STATEMENT OF CONFLICT OF INTERESTS

The authors declare no conflicts of interest related to this study.

LICENSING

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