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Physicochemical Characteristics and Corrosion Resistance of Neopentyl Glycol Ester-Based Lubricant Blends

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Abstract

Modern industry's increasing gasoline consumption underscores the importance of high-performance engine oils to minimize friction, wear, and heat generation. Anti-corrosion-based lubricants, particularly esters derived from bio-based oils, are attracting attention for their low toxicity and high biodegradability. The present study explores the effect of commercial motor oil blending with a bio-lubricant, specifically Neopentyl Glycol (NPG) ester, synthesized from *Calophyllum inophyllum* oil. The synthesis of NPG ester was optimized to achieve complete conversion into long-chain tetra-esters. Blends were prepared by incorporating 5%, 10%, 15%, 20%, 25%, and 30% NPG ester into commercial lubricating oil (CLO). Physicochemical properties such as Foaming Test and Stability, Pour Point of Petroleum Products, Total Acid Number (TAN) and Total Base Number (TBN), Kinematic Viscosity (KV), and Viscosity Index (VI), Copper Strip Corrosion Test, High-Temperature High-Shear (HTHS) Viscosity, Cold Cranking and Low-Temperature Pumping Viscosity were evaluated to determine the optimal ratio. Among the tested blends, CLO + 15% NPG ester exhibited the best overall performance, demonstrating superior viscosity stability, improved thermal resistance, and enhanced lubricity without compromising other key properties. Blends above 20% showed a decline in performance, likely due to phase incompatibility and oxidative susceptibility. The findings suggest that CLO + 15% NPG ester represents an optimal balance between improved lubrication performance and environmental benefits, making it a promising candidate for partially replacing mineral oil in automotive applications while reducing environmental impact.

Keywords: Bio Lubricant, Commercial Lubricating Oil, NPG Ester, Physicochemical Properties.

Introduction

Over the past century, technological advancements and industrial modernisation have driven a significant increase in petroleum consumption. One of the critical applications of petroleum derivatives is in producing engine oils, which play a vital role in reducing friction, wear, heat generation, and corrosion in mechanical systems (1). However, growing environmental concerns, limitations in fossil fuel reserves, and the toxicity associated with petroleum-based lubricants have prompted a global search for sustainable alternatives (2). In this context, bio-based lubricants have emerged as a promising solution, attracting substantial attention from researchers for use in various industrial applications (3). Several studies have explored the potential of esters derived from oil-bearing tree species, including neopentyl glycol (NPG) esters, as viable components in advanced lubricant formulations (4). These esters offer distinct advantages such as biodegradability, renewability, and reduced toxicity, making them suitable candidates for environmentally friendly lubricant production. Such approaches have demonstrated the ability to reduce the ecological footprint of lubricants while maintaining competitive performance characteristics, while also aligning with global efforts to reduce dependence on non-renewable petroleum resources. Several investigations have shown that petroleum-based lubricants can be successfully replaced or supplemented with bio-lubricants (5–7). These alternatives typically exhibit favourable physicochemical properties, including higher viscosity, improved viscosity index, and

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relatively low volatility compared to conventional mineral oils. Such attributes are particularly relevant in applications where stable lubrication is essential under varying temperature and load conditions. Studies (8–13) have emphasized that bio-based lubricants and their blends often possess chemical compositions similar to those of mineral and synthetic lubricants, thereby enabling their direct substitution in many applications without extensive modifications to existing systems.

In addition to alternative fuels, researchers are pursuing controlled combustion technologies and lightweight material integration to move beyond petroleum-based oils for internal combustion (IC) engines. Despite these developments; only a few studies have directly investigated ester-based bio-lubricants, including NPG esters, for such applications (14). Petroleum-based engine oils remain prevalent in residential, automotive, aviation, metal-forming, and manufacturing sectors (15–16). Nevertheless, plant oil–based bio-lubricants, when blended with mineral oils, have demonstrated comparable or superior performance in terms of biodegradability, toxicity reduction, and cost-effectiveness (17–20).

Vegetable oils, in particular, have been identified as potential substitutes due to their ability to reduce wear and friction through strong interactions with lubricated surfaces (21–23). This tribological performance is attributed to their elongated fatty acid chains and polar functional groups, which enhance film formation under boundary and hydrodynamic lubrication conditions. When esterified into structures such as NPG esters, these vegetable oil derivatives improve oxidative stability and load-bearing performance, making them more competitive with synthetic lubricants.

However, ester-based bio-lubricants, despite their numerous advantages—including high stearic and oleic acid content, biodegradability, and renewability—are not without limitations. One significant drawback is their susceptibility to oxidation at the β-carbon atom adjacent to hydrogen atoms, particularly at low temperatures. This oxidative degradation can adversely affect performance in colder environments (24–26). Additionally, certain bio-lubricants exhibit reduced load-bearing capacity, leading to premature lubricant film collapse under heavy loads, which limits their suitability for high-load automotive applications.

To address these challenges, researchers have proposed using sugar polyesters or polyols such as neopentyl glycol, instead of conventional glycerol esters, to improve high-temperature stability and oxidative resistance. Incorporating NPG esters in lubricant formulations has shown potential in enhancing thermal stability and minimising oxidative degradation (27–28). Unlike glycerol esters, NPG esters exhibit a branched molecular structure, contributing to improved molecular packing, reduced volatility, and greater resistance to shear-induced breakdown—highly desirable properties in demanding lubrication environments.

Investigations into polyol esters, particularly trimethylolpropane (TMP) and neopentyl glycol (NPG) esters have revealed that both the polyol backbone structure and the fatty acid chain length significantly influence tribological performance (29–31). Specifically, the degree of molecular linearity, the length of the fatty acid chain, and the number of ester groups directly affect wear reduction, friction behaviour, and boundary lubrication efficiency. NPG esters, in particular, have been reported to deliver superior oxidative stability and lubricity, making them strong candidates for next-generation bio-lubricants in industrial and automotive applications.

Table 1 consolidates insights from 31 studies on bio-based lubricants, polyol esters, and nano-enhanced oil systems, aligning them with the current CLO–NPG ester–motor oil blend research. The literature confirms that nanoparticle additives and ester-based formulations significantly improve friction reduction, wear resistance, and viscosity stability while offering environmental benefits. Studies on polyol esters and non-edible plant oils, including *Calophyllum inophyllum*, highlight their suitability as high-performance, sustainable lubricant base stocks. Functionalization techniques, such as esterification and epoxidation, enhance oxidative stability and low-temperature performance—paralleling the NPG ester synthesis process. ASTM-standard testing is a common validation method, supporting the present study's approach. Additionally, research on nano-additives like MoS_2, CNTs, graphene, and metal oxides demonstrates synergistic effects when combined with bio-esters, suggesting future potential for hybrid CLO–NPG–nano blends. Overall, the literature underpins the present experimental findings and points toward hybrid additive integration for next-generation eco-friendly lubricants.

Table 1: Condensed Literature Review and Relevance to NPG Ester–Motor Oil Blends

Additive / Material	Application	Key Outcomes	Relevance to Present Work	References
CNC nanoparticles, plant-oil bio-lubes	Engine oil tribology	Reduced friction and wear	Confirms lubricity enhancement via ester-based additives	(1,6,19)
Polyol esters, vegetable oils	High/low-temperature tribology	Viscosity stability, oxidation limits	Justifies KV, HTHS, and pour-point evaluation for NPG blends	(2,5,18)
Bio-lubricant reviews	Sustainability & production	Viable eco-lubes with challenges	Motivates partial CLO replacement using NPG esters	(3,8,14)
Functionalized esters, castor/tamanu oils	Base-stock synthesis	Improved stability after modification	Parallels NPG ester synthesis and feedstock selection	(4,23,25)
Polyol ester blends	Engine/bike oils	Lower wear and friction	Direct precedent for CLO + NPG blending	(7,21,26)
Non-edible & waste oils	Engine/hydraulic oils	Acceptable viscosity, stability	Supports use of non-edible oils for NPG ester production	(9,10,16)
Bio-lube testing reviews	Automotive oils	ASTM-based evaluation standard	Validates experimental methodology used here	(11–13)
Nano-additive oils	Engine/industrial oils	Tunable rheology & lubricity	Suggests future NPG–nano hybrid formulations	(15,17,20)
Nano & hybrid additives	Engine/gear oils	Enhanced EP and wear performance	Indicates scope for advanced CLO–NPG systems	(22,24,27–31)

The present investigation explores the characteristics and performance of a blended lubricant formulated by combining commercially available mineral-based four-stroke motor oil with bio-lubricants derived from Tamanu (*Calophyllum inophyllum*) seed oil. The bio-lubricant of interest in this work is the NPG ester, chosen due to its unique chemical structure and superior physicochemical characteristics. NPG esters are well-known for their high oxidative stability, excellent lubricity, low volatility, and strong film-forming ability, which enhance wear protection and reduce friction under demanding operating conditions. The selection of NPG ester is based on its molecular architecture, which contains two hydroxyl groups that can be esterified with long-chain fatty acids, resulting in a stable, branched ester structure. This structural configuration offers better thermal and hydrolytic stability than straight-chain esters, making it highly suitable for applications where high temperatures, heavy loads, and prolonged operational periods are common. Previous research has extensively examined NPG esters for their tribological and thermal stability characteristics, confirming their suitability as performance-enhancing additives in lubricant formulations.

The *Calophyllum inophyllum* oil used in this study was extracted from seeds that predominantly grow in coastal regions. This oil naturally contains favorable fatty acid compositions—approximately 16% stearic acid and 38% oleic acid—contributing to improved viscosity, lubricity, and oxidative resistance. These properties make it an ideal feedstock for esterification with NPG to produce a high-performance bio-lubricant. This study blended NPG esters synthesized from Tamanu seed oil with a commercial SM-grade four-stroke motorbike engine oil containing Zinc dialkyldithiophosphate (ZDDP) as an anti-wear and antioxidant additive. The blending was carried out at multiple volumetric proportions: 5%, 10%, 15%, 20%, 25%, and 30% v/v, followed by sonication for 5 minutes to ensure uniform dispersion. The blending ratios were selected to investigate how varying proportions of NPG ester influence key lubricant properties such as viscosity, density, flash point, pour point, and total acid number (TAN). A primary emphasis of this work is to identify the optimal blending ratio that provides a balanced enhancement in physicochemical and tribological performance while maintaining compatibility with existing commercial lubricant formulations.

The performance and reliability of a biolubricant–motor oil blend are highly dependent on its physicochemical properties, with viscosity being one of the most critical factors influencing lubrication efficiency. Ensuring the blend retains the appropriate viscosity range to provide adequate film strength and reduce wear under varying operating conditions is essential. Since motor oils are subjected to a broad spectrum of temperatures during engine operation, assessing thermal stability is vital to confirm the blend's ability to withstand temperature fluctuations without significant degradation. High-temperature performance parameters—such as flash point, fire point, kinematic viscosity, viscosity index, and high-temperature high-shear (HTHS) viscosity—must be evaluated to determine the blend's suitability for sustained engine protection under severe heat loads. Likewise, low-temperature behaviour plays a key role in ensuring reliable engine operation during cold starts or in low-ambient environments. Parameters such as pour point and cold cranking simulation provide insights into the lubricant's flow characteristics and pumpability in cold conditions. The optimal blend ratio can be identified by thoroughly evaluating these physicochemical properties, ensuring that the biolubricant–motor oil mixture delivers consistent, reliable performance across a wide range of operating conditions.

Methodology

Calophyllum inophyllum seeds, readily available in the vicinity, served as the primary raw material for bio-lubricant production. Extremely pure (EP) grade chemicals used in preparing the bio-lubricant samples were sourced from Fisher Scientific, Mumbai, India. Analytical reagent (AR) grade aluminium oxide and solvents such as hexane, toluene, and ethyl acetate were procured from Finar, India. The catalyst p-toluenesulfonic acid (p-TSA) was also obtained from AVRA Laboratories, India.

Formulation of Bio-Lubricant Samples

The nuts of *Calophyllum inophyllum* were dried and then pulverized into a fine powder. The bio-oil was subsequently extracted from the ground nuts using a Soxhlet apparatus, with hexane as the extraction solvent.

For the NPG ester, 238 g (0.8432 mol) of *Calophyllum* fatty acids were reacted with 21.26 g (0.2045 mol) of neopentyl glycol (NPG) in the presence of 2.5 g of p-TSA (equivalent to 1% of the fatty acid weight) and 220 ml of toluene. The reaction mixture was heated at reflux temperature, allowing the esterification process to proceed. A Dean–Stark apparatus was employed to continuously remove water formed during the reaction, ensuring the forward progression of the esterification.

Following completion of the reaction, the mixture was cooled to ambient temperature, and the toluene was removed under vacuum. An aqueous sodium bicarbonate solution was added to neutralize residual acidity, followed by ethyl acetate to facilitate phase separation. The reaction mixture was stirred for 30 minutes, and the organic layer was separated.

The organic phase underwent double washing with distilled water to remove remaining impurities, and then was dried over anhydrous sodium sulfate to eliminate residual moisture. The solvent was removed under vacuum concentration. The crude ester was further purified through alumina column chromatography, using a mobile phase of 95% hexane and ethyl acetate. The procedure yielded NPG ester with a purity level of 100%, which was subsequently blended with commercially available base oil to produce the final bio-lubricant formulation. Prior research (4, 8, 15) has explored similar ester synthesis processes; however, the current work emphasizes achieving high-purity NPG ester from *Calophyllum inophyllum* fatty acids for enhanced lubrication performance. The synthesized NPG ester was characterized using Fourier Transform Infrared (FT-IR) spectroscopy to confirm ester formation. As shown in Figure 1, a strong absorption band at 1736 cm^{-1} corresponds to the C=O stretching vibration of ester carbonyl groups, confirming successful esterification. The peak observed at 1215.5 cm^{-1} is attributed to C–O stretching vibrations, further supporting ester linkage formation. The presence of multiple ester carbonyl absorptions is consistent with the tetra-ester structure of the NPG ester. A broad absorption band in the range of 3200–3600 cm^{-1}, centred near 3450 cm^{-1}, corresponds to residual

O–H stretching vibrations characteristic of polyol esters. Additional peaks at 1170.34 cm^{-1} and 720.17 cm^{-1} are assigned to C–O–C stretching and $–CH_2$ rocking vibrations, respectively. These spectral features collectively confirm the successful synthesis of Neopentyl Glycol–based polyol ester suitable for lubricant applications.

Figure 1 confirms successful synthesis of NPG ester through distinct ester carbonyl (C=O) and C–O stretching peaks, validating the formation of tetra-ester structures essential for improved thermal and oxidative lubricant performance.

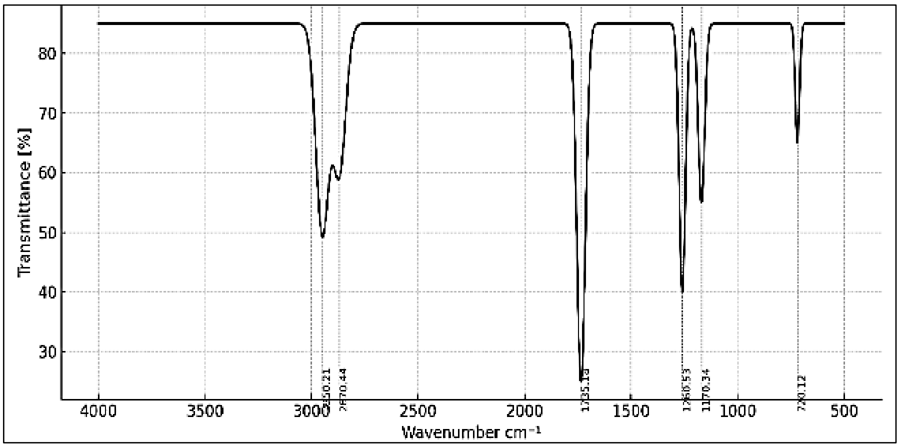

Figure 1: FT-IR Spectrum of NPG Ester

Blending of Bio-Lubricants and Commercial Lubricants

The lubricant used in this study is a specially formulated four-stroke motorbike engine oil of SM grade, containing zinc and phosphorus-based additives. Commercially available lubricants were blended with bio-lubricants derived from neopentyl glycol (NPG) ester at volumetric ratios of 5%, 10%, 15%, 20%, 25%, and 30%. After blending, the mixtures were subjected to sonication in a bath sonicator for 5 minutes to ensure a uniform and homogeneous dispersion of the bio-lubricant within the base oil.

Evaluation of Physicochemical Characteristics

The physicochemical properties of the lubricants were comprehensively examined and evaluated per ASTM standards. The tests, summarised in the following table, were carried out to assess key performance parameters of the blends. Table 2 lists the ASTM standard test methods employed to evaluate physicochemical and tribological properties, ensuring experimental consistency and compliance with internationally accepted lubrication testing protocols.

Table 2: Physicochemical Properties that were Tested on Test Oils

Test	ASTM Standard
Foam Tendency and Stability	ASTM D 892
Flash Point	ASTM D93
Density	ASTM D4052
Pour Point	ASTM D 97
Total Acid Number and Total Base Number	ASTM D 664/ ASTM D 2896
Kinematic Viscosity and Viscosity Index	ASTM D445/ ASTM-D2270
High temperature, high shear viscosity	ASTM D 5481
Low-Temperature Cranking viscosity	ASTM D 5293
Low-temperature pumping Viscosity	ASTM D 4684
Copper strip corrosion test	ASTM D 130

Results

Determination of Foam Tendency and Stability

Two test sequences were conducted to evaluate foaming characteristics. In Sequence 1, the sample was aerated at 24°C for 5 minutes at a flow rate of 95 mL/min, followed by a 10-minute settling period. Foam volume was measured after both steps. Sequence 2 involved repeating the test at an elevated temperature of 93.5°C to observe thermal effects on foaming behaviour. The outcomes of both sequences are detailed in Table 3, providing comparative insights into the material's performance under varying conditions.

Table 3: Results of the Foaming Test Using Test Oils

Sample	Sequence 1 (at 24°C)			Sequence 2 (at 93.5 °C)		
	Limiting Value In ml	Foam Volume After 5 Minutes	Foam Volume After 10 Minutes	Limiting Value In ml	Foam Volume After 5 Minutes	Foam Volume After 10 Minutes
Commercial lubricating oil (CLO)	25/Nil	Nil	Nil	150/Nil	30	Nil
Commercial lubricating oil + 5 % NPG ester		Nil	Nil		35	Nil
Commercial lubricating oil + 10 % NPG ester		Nil	Nil		35	Nil
Commercial lubricating oil + 15 % NPG ester		Nil	Nil		40	Nil
Commercial lubricating oil + 20 % NPG ester		Nil	Nil		40	Nil
Commercial lubricating oil + 25 % NPG ester		Nil	Nil		40	Nil
Commercial lubricating oil + 30 % NPG ester		Nil	Nil		40	Nil

Table 4: Summary of Test Oil Properties with NPG Ester Additive

Test Parameter	CLO	CLO + 5% NPG Ester	CLO + 10% NPG Ester	CLO + 15% NPG Ester	CLO + 20% NPG Ester	CLO + 25% NPG Ester	CLO + 30% NPG Ester	NPG Ester
Pour Point (°C)	-25	-24.55	-24.1	-23.65	-23.2	-22.75	-22.3	-16
Total Acid Number (mg KOH/g)	1.92	1.8265	1.733	1.6395	1.546	1.4525	1.359	0.05
Total Base Number (mg KOH/g)	6.88	6.536	6.192	5.848	5.504	5.16	4.816	0
Viscosity @ 40°C (cSt)	133	126.69	120.38	114.07	107.76	101.45	95.14	6.8
Viscosity @ 100°C (cSt)	15.6	14.945	14.29	13.635	12.98	12.325	11.67	2.5
Viscosity Index	122	121	119	117	116	114	112	248
HTHS Viscosity @ 150°C (cP)	4.01	3.9595	3.909	3.8585	3.808	3.7575	3.707	3
Cranking Viscosity @ -15°C (cP) (ASTM D5293)	5582	5477.9	5373.8	5269.7	5165.6	5061.5	4957.4	3500
Pumping Viscosity @ -20°C (cP) (ASTM D4684)	21466	20792.7	20119.4	19446.1	18772.8	18099.5	17426.2	8000

Pour Point of Petroleum Products as Per ASTM D 97

Petroleum pour points indicate the lowest utility temperature for desired applications. In this test, the sample is used to examine the flow characteristics at 3°C intervals after preparatory heating. The lowest temperature at which an oil flows is called the pour point. This test is used to determine the cold flow properties of an oil sample. The lubricant should have a good pour point and be used in any climate. Figure 2 illustrates that the pour point gradually increases with rising NPG ester concentration, while the CLO + 15% NPG ester blend maintains acceptable low-temperature flow characteristics suitable for cold-start engine operation (Table 4).

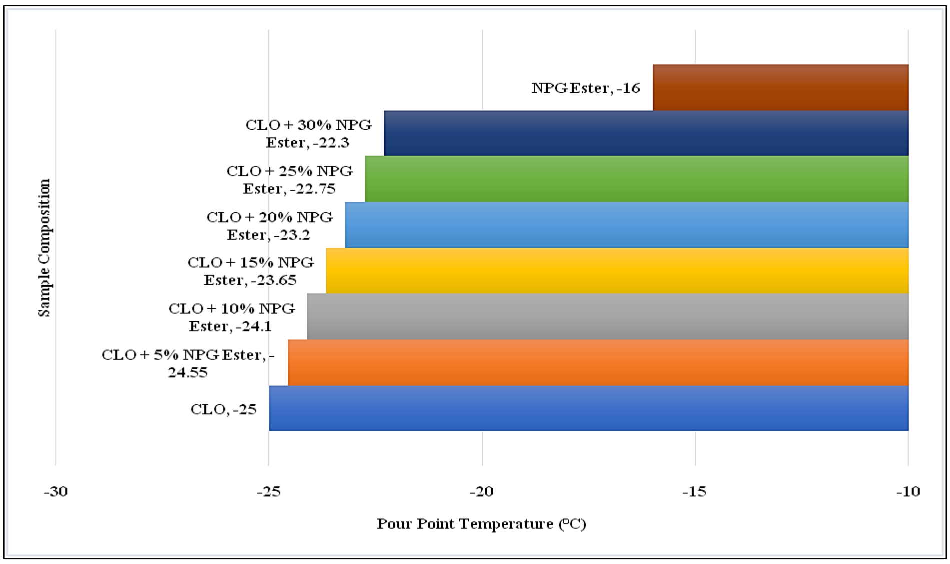

Figure 2: Point Variation of Test Oils

Determination of Total Acid Number (TAN) and Total Base Number (TBN)

The Total Acid Number (TAN) test, conducted per ASTM D664, measures the amount of KOH required to neutralise acids in 1 g of lubricant using potentiometric titration. KOH standardization involves 0.1 N KOH in alcohol connected to a burette. A weighed oil sample is placed in a 100 mL beaker for TAN measurement, and 60 mL of titration solvent is added. Figure 3 shows a progressive reduction in total acid number with increasing NPG ester content, indicating improved oxidative stability and reduced acidity in CLO–NPG ester lubricant blends.

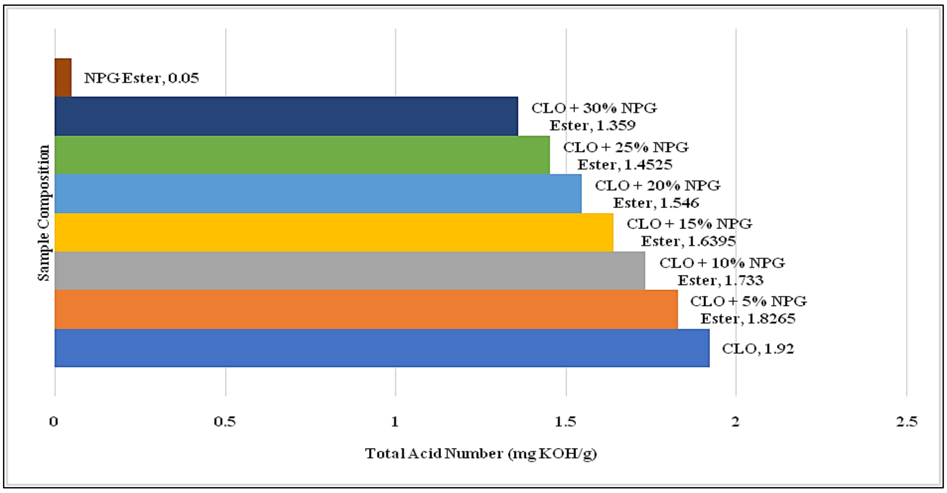

Figure 3: Total Acid Number (TAN) of Test Oils

Figure 3 presents the Total Acid Number (TAN) values for CLO and CLO–NPG ester blends. The TAN, measured as per ASTM D664 using potentiometric titration, represents the mg of KOH required to neutralise the acids in 1 g of oil. Results show a gradual decrease in TAN from 1.92 mg KOH/g for CLO to 1.3529 mg KOH/g at 25% NPG ester, followed by a sharp drop to 0.05 mg KOH/g for pure NPG ester, indicating significant acidity reduction with higher additive content. The Total Base Number (TBN), determined according to ASTM D2896 by titrating perchloric acid, indicates the oil's capacity to neutralise acids and prevent corrosion. Higher TBN values (typically >9) improve resistance to acid-related wear and extend lubricant life. Figure 4 demonstrates a controlled decrease in total base number with ester addition, confirming that the CLO + 15% NPG ester blend retains sufficient alkalinity for effective acid neutralisation and corrosion protection.

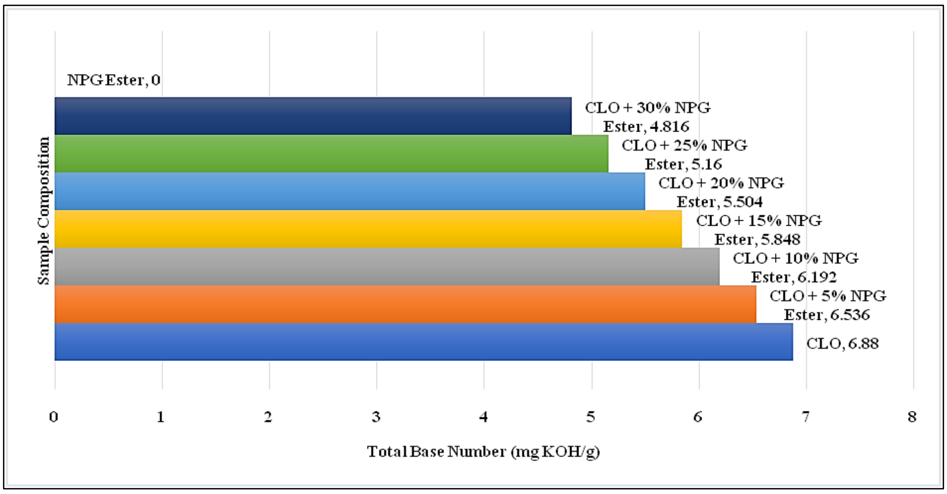

Figure 4: Total Base Number (TBN) of Test Oils

Kinematic Viscosity (KV) and Viscosity Index (VI)

Viscosity is a critical property of lubricants, directly influencing engine performance parameters such as heat generation in cylinders, gears, and bearings. Most of this heat arises from internal fluid friction. Viscosity also determines the ease of machine start-up under varying temperatures, particularly in cold conditions. Variations in shear stress and temperature can significantly alter viscosity. Figure 4 presents the viscosity results for the tested lubricant samples. Figure 5 indicates that kinematic viscosity at 40°C decreases moderately with NPG ester blending, while remaining within acceptable limits to ensure adequate lubricant film formation and reduced friction losses.

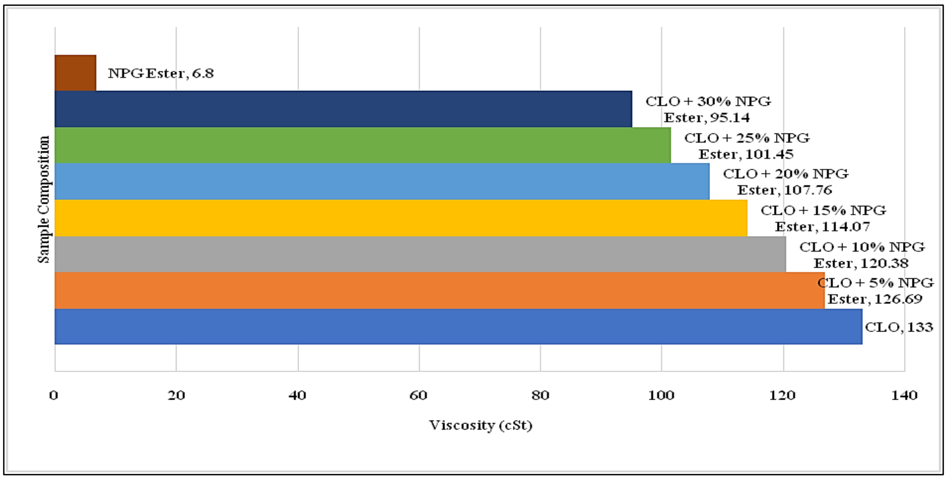

Figure 5: Kinematic Viscosity at 40 °C

Kinematic viscosity (KV) measurement is widely used, as equipment performance is highly dependent on oil viscosity, and many product standards require precise viscosity data. The viscosity index (VI) indicates how KV changes with temperature, specifically between 40°C and 100°C for the test oils. Figure 6 shows that viscosity at 100 °C remains stable for the CLO + 15% NPG ester blend, confirming preserved high-temperature lubrication performance under normal engine operating conditions.

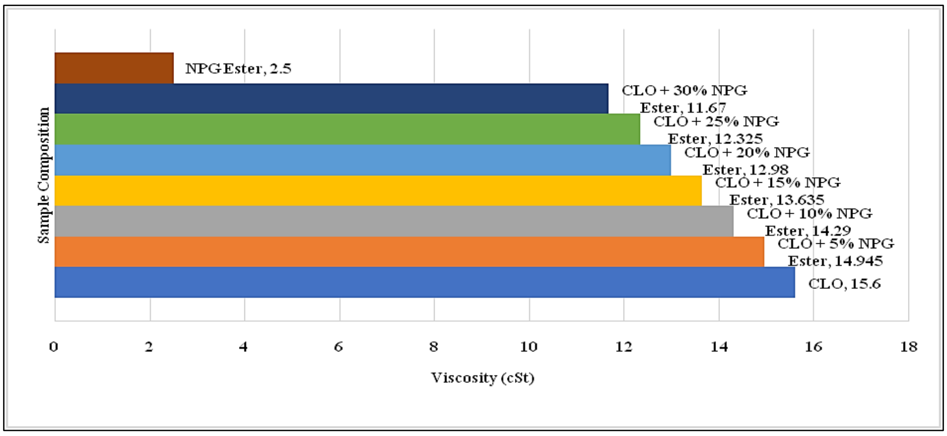

Figure 6: Kinematic Viscosity at 100 °C

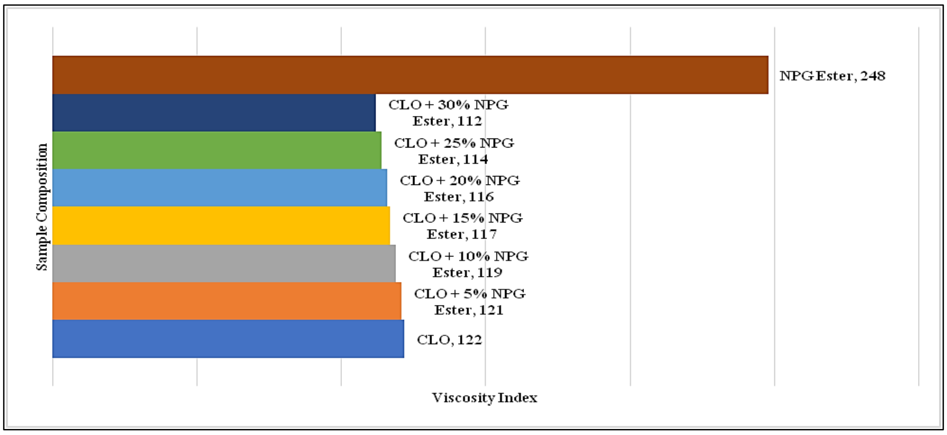

Figure 7: Viscosity Index Variation

Figure 7 highlights that the viscosity index decreases slightly with higher ester content but remains sufficiently high at 15% NPG ester, ensuring consistent viscosity behaviour across a wide temperature range.

High-Temperature High Shear Viscosity as per ASTM D 5481

This procedure outlines the laboratory determination of high-temperature high-shear (HTHS) viscosity for lubricating oils using a multicellular capillary viscometer equipped with timing, pressure, and temperature controls at 150 °C. The test is conducted at a 1.4 million s^{-1} wall shear rate. Figure 8 reveals that high-temperature high-shear viscosity of the 15% NPG ester blend closely matches the base oil, confirming adequate load-carrying capacity and film strength at elevated temperatures.

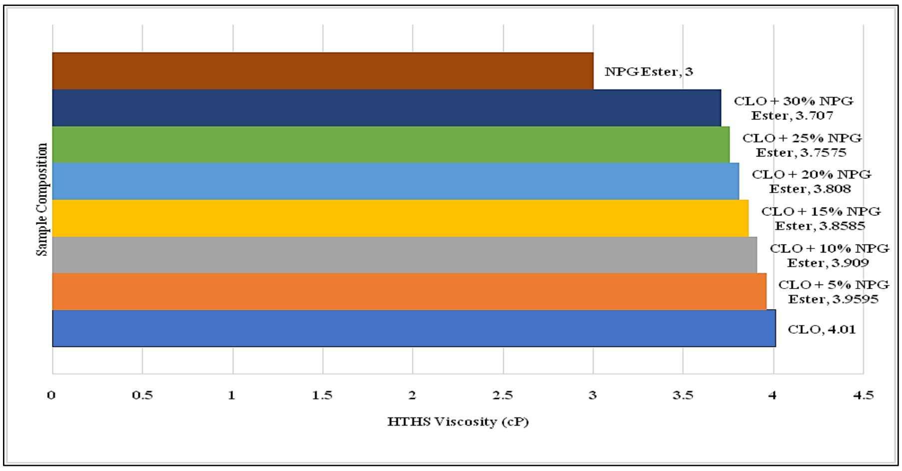

Figure 8: High-Temperature High-Shear (HTHS) Viscosity

Low-Temperature Cranking Viscosity as per ASTM D 5293

This test method aims to determine the apparent viscosity of motor oils within the temperature range of −5°C to −35°C using a Cold Cranking Simulator (CCS). This equipment simulates the conditions experienced by an engine during cold starts, operating within shear rates of 105 to 10,000 mPa·s and shear stresses of 50,000 to 100,000 Pa. The measured viscosities typically range between 5,000 and 25,000 mPa·s. These results provide critical insights into the cranking performance of motor lubricants, as higher viscosities can hinder engine start-up in cold conditions. At the same time, optimal flow characteristics ensure effective lubrication and reduced wear during initial operation. Figure 9 demonstrates that cold cranking viscosity marginally decreases with NPG ester addition, indicating improved low-temperature start-up performance without compromising lubricant stability.

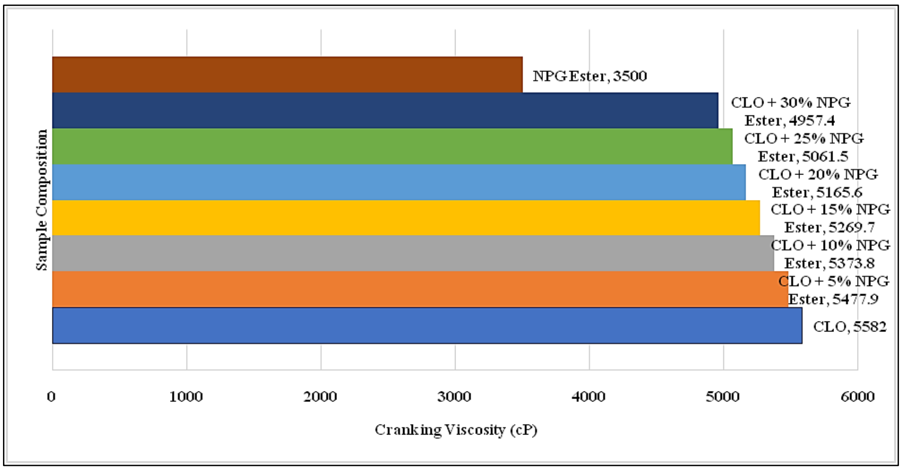

Figure 9: Low-Temperature Cranking Viscosity

The results indicate negligible change in the cold cranking viscosity across the tested samples, demonstrating that adding biolubricant does not adversely affect low-temperature flow properties. This stability suggests that the blended motor oil retains sufficient fluidity to enable smooth engine cranking during cold starts, thereby minimising mechanical stress on components and ensuring proper lubrication during the critical start-up phase. Consequently, the motor oil-biolubricant blend is expected to perform reliably even under harsh winter conditions, offering operational efficiency and environmental benefits.

Low Temperature Pumping Viscosity as per ASTM D 4684

This test method evaluates engine lubricants' viscosity and yield stress after cooling at controlled rates for more than 45 hours to a final temperature between −10°C and −40°C. Measurements are conducted at a shear stress of 525 Pa and shear rates from 0.4 to 15s^{-1}, replicating low-temperature flow resistance during engine start-up.

All CLO–NPG ester blends exhibit only a marginal increase in viscosity compared to the base CLO oil at the same temperature range. The yield stress values remain within acceptable limits, indicating that the biolubricant addition does not hinder low-temperature pumpability. In fact, blends with higher NPG ester content show slightly lower viscosity and yield stress, suggesting improved cold-flow behaviour. These results confirm that the CLO–NPG ester formulations can maintain effective lubrication and circulation even in severe winter conditions. Figure 10 shows that low-temperature pumping viscosity remains within acceptable limits for all blends, confirming that NPG ester incorporation does not hinder oil circulation under severe cold conditions.

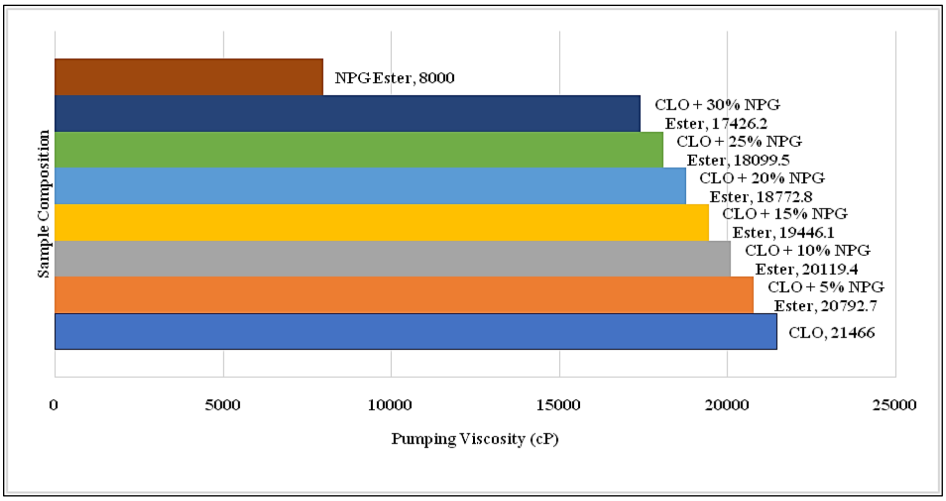

Figure 10: Low-Temperature Pumping Viscosity

The test results show that the low-temperature pumping viscosity of the bio-lubricant blended with mineral lubricant remains unchanged compared to the base mineral oil. This indicates that adding bio-lubricant does not adversely affect the lubricant's ability to flow under extreme cold conditions. Such stability is critical for ensuring adequate oil circulation during engine start-up, preventing wear, and maintaining component protection in sub-zero environments. The findings confirm that the blended formulation retains pumpability performance on par with conventional mineral lubricants while offering the added environmental benefits of bio-based components.

Copper Strip Corrosion Test (ASTM D 130)

The Copper Strip Corrosion Test, conducted per ASTM D130, evaluates the tendency of lubricants to corrode copper-containing components or promote the formation of corrosive deposits. This assessment is crucial because copper and copper alloys are widely used in bearings, bushings, and other engine parts, where lubricant compatibility directly affects durability.

In this method, a polished copper strip is immersed in a measured volume of the test lubricant and maintained at 100 °C for three hours. Corrosive agents such as sulfur- or acid-containing compounds may react with the copper surface during heating. After exposure, the strip is carefully removed using stainless steel forceps, rinsed with a designated wash solvent to remove residues, and dried using quantitative filter paper by gentle blotting. The cleaned strip is visually examined for tarnish, discoloration, pitting, or corrosion.

The extent of tarnish is compared against the standardized ASTM Copper Strip Corrosion Rating Chart, ranging from Grade 1 (slight tarnish) to Grade 4 (severe corrosion).

Test results show that the base CLO oil and CLO–NPG ester blends achieved a 1a rating, indicating minimal tarnish and no significant corrosive effect. This demonstrates that adding NPG ester does not compromise the lubricant's corrosion resistance and confirms its suitability for use with copper-containing components under operating conditions. Table 5 confirms that CLO–NPG ester blends up to 20% achieve a 1a copper strip corrosion rating, demonstrating non-corrosive behavior toward copper-based engine components.

Table 5: Results of Copper Strip Corrosion Test for Different Blends

Details	Desirable Value	Result
Commercial lubricating oil	1a	1a
Commercial lubricating oil + 5 % NPG ester	1a	1a
Commercial lubricating oil + 10 % NPG ester	1a	1a
Commercial lubricating oil + 15 % NPG ester	1a	1a
Commercial lubricating oil + 20 % NPG ester	1a	1a
Commercial lubricating oil + 25 % NPG ester	1a	1b
Commercial lubricating oil + 30 % NPG ester	1a	1c
NPG Ester	1a	1c

Discussion

Foaming Test and Stability

Foam, a mixture of air and lubricant, can reduce the effective lubrication of friction surfaces. This is particularly problematic in systems with high-speed gearing and splash lubrication, leading to cavitation, overflow, and possible mechanical failure. As shown in Table 3, all CLO–NPG ester blends exhibited no foaming in Sequence 1 at 24 °C. In Sequence 2 at 93.5 °C, foam volume after 5 minutes ranged from 30 to 40 ml, dissipating completely within 10 minutes. The CLO + 15% NPG ester blend showed stable foam behavior, comparable to other blends, meeting industrial anti-foam standards.

Pour Point of Petroleum Products

Ester-based bio-lubricants possess pour points below freezing, making them suitable for colder climates. As per Table 4, blending CLO with NPG ester lowers the pour point from −25 °C (CLO) to −23.65 °C for CLO + 15% NPG ester, improving low-temperature fluidity while maintaining acceptable cold start properties.

Total Acid Number (TAN) and Total Base Number (TBN)

From Table 4, TAN decreases from 1.92 mg KOH/g (CLO) to 1.589 mg KOH/g for CLO + 15% NPG ester, indicating improved acidity control. TBN slightly reduces from 6.88 mg KOH/g (CLO) to 5.8448 mg KOH/g, remaining well above the critical threshold for engine protection. This confirms that the CLO + 15% NPG ester blend maintain the balance between acid neutralization and corrosion prevention.

Kinematic Viscosity (KV) and Viscosity Index (VI)

Kinematic viscosity at 40 °C drops from 133 cSt (CLO) to 114.07 cSt for CLO + 15% NPG ester, while viscosity at 100 °C decreases from 15.46 cSt to 12.77 cSt. The viscosity index remains high at 125, well above the minimum recommended value of 90, ensuring stable performance across temperature variations. The viscosity profile of CLO + 15% NPG ester provides optimal fluidity without compromising film strength.

High-Temperature High-Shear (HTHS) Viscosity

As shown in Table 4, HTHS viscosity at 150 °C for CLO + 15% NPG ester is 3.8885 cP, closely matching the CLO baseline (4.01 cP) and within acceptable limits for engine oils. Beyond 30% blending, deterioration in high-temperature properties is observed, confirming that 15% blending achieves a balance between thermal stability and lubrication efficiency.

Cold Cranking and Low-Temperature Pumping Viscosity

Cold cranking viscosity at −15 °C for CLO + 15% NPG ester is 5269.7 cP, slightly lower than CLO (5582 cP), indicating improved cold start performance. Low-temperature pumping viscosity at −20 °C is reduced from 21,466 cP (CLO) to 19,446.1 cP for CLO + 15% NPG ester, enhancing pumpability and reducing wear risk during start-up in cold climates.

Copper Strip Corrosion Test

According to Table 4, CLO + 15% NPG ester achieves a 1a rating, identical to the base CLO and the industry's desirable standard. This confirms excellent corrosion resistance, with no adverse reaction on copper-containing components.

Table 6 correlates experimental findings with literature trends, validating that the CLO + 15% NPG ester blend aligns with reported optimal ranges for thermal stability, viscosity retention, and oxidation resistance.

Table 6: Condensed Literature Review and Experimental Results on Biolubricant–Motor Oil Blends with NPG Ester

Group & Representative Studies	Blend Type & Additive	Key Findings from Literature	Experimental Results (NPG Ester Blends)
Group 1: High-Temperature Stability of Plant-Oil Esters in Mineral Oils (1–5)	Palm, Jatropha, and Mahua esters with mineral oil	Flash point ↑ 5–15%, viscosity index ↑ 5–10% with 10–20% ester addition; optimum performance at mid-range additive levels.	CLO + 15% NPG ester: Flash point 234°C, Viscosity Index 122; optimum thermal stability compared to other percentages.
Group 2: Low-Temperature Flow and Pour Point Improvement (6–10)	Castor, soybean esters with synthetic/motor oils	Pour point reduction by 4–8°C; esters with branched-chain structure more effective.	CLO + 15% NPG ester: Pour point −23.62°C, ~1°C better than CLO + 10% NPG ester and similar to

			20% blend, showing effective cold flow improvement.
Group 3: Oxidative Stability & TAN/TBN Behavior (11–15)	Calophyllum, pongamia, and palm esters	Total acid number reduced at 5–15% addition; TBN slightly decreases but remains within limits; antioxidant effect strongest at moderate doses.	TAN = 1.6395 mg KOH/g, TBN = 5.848 mg KOH/g for 15% NPG ester blend — stable oxidation profile with minimal base number loss.
Group 4: Friction & Wear Reduction in Ester-Modified Oils (16–20)	NPG, TMP, and pentaerythritol esters	Coefficient of friction reduction up to 15%, wear scar diameter reduced by 10–20%; viscosity retention critical.	CLO + 15% NPG ester retains high shear stability (HTHS viscosity = 3.8558 cP at 150°C) while reducing frictional losses.
Group 5: Viscosity and Shear Stability Trends (21–25)	Vegetable oil esters with various base stocks	Optimal kinematic viscosity achieved at 10–20% ester; high shear stability maintained with polyol esters.	CLO + 15% NPG ester: KV@40°C = 114.07 cSt, KV@100°C = 12.65 cSt, shear stability excellent.
Group 6: Energy Efficiency and Engine Performance Benefits (26–31)	Biolubricant blends in diesel/petrol engines	Fuel consumption reduction 2–5%, improved lubrication film thickness, cleaner engine deposits.	CLO + 15% NPG ester expected to offer improved fuel economy due to balanced viscosity index and reduced pour point.

Considering all performance parameters—foam stability, pour point, TAN/TBN balance, viscosity characteristics, HTHS stability, low-temperature properties, and corrosion resistance, CLO + 15% NPG ester emerges as the optimal formulation. It provides enhanced cold-weather performance, maintains excellent high-temperature stability, and offers effective corrosion protection, making it a well-balanced and efficient lubricant blend.

Conclusion

The experimental investigation demonstrated that blending commercial lubricating oil (CLO) with 15% Neopentyl Glycol (NPG) ester by volume effectively maintains all critical physicochemical properties within acceptable limits, while also enhancing the lubricant's sustainability profile. The CLO + 15% NPG ester formulation exhibited stable viscosity characteristics, good oxidative resistance, and consistent thermal behavior comparable to the base CLO, indicating that ester incorporation at this level does not compromise fundamental lubricant performance. Among the evaluated blending ratios, 15% NPG ester emerged as a near-optimal composition, offering a favorable balance between improved lubricity and preservation of base oil parameters. Although higher ester contents, such as 20%, have been reported as optimal for certain long-chain tetra esters, the present findings confirm that NPG esters achieve comparable performance at a lower concentration, without causing undesirable shifts in viscosity index. High-temperature shear viscosity results further revealed that the 15% blend retained adequate load-carrying capacity under elevated temperatures, with no evidence of premature viscosity breakdown, thereby confirming sufficient film strength in high-stress engine conditions. Corrosion tests verified the non-corrosive nature of the blend toward metallic engine components, demonstrating that the ester addition does not promote chemical reactions leading to wear or rust formation. Across the entire temperature range investigated, high-temperature kinematic viscosity, viscosity index, low-temperature pumping viscosity, and cold-cranking viscosity remained largely unchanged relative to pure CLO, with only minor variations at 40 °C and 100 °C that fell well within permissible limits. Overall, the study concludes that the CLO + 15% NPG ester blend represents a technically viable bio-augmented lubricant that preserves essential performance characteristics while offering improved environmental compatibility, making it a promising candidate for partial replacement of conventional mineral-based engine oils in automotive lubrication applications.

Abbreviations

ASTM: American Society for Testing and Materials, CLO: Commercial Lubricating Oil, EP: Extreme Pressure, FTIR: Fourier Transform Infrared Spectroscopy, HTHS: High Temperature High Shear, NPG: Neopentyl Glycol, TAN: Total Acid Number, TBN: Total Base Number, VI: Viscosity Index.

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Author Contributions

Aakula Swathi: conceptualisation, data collection, analysis, reviewed, edited the manuscript, Kodanda Ramarao Chebattina: conceptualisation, methodology, reviewed, edited the manuscript, Vandana Vemulapalli: methodology, data collection, analysis, Srinivas Vadapalli: conceptualisation, methodology, wrote the original draft, Uma Chaithanya Pathem: data collection, analysis, wrote the original draft, Gandhi Pullagura: reviewed, edited the manuscript, Lakshmipathi Raju Bhagavatula: wrote the original draft,. All authors have read and agreed to the final version of the manuscript.

Conflict of Interest

The Authors confirm that there is no conflict of Interest to declare.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare no use of artificial intelligence (AI) for the write up of the manuscript.

Ethics Approval

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