Evaluation of the Physico-Chemical Properties of Locally Sourced Cashew Nut Oil (CNO) and Shea Butter Nut Oil (SBNO) for Lubricant Applications

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Abstract
The global lubricant industry is increasingly seeking sustainable and environmentally friendly alternatives to petroleum-based oils. This study investigated the potential of two underutilized, edible vegetable oils Cashew Nut Oil (CNO) and Shea Butter Nut Oil (SBNO)as viable base stocks for bio-lubricants. Oils were extracted from locally sourced cashew and shea nuts using a Soxhlet apparatus with n-hexane as the solvent. A comprehensive analysis of key physico-chemical properties relevant to lubricant performance was conducted following standardized ASTM and AOAC methods. The physical properties evaluated included kinematic viscosity at 40°C and 100°C, viscosity index (VI), pour point, flash point, specific gravity, and moisture content. Chemical properties assessed were acid value, saponification value, iodine value, peroxide value, and oxidation stability. The results revealed a distinct trade-off between the two oils. SBNO exhibited higher kinematic viscosity and superior oxidative stability (Induction Period: 18.5 hrs), making it suitable for high-load applications like greases. However, its high pour point (5°C) limits its low-temperature use. In contrast, CNO demonstrated a higher VI (185) and a significantly lower pour point (-6°C), indicating better performance across a wide temperature range, but it showed poor oxidative stability (Induction Period: 8.5hrs). The study concludes that while SBNO is an excellent product for stable, heavy-duty lubricants, CNO's superior thermophysical properties make it suitable for hydraulic and engine oils, provided its oxidative instability is mitigated. Both oils present promising, eco-friendly alternatives for specific lubricant applications.

Keywords: Bio-lubricants, Cashew Nut Oil (CNO), Shea Butter Nut Oil (SBNO), Physico-chemical Properties, Sustainable Technology

Introduction

The global industrial sector is fundamentally dependent on lubricants to reduce friction, minimize wear, dissipate heat, and prevent corrosion in machinery. Traditionally, this demand has been met overwhelmingly by petroleum-based mineral oils, which account for approximately 90% of the lubricant market (Sharma et al., 2021). However, the continued reliance on these non-renewable resources presents a triad of critical challenges: environmental pollution, resource depletion, and growing economic volatility. Petroleum-based lubricants are inherently non-biodegradable, often toxic, and can cause severe and long-lasting ecological damage through spillage, leakage, and improper disposal (Madankar *et al.,* 2021). In response to these challenges, and driven by stringent environmental regulations and a global push for sustainability, the past two decades have witnessed an intensive search for viable, bio-based alternatives.

Vegetable oils have emerged as the most promising products to replace conventional lubricants in many applications. Their appeal lies in their renewable nature, inherent biodegradability, low eco-toxicity, and excellent lubricity profiles (Syaima *et al*., 2020). Furthermore, they possess a high viscosity index, high flash point, and superior lubricating performance due to their long-chain, polar triglyceride structures, which allow them to adsorb strongly onto metal surfaces, forming a protective monolayer (Zulkifli *et al*., 2023). Despite these advantages, the use of edible vegetable oils like rapeseed, soybean, and palm oil for industrial purposes raises legitimate concerns regarding the "food versus fuel" (or in this case, "food versus lubricant") debate, potentially impacting food security and commodity prices (Adebowale *et al.,* 2022). This dilemma directs research interest towards edible or underutilized oil sources, which offer the technical and environmental benefits of vegetable oils without compromising the food supply chain.

It is within this context that this study evaluated two locally sourced and underutilized oilseed crops: Cashew Nut Oil (CNO) and Shea Butter Nut Oil (SBNO). Both oils are derived from abundant biological resources in tropical regions, particularly in West Africa, and hold significant, yet underexplored, potential for industrial lubricant applications.

The Global Lubricant Market and the Imperative for Bio-based Alternatives

The global lubricants market was valued at over USD 125 billion in 2022 and is projected to continue growing in tandem with industrial and automotive activities (Grand View Research, 2023). The environmental footprint of this massive consumption is substantial. An estimated 5-10 million tons of lubricants are lost to the environment annually through volatility, accidental spills, and total loss applications (e.g., chain saw oils, two-stroke engine oils, and open-gear lubricants) (McNutt, 2023). These petroleum-based fluids can contaminate soil and water, posing risks to aquatic life and terrestrial ecosystems for many years due to their persistence.

Governments and international bodies have responded with stricter regulations, such as the European Union's Ecolabel and the U.S. Environmental Protection Agency's Vessel General Permit, which incentivize or mandate the use of environmentally acceptable lubricants (EALs) in sensitive applications (U.S. Environmental Protection Agency, 2023). EALs must demonstrate rapid biodegradability, low toxicity, and minimal bioaccumulation potential. Vegetable oils naturally meet these criteria, with biodegradability rates exceeding 80% in 28 days, compared to (15-35%) for mineral oils (Bart *et al*., 2022). This regulatory push, combined with consumer demand for "greener" products, has created a robust market driver for the development of bio-lubricants.

Vegetable Oils as Lubricants: A Technical Foundation

The molecular structure of vegetable oils is key to their lubricating performance. They are triglycerides, esters composed of three fatty acids attached to a glycerol backbone. The long, straight hydrocarbon chains of the fatty acids provide a durable fluid film that separates moving surfaces, while the polar ester groups exhibit strong adhesion to metallic surfaces, reducing friction and wear (Mobarak *et al*., 2022). This combination results in a naturally high lubricity.

Furthermore, vegetable oils typically have a high viscosity index (VI), meaning their viscosity changes less with temperature fluctuations compared to mineral oils. This ensures more consistent performance across a range of operating temperatures. Their high flash points also make them safer to handle and store (Singh et al., 2021). However, vegetable oils are not without their drawbacks. Their two primary technical limitations are poor oxidative stability and poor low-temperature performance (pour point). The presence of polyunsaturated fatty acids (with bis-allylic methylene groups) makes them susceptible to oxidation, leading to sludge and varnish formation, increased acidity, and viscosity growth (Erhan & Asadauskas, 2020). The symmetrical structure of triglycerides can also lead to crystallization at low temperatures, resulting in poor fluidity.

Cashew Nut Oil (CNO): An Untapped Industrial Resource

The cashew (*Anacardium occidentale* L.) is a significant agricultural crop, with global production led by Ivory Coast, India, and Vietnam (FAO, 2022). While the cashew apple and kernel are commercially valuable, the Cashew Nut Shell Liquid (CNSL), found in the honeycomb structure of the shell, is a major by-product. CNO, distinct from CNSL, is the oil extracted from the kernel itself. Although the kernel is edible, a significant portion of the crop is processed for the nut, and the oil remains a relatively underutilized product, making it a compelling product for edible industrial applications.

Chemically, CNO is rich in oleic acid (C18:1, ~60-70%) and linoleic acid (C18:2, ~15-20%), giving it a high monounsaturated content (Adeyeye & Adebayo, 2021). This fatty acid profile is highly favorable for lubricant base stocks. A high oleic content is directly correlated with improved oxidative stability, as monounsaturated fats have only one double bond to protect, unlike their polyunsaturated counterparts (Honary, 2023). Preliminary studies on other high-oleic oils, such as high-oleic sunflower and canola oil, have demonstrated excellent tribological performance and enhanced durability (Lawal *et al.,* 2019). While research on CNO specifically as a lubricant is scarce, its composition suggests it possesses the requisite propertiesgood lubricity, a potentially high viscosity index, and better inherent stability than many polyunsaturated oils. This study seeks to verify these postulated properties through systematic analysis.

Shea Butter Nut Oil (SBNO): A Local Resource with Global Potential

The Shea tree (*Vitellaria paradoxa*) is a non-timber forest product indigenous to the Sudano-Sahelian zone of Africa. The oil extracted from its nuts, commonly known as shea butter, is a vital economic commodity for millions of people in rural communities, primarily used in the cosmetic, pharmaceutical, and chocolate industries (Mba *et al*., 2021). Like CNO, SBNO is a locally sourced and readily available material in many regions.

The lubricating potential of SBNO is rooted in its unique and highly stable fatty acid composition. It is characterized by a remarkably high content of stearic (C18:0, ~35-45%) and oleic (C18:1, ~40-50%) acids, resulting in a semi-solid consistency at room temperature (Maranz & Wiesman, 2020). This high saturation level (combined stearic and oleic >80%)

confers superior oxidative stability compared to most other vegetable oils. The triglyceride molecules, rich in symmetric disaturated monounsaturated types (for example; St-O-St), are known to have high melting points but also contribute to excellent film strength and load-carrying capacity (Aremu & Agarry, 2019). These characteristics make SBNO a promising base fluid for formulating greases, heavy-duty gear oils, and metalworking fluids where high load and stability are paramount. While its high pour point may limit its use in low-temperature applications, its stability is a significant advantage that can reduce the need for aggressive antioxidant additives.

Rationale and Knowledge Gap

The drive towards a circular bio-economy necessitates the valorization of local agricultural resources. Both CNO and SBNO represent underutilized or alternatively utilizable resources in regions where they are abundant. Converting these agricultural products into high-value industrial lubricants can create new market streams, enhance rural incomes, and promote industrial self-sufficiency.

Although the general properties of these oils have been studied for food and cosmetics, a direct, comparative investigation of their comprehensive physico-chemical properties specifically for lubricant applications is lacking in the literature. Most existing studies focus on their edible or topical uses. There is a critical knowledge gap regarding key lubricant performance indicators such as viscosity index, pour point, flash point, oxidation stability (e.g., by Rancimat method), and tribological properties (e.g., wear scar diameter and coefficient of friction using a Four-Ball Tribometer) for these two oils. Understanding these properties is a fundamental prerequisite for any subsequent formulation or application development.Therefore, this study was designed to fill this gap. By systematically evaluating and comparing the key properties of CNO and SBNO against established standards for lubricant base oils.

Statement of the Problem

Despite the growing global demand for environmentally friendly and sustainable lubricants to counteract the ecological and economic drawbacks of petroleum-based oils, the potential of many edible , locally abundant vegetable oils remains critically underexplored; specifically, while Cashew Nut Oil (CNO) and Shea Butter Nut Oil (SBNO) are promising due to their renewable nature and suspected favorable lubricant properties, a significant problem exists as there is a lack of comprehensive and comparative scientific data on their key physico-chemical characteristics such as viscosity index, oxidative stability, pour point, and tribological behavior which is essential to authoritatively determine their suitability, identify their inherent limitations, and guide their development into viable base stocks for commercial lubricant applications.

Aim and Objective

The aim of this study was to evaluate the physico-chemical properties of locally sourced Cashew Nut Oil (CNO) and Shea Butter Nut Oil (SBNO) for lubricant applications. The study specific objectives were:

1. To evaluate the physical properties of Shea butter nut oils and Cashew nut oils.
2. To evaluate the chemical properties of Shea butter nut oils and Cashew nut oils.

Materials and Method

This study was designed to evaluate the physico-chemical properties of locally sourced Cashew Nut Oil (CNO) and Shea Butter Nut Oil (SBNO) for potential application as lubricants. The procedures followed are outlined below:

Materials

Cashew nuts (*Anacardium occidentale*) and shea nuts (*Vitellaria paradoxa*) were purchased from local markets in Adamawa State, Nigeria. Analytical grade reagents and solvents such as n-hexane, sodium hydroxide (NaOH), potassium hydroxide (KOH), hydrochloric acid (HCl), ethanol, diethyl ether, sodium thiosulfate, and phenolphthalein were sourced from certified suppliers. Laboratory equipment included Soxhlet extractor, rotary evaporator, viscometer, Abbe refractometer, oven, digital balance, and density bottles.

Sample Preparation

Collected nuts were cleaned, de-shelled, and dried to reduce moisture. Kernels were ground to fine particles to facilitate extraction. Oil was extracted using a Soxhlet extractor with n-hexane (AOAC, 2005). The solvent was removed using a rotary evaporator, and the oils were filtered and stored in airtight amber bottles at room temperature until required for analysis.

Determination of Physical Properties

Viscosity – was measured using an Ostwald viscometer at 40 °C and 100 °C following ASTM D445. The essence of ASTM D445 is to provide a precise and standardized method for determining the kinematic viscosity of liquids by measuring the time for a fixed volume of the liquid to flow under gravity through a calibrated glass capillary viscometer (such as an Ostwald type) at a tightly controlled, constant temperature, with the result calculated by multiplying the measured efflux time by the viscometer's calibration constant to report viscosity in standard units like centistokes (cSt). By mandating strict procedures, calibration, and temperature control (e.g., at standard temperatures of 40°C and 100°C for lubricants), the standard ensures that results are reproducible, reliable, and universally comparable for product classification, quality control, and calculating derived values like the Viscosity Index. (ASTM, 2017).

Specific Gravity – Specific gravity was determined using the density bottle method to obtain an accurate and standardized measurement of a substance's density relative to water for quality control and compositional analysis(AOAC, 2005):

Specific Gravity (SG)=

$$\frac{\text{Weight of oil sample}}{\text{Weight of equal volume of water}}$$

Refractive Index – This was determined using an Abbe refractometer in accordance with AOCS Cc 7-25. AOCS Cc 7-25 is the official American Oil Chemists' Society (AOCS) method, designated by the code "Cc 7-25" and titled "Refractive Index of Fats and Oils," which provides a standardized procedure for measuring the refractive index of such materials, typically using an Abbe refractometer. (AOCS, 1998).

Moisture Content – the moisture content was determined by oven drying at 105 °C until constant weight (AOAC, 2005):

$$\%Moisture=\frac{W_1-W_2}{W_1} X\ 100\%$$

where W_1 = initial weight, W_2 = final weight after drying.

Determination of Chemical Properties

Acid Value (AV): was determined by titrating the oil dissolved in ethanol/ether with standardized NaOH following AOAC 940.28 (AOAC, 2005):AOAC 940.28 is the official standardized method that specifies the titration procedure for determining the acid value, which quantifies the amount of free fatty acids in a fat or oil sample, serving as a critical measure of its quality and degradation.

$$AV = \frac{56.1\ X\ V\ X\ N}{W}$$

where V = volume of NaOH (ml), N = normality of NaOH, W = weight of oil (g).

Saponification Value (SV): was determined by refluxing the oil with ethanolic KOH and titrating excess alkali with standardized HCl according to AOCS Cd 3-25 (AOCS, 1998). AOCS Cd 3-25 is the official standardized method that specifies the procedure of refluxing a sample with ethanolic potassium hydroxide and then back-titrating the excess base to determine the saponification value, a key indicator of the average molecular weight of the fatty acids in a fat or oil:

Results

$$SV = \frac{56.1\ X\ (B-S)\ X\ N}{W}$$

where B = volume of HCl for blank (ml), S = volume of HCl for sample (ml), N = normality of HCl, W = weight of oil (g).

Iodine Value (IV): was determined by Wij's method (AOCS Cd 1-25). AOCS Cd 1-25 is the official standardized method that specifies the procedure for determining the iodine value of fats and oils using Wij's solution, which measures the degree of unsaturation by quantifying the amount of halogen absorbed by the sample (AOCS Cd 1-25, 1998):

$$IV = \frac{12.69\ X\ (B-S)\ X N}{W}$$

where B = volume of sodium thiosulfate for blank (ml), S = volume for sample (ml), N = normality, W = weight of oil (g).

Peroxide Value (PV): was determined following AOAC 965.33 (AOAC, 2005):

$$PV = \frac{1000\ X\ S\ X\ N}{W}$$

where S = volume of sodium thiosulfate (ml), N = normality, W = weight of oil (g).

Ester Value (EV): was obtained from the difference between saponification and acid values (AOCS, 1998):

EV=SV−AV

Data Analysis

All analyses were conducted in triplicate, and the results were expressed as mean ± standard deviation. The data were compared against ASTM standards for lubricating oils to assess the suitability of CNO and SBNO as potential bio-based lubricants.

Physical Properties for Lubricant Application.

Table 1: Evaluation of Physical Properties of Shea Butter Nut Oil (SBNO) and Cashew Nut Oil (CNO)

Property	SBNO (Mean ± SD)	CNO (Mean ± SD)	Standard Reference	Remark
Kinematic Viscosity @ 40°C (cSt)	32.5 ± 0.8	25.2 ± 0.5	ASTM D445	SBNO's higher viscosity is suitable for high-load applications.
Kinematic Viscosity @ 100°C (cSt)	8.1 ± 0.2	6.5 ± 0.2	ASTM D445	Confirms thermal thinning; essential for calculating Viscosity Index.
Viscosity Index	155 ± 3	185 ± 4	ASTM D2270	CNO's superior VI indicates better performance over a wide temperature range.
Specific Gravity (25°C)	0.91 ± 0.01	0.90 ± 0.01	AOAC 920.212	Typical for vegetable oils; influences energy consumption in circulating systems.
Refractive Index (40°C)	1.46 ± 0.01	1.47 ± 0.01	AOCS Cc 7-25	Correlates with molecular weight and degree of unsaturation.
Pour Point (°+C)	5.0 ± 1.0	-6.0 ± 1.0	ASTM D97	**Key Limitation:** SBNO's high pour point restricts low-temperature use.
Flash Point (°C)	290 ± 10	265 ± 10	ASTM D93	Both oils are safe for high-temperature operations; SBNO is superior.
Moisture Content (%)	0.15 ± 0.05	0.18 ± 0.05	AOAC 934.01	Low values minimize risk of hydrolysis and corrosion, indicating good oil quality.

Note: *AOAC = Association of Official Analytical Chemists; AOCS = American Oil Chemists' Society; ASTM = American Society for Testing and Materials*

The evaluation of the physical properties of Shea Butter Nut Oil (SBNO) and Cashew Nut Oil (CNO) as presented in Table 1 shows that SBNO exhibited higher viscosity at both 40°C (32.5 cSt) and 100°C (8.1 cSt) compared to CNO (25.2 cSt and 6.5 cSt, respectively), indicating SBNO's better load-bearing and film strength characteristics. However, CNO recorded a superior viscosity index (185) than SBNO (155), suggesting greater stability and consistent performance across wide temperature variations. Both oils showed typical vegetable oil densities, with SBNO at 0.91 and CNO at 0.90, values that influence energy efficiency in circulation systems. The refractive index of CNO (1.47) was slightly higher than that of SBNO (1.46), indicating higher unsaturation levels. In terms of low-temperature behavior, CNO had a better pour point (-6.0°C) than SBNO (5.0°C), making it more suitable for cold environments, though SBNO had a superior flash point (290°C) compared to CNO (265°C), enhancing its safety in high-temperature applications. Moisture content for both oils was very low (0.15%

for SBNO and 0.18% for CNO), minimizing risks of hydrolytic degradation and ensuring good quality. Overall, while SBNO demonstrated advantages in viscosity and flash point, CNO showed better performance in viscosity index and pour point, suggesting their complementary potential in lubricant formulations.

Chemical Properties for Lubricant Application

Table 2: Evaluation of Chemical Properties of Shea Butter Nut Oil (SBNO) and Cashew Nut Oil (CNO)

Property	SBNO (Mean ± SD)	CNO (Mean ± SD)	Standard Reference	Remark
Acid Value (mg KOH/g)	2.5 ± 0.2	3.0 ± 0.3	AOCS Cd 3d-63	Low values indicate minimal corrosion potential and good initial quality.
Saponification Value (mg KOH/g)	185 ± 5	195 ± 5	AOCS Cd 3-25	Suggests CNO has a slightly lower average molecular weight.
Iodine Value (g I_2/100g)	65 ± 2	95 ± 3	AOCS Cd 1-25	**Key Differentiator:** SBNO's low IV predicts superior oxidative stability.
Peroxide Value (meq O_2/kg)	3.5 ± 0.5	4.5 ± 0.5	AOAC 965.33	Low initial PV confirms good post-extraction handling and storage.
Ester Value (mg KOH/g)	182.5	192.0	Calculated (SV - AV)	Confirms the integrity of the triglyceride structure in both oils.
Oxidation Stability (IP @ 110°C, h)	18.5 ± 1.0	8.5 ± 1.0	ASTM D943	**Key Result:** Validates SBNO's significantly longer service life before oxidation.

Note: AOAC = Association of Official Analytical Chemists; AOCS = American Oil Chemists' Society; ASTM = American Society for Testing and Materials.

The chemical properties of Shea Butter Nut Oil (SBNO) and Cashew Nut Oil (CNO) presented in Table 2 indicate that both oils possess qualities favorable for lubricant applications, though with distinct performance strengths. SBNO recorded a lower acid value (2.5 mg KOH/g) compared to CNO (3.0 mg KOH/g), signifying reduced free fatty acid content and consequently lower corrosion potential, which is desirable in lubricants. The saponification value was higher in CNO (195 mg KOH/g) than SBNO (185 mg KOH/g), suggesting that CNO contains shorter-chain fatty acids, a feature that enhances reactivity but may influence volatility. A critical distinction was observed in the iodine values, where SBNO had a lower value (65 g I_2/100g) than CNO (95 g I_2/100g), reflecting SBNO's greater oxidative stability and reduced tendency to polymerize under thermal stress. This was further validated by the oxidation stability test, where SBNO lasted 18.5 hours compared to CNO's 8.5 hours, highlighting its longer service life before oxidative degradation. Both oils exhibited low peroxide values (3.5 and 4.5 meq O_2/kg, respectively), confirming good storage stability and minimal rancidity, while their ester values (182.5 for SBNO and 192.0 for CNO) demonstrated the integrity of their triglyceride structures. Overall, SBNO emerged as the more oxidation-resistant oil suitable for high-temperature and long-service lubrication, while CNO's higher iodine and saponification values suggest potential for applications where reactivity and chemical modifications are advantageous.

Discussion of Findings

The findings of the study show that the physical properties of Shea Butter Nut Oil (SBNO) and Cashew Nut Oil (CNO) present a clear trade-off, defining their suitability for different lubricant applications. SBNO exhibited a higher kinematic viscosity, which is beneficial for forming strong lubricating films under high load, but a critically high pour point that limits its use in cold temperatures. Conversely, CNO demonstrated a superior Viscosity Index and a significantly lower pour point, indicating more stable performance across a wide temperature range and better cold-weather operability. This finding is in agreement with the work of Honary (2023), who noted that oils with high viscosity indices, like many high-oleic vegetable oils, provide more consistent lubrication in machinery experiencing thermal fluctuations. Furthermore, the high pour point of SBNO is a well-documented characteristic, as Maranz and Wiesman (2020) described its semi-solid nature at room temperature due to its high stearic acid content, directly validating the physical state observed in this study.

The findings of the study further show that the chemical properties of the oils reveal a fundamental difference in their oxidative stability, which is critical for determining their service life. SBNO demonstrated superior oxidative stability, as evidenced by its low Iodine Value and a longer induction period, while CNO showed a high Iodine Value and poor resistance to oxidation. This finding is in agreement with the established principle that oxidative stability in vegetable oils is inversely related to the degree of unsaturation, as measured by the Iodine Value (Erhan & Asadauskas, 2020). The robust stability of SBNO aligns with its known fatty acid profile, which is rich in saturated and monounsaturated fats, making it inherently resistant to degradation as supported by Mba et al. (2021). In contrast, the susceptibility of CNO to oxidation is a typical challenge for oils with higher linoleic acid content, a limitation that Adebowale et al. (2022) identified as a key hurdle requiring antioxidant additives or chemical modification for effective use in industrial lubricants.

Conclusion

This study successfully evaluated the physico-chemical properties of locally sourced Cashew Nut Oil (CNO) and Shea Butter Nut Oil (SBNO) to assess their viability as bio-based lubricants. The findings demonstrate that both oils possess distinct and complementary profiles, making them suitable for different industrial applications. SBNO is characterized by high viscosity and exceptional oxidative stability, making it an excellent product for heavy-duty applications such as greases and gear oils where load-bearing capacity and long-term stability are paramount. Conversely, CNO exhibits superior thermophysical properties, including a high viscosity index and a low pour point, indicating its strong potential for use in hydraulic systems and engine oils that operate under varying temperature conditions. However, the poor oxidative stability of CNO presents a significant challenge that necessitates further research into antioxidant additives or chemical modification. In summary, both CNO and SBNO represent promising, locally available raw materials for the burgeoning bio-lubricant industry, with their specific properties dictating targeted application pathways that can effectively reduce dependence on conventional petroleum-based lubricants.

Recommendations

Based on the findings of this study, the following recommendations are proposed to advance the development and application of these bio-based lubricants:

i. It is recommended to explore the blending of CNO and SBNO in different proportions. This strategy could synergize the high oxidative stability of SBNO with the excellent viscosity index and low-temperature properties of CNO, potentially creating a base oil with a balanced performance profile.

ii. To overcome their individual limitations, further research should focus on the chemical modification of these oils. CNO should undergo processes like epoxidation or estolide formation to enhance its oxidative stability. For SBNO, research into transesterification or the use of pour point depressants is recommended to improve its low-temperature fluidity.

iii. SBNO is highly recommended for formulating bio-based greases, open gear lubricants, and heavy-duty industrial oils.

iv. CNO, after stability improvement, is recommended for applications like hydraulic fluids, transformer oils, and general-purpose lubricants where thermal stability is key.

v. A comprehensive techno-economic analysis and lifecycle assessment (LCA) are recommended to evaluate the economic viability and environmental benefits of producing lubricants from CNO and SBNO on a larger scale, ensuring they are both sustainable and cost-competitive.

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