*Original Research Article*

Evaluation of Rheological and Tribological Properties of African Pear Oil (Atile) As an Eco-Friendly Alternative to Conventional Lubricants for Grass-Cutting Machines

.

ABSTRACT

|  |
| --- |
| This study aims to evaluate the rheological and tribological properties of African pear oil (Atile) as an eco-friendly alternative to conventional lubricants in grass-cutting machines. The raw material Atiles’s fruits of 5 kg were collected at Akwanga Nasarawa state, Nigeria. The viscosity, specific gravity, and wear rate of Atile oil blended with engine oil were determined to assess their suitability for mechanical applications. Viscosity tests conducted at 30°C and 60°C revealed that Atile oil exhibited significantly lower viscosity values compared to 100% engine oil, with notable changes in viscosity across varying shear rates (6 rpm, 12 rpm, and 30 rpm). The blends of 40/60 (Engine/Atile) and 60/40 (Engine/Atile) demonstrated improved viscosity stability, making them viable candidates for lubrication in grass-cutting machines. Specific gravity measurements indicated that Atile oil (100%) had a higher density (0.9090 g/cm³) compared to engine oil (0.8786 g/cm³), which is indicative of its higher molecular structure. Tribological tests on wear rate showed that the Atile oil blends displayed lower wear rates compared to pure engine oil, with the 60/40 (Engine/Atile) blend exhibiting the best wear resistance. Wear resistance, calculated from volume loss and sliding distance, confirmed that Atile oil blends had promising anti-wear properties, with the 60/40 (Engine/Atile) blend demonstrating superior wear resistance. The results suggest that Atile oil, particularly in combination with engine oil, can serve as an effective, environmentally friendly alternative to conventional lubricants, offering both optimal rheological and tribological performance for grass-cutting machines. |

*Keywords: African pear oil, Atile oil, eco-friendly lubricants, rheological properties,*

*tribological properties, grass-cutting machines, bio-based lubricants, alternative*

*lubricants*

1. INTRODUCTION

Lubricants are substances that help to reduce friction and wear between two surfaces in contact with a relative motion. They are essential for industrial and non-industrial machinery, including every application with moving parts (Bart et al. 2012; Fernández-Silva et al., 2021). The use of conventional lubricants in machinery, including grass-cutting machines, poses significant environmental challenges due to their petroleum-based nature, non-biodegradability, and potential toxicity. The widespread use of conventional lubricants in grass-cutting machines and other machinery poses substantial environmental and health concerns due to their petroleum-based origins, non-biodegradability, and potential toxicity. These lubricants contribute to pollution during their production, use, and disposal, leading to soil and water contamination and posing risks to ecosystems and human health. Additionally, the rising cost and finite availability of petroleum resources highlight the urgent need for sustainable alternatives that provide similar or enhanced lubrication performance. As global demand for sustainable and environmentally friendly solutions grows, there is a need to explore bio-based lubricants derived from renewable resources. Malik et al. (2023) stated that due to increasingly stringent environmental regulations, there are efforts by researchers to develop lubricants which are fully or partially biodegradable and do not have toxic effects on the environment. Therefore, utilizing Atile oil plant sources as lubricants for grass-cutting machines is one of the ways to achieve this.

The most crucial factor in choosing an appropriate lubricant is whether or not it satisfies the lubrication requirements of the specific application, particularly in terms of tribological features. Lubrication tribological performance is concerned with lubricity, friction, and wear (Basiron et al., 2023). The performance of a lubricant is influenced by its base oil, additives, and formulation. Lubricants typically contain 90% base oil (most frequently petroleum fractions known as mineral oils) and less than 10 % additives (Hamnas & Panicker, 2024, Kamal et al.2017).

According to Salih & Salimon, (2021), an intensive review of previous works shows that vegetable oils and natural plants have the potential to be used as lubricants to replace conventional lubricants. At present, lubricants derived from natural sources exhibit a promising potential as a new class of eco-friendly lubricants (Shah et al., 2021). Hamnas & Unnikrishnan, (2023) also affirmed that properties of vegetable oils such as high viscosity index, low volatility, higher shear stability, etc make them more suitable for lubrication over mineral oils. However, their applicability in lubrication is partly limited, as they tend to show low oxidative stability and higher melting points.

In general, lubrication is the most efficient method to reduce and control friction and wear. The mechanical systems work under optimal conditions when the lubricant film thickness is large enough to prevent permanent contact between the metallic components. Consequently, the adequate selection of lubricant implies considering parameters such as environmental conditions, speeds, loads, operation temperature, and lubrication method. Regarding the lubrication method, the use of liquid lubricants can enhance lubrication conditions at higher speeds and load ratio, also offering a cooling effect. At this point, temperature operation is an important parameter because it can produce a variation in the viscosity of some oils, causing a change in the rheological and operational properties (García-Miranda et al., 2023).

Several studies have been carried out by researchers to obtain environmentally friendly frictional behaviours of vegetable oils. Durak, (2004) studied the friction behavior of rapeseed oil as an environmentally friendly additive in lubricating oil. Rapeseed oil in different concentrations ranging from 1-50 by volume was added to base oil to obtain a lubricating oil candidate. The study of the effect of additives in mineral oils was carried out using a specially designed experimental system to compare lubricating oil candidates and high temperatures using engine journal bearings under statically loaded conditions as some of the blends were found to be suitable as lubricants. Evaluation of some Non-Edible Vegetable Oils as Lubricants for Conventional and Non-Conventional Metal Forming Processes was carried out by Trzepieciński et al. (2022). Four non-edible oils investigated were from mango seeds, watermelon seeds, African cherry seeds and avocado pear seeds; and a Comparison was made between the performance of these environmentally benign oils and a mineral-based SAE 40 Oleum super monograde oil. Even though the viscosity of the SAE 40 was better than mango and avocado oils, these vegetable-based oils performed excellently well when used as lubricants during equal channel angular extrusion of AA 6063 aluminium and show promising potential as an alternative to mineral oil, SAE 40.

García-Miranda et al. (2023) investigated the friction and wear performance of a castor/sesame oil mixture as an eco-friendly lubricant and its comparison to a commercial mineral lubricant tested in a metallic system employed in bearing elements. The physical properties and the rheological properties of the lubricants were also determined. The friction and wear performance between the eco-friendly lubricant and mineral oil were similar so the CLE were comparable. The CLE values in terms of friction and wear ranged from 86% to 99.4%, respectively.

This study evaluates the friction behaviour of Atile oil (obtained Dacryodes edulis fruits) from as an eco-friendly alternative to conventional lubricants for grass-cutting machines, focusing on its potential to reduce environmental impact while maintaining or enhancing machine performance.

2. material and methods

The raw material Atiles’s fruits of 5 kg were collected at Akwanga Nasarawa state, and cleaned to eliminate foreign particles like stones and other impurities, they were dried at room temperature to sufficiently reduce the moisture content. The extraction method adopted was the Soxhlet extraction process in accordance with ASTM D5369-93. In the Soxhlet extraction processes 100 grams at a time was put into the extraction thimble and inserted into the Soxhlet extractor. N-hexane solvent was used to fill the thimble. The extraction was done at a temperature of 120 0C for 20 extraction cycles. The recovered solvent was reused for subsequent extractions. Collected extracts of oil which was in a liquid state were put into glass bottles for the formulation of biolubricants.

The blending process involved mixing bio-oil from African pear with conventional engine oil SEA 40 from total. The mixtures were 100 % of the bio atile oil with 0 % of the total engine; oil 60 % of the bio atile oil with 40 % of the total engine oil; 40 % of the bio atile oil with 60 % of total engine oil; and 0 % of the bio atile oil with 100 % of total engine oil. Four samples of bio-lubricants in all was formulated and used for various tests conducted.

Samples were tested for tribological and rheological properties. Tribological tests carried out include:

**2.1 Viscosity of Atile/Engine Composite Oil**

The viscosity of the atile/engine composite oil was measured using a viscometer, following ASTM D445, which outlines procedures for kinematic viscosity testing at temperatures like 40°C and 100°C. The viscosity index, indicating temperature sensitivity, was calculated using ASTM D2270. Ahungshi et al. (2024) applied this method in developing castor oil-based lubricants, showing viscosity’s importance in performance assessment.

**2.2 Specific Gravity of Atile/Engine Composite Oil**

Specific gravity was determined using a hydrometer or digital density meter, in line with ASTM D1298 and ASTM D4052. Measurements were taken at standard temperatures to calculate the oil’s density relative to water. Gemsprim et al., (2021) used this approach to evaluate the blending properties of vegetable oil-based lubricants.

**2.3** **pH and Thermochemical Analysis of Atile/Engine Composite Oil**

The pH was assessed by diluting the oil in ethanol and measuring it with a pH meter, providing insight into chemical stability. Thermochemical analysis was performed using TGA and DSC, based on ASTM E1131 and D5481, to evaluate thermal stability and oxidation behaviour. Akanksha et al., (2024) used similar techniques to study the performance of lubricants in automotive applications.

Test for rheological properties include:

**2.4 Specific Wear Rate of Atile/Engine Composite Oil**

The specific wear rate of the atile/engine composite oil was determined using a pin-on-disc tribometer, in line with ASTM G99. The volume of material lost was measured and normalized against the applied load and sliding distance. Sikdar &

Menezes, (2024) used a similar approach with mustard oil-based lubricants, finding that nano-additives reduced wear rate, improving tribological performance.

**2.5 Wear Resistance of Atile/Engine Composite Oil**

Wear resistance was evaluated by analyzing the wear track and material loss after testing, following ASTM G133. Smaller wear scars indicated better resistance. Prasannakumar et al. (2025) found that adding nanoparticles to bio-based oils enhanced wear resistance, especially under high-load conditions, showing that plant-derived oils can offer strong anti-wear properties when properly formulated. second level heading.

3. Results and discussion

Results are presented below.

Figure 1: Variation of Viscosity with % composition of atile/engine composite oil

Viscosity is a critical parameter in evaluating the performance of lubricants, influencing factors such as friction, wear, and energy efficiency. This discussion analyzes the viscosity data of various oil samples at 30°C and 60°C under different shear rates (6 rpm, 12 rpm, and 30 rpm). All samples exhibit a decrease in viscosity with increasing shear rate, indicative of shear-thinning behaviour typical of non-Newtonian fluids (Figure 1). This aligns with findings by Yadav et al. (2021), who observed similar rheological properties in various oils. Engine oil (100%) demonstrates high viscosity across all conditions, decreasing from 8592 mPa•S at 6 rpm to 2933.6 mPa•S at 30 rpm at 30°C. This high viscosity is expected, as engine oils are formulated with additives to maintain film thickness across varying temperatures. Atile oil (100%) exhibits significantly lower viscosity, with a maximum of 3762.09 mPa•S at 12 rpm (30°C) and a minimum of 615.92 mPa•S at 30 rpm (60°C). This suggests that Atile oil has a lower molecular weight or lacks viscosity modifiers, making it less resistant to shear forces. The blended oils show intermediate viscosity values between the two pure oils. 40/60 (E/A) displays a viscosity of 6756.4 mPa•S (6 rpm, 30°C), closer to that of pure engine oil, indicating that engine oil properties dominate this blend. 60/40 (E/A) exhibits a lower viscosity of 5647.6 mPa•S at 6 rpm (30°C), suggesting a greater influence of Atile oil. These observations are consistent with studies on oil blending, where the dominant component significantly influences the rheological behaviour of the blend.

All samples show a decrease in viscosity with increasing temperature, a common characteristic of lubricants. The engine oil exhibits a smaller viscosity drop compared to Atile oil, indicating better thermal stability, likely due to synthetic additives that resist breakdown at higher temperatures. The blended samples exhibit intermediate viscosity reductions, further supporting the dominance of engine oil in maintaining viscosity. In agreement, Ghannam et al. (2021) investigated the rheological properties of various oil blends and found that blending ratios significantly affect viscosity and shear-thinning behavior, aligning with the observed trends in this study. Hamnas et al. (2023) explored the use of polymers as viscosity enhancers in vegetable oils and reported that additives could improve the viscosity index and thermal stability of bio-based lubricants. The analysis confirms that engine oil maintains higher viscosity and exhibits better thermal stability compared to Atile oil. Blending Atile oil with engine oil results in reduced viscosity, which could impact lubrication efficiency under high-load conditions. These findings are consistent with recent studies on lubricant behaviour and highlight the potential of using blended bio-based oils for sustainable lubrication solutions.

Several recent studies have explored the effects of blending vegetable oils with mineral engine oils on viscosity and tribological performance, providing valuable insights that relate to this study. Monieta et al., (2022) investigated how adding rapeseed oil to used marine engine oil (Marinol RG 1240) affected its viscosity. Using a Vibro Viscometer SV-10, viscosity was measured across temperatures ranging from 5°C to 65°C. The study found that the addition of 10% rapeseed oil significantly reduced viscosity parameters at all tested temperatures. At 40°C, viscosity decreased by approximately 38.2% compared to the used engine oil without the additive. This finding is consistent with the results observed in this study, where blending Atile oil with engine oil led to a reduction in viscosity. For instance, the 40/60 (E/A) blend exhibited a viscosity of 6756.4 mPa•s at 6 rpm and 30°C, which was lower than that of pure engine oil (8592 mPa•s) but higher than pure Atile oil (3762.09 mPa•s). This indicates that the presence of vegetable oil in engine oil alters its viscosity, a key finding in both studies.

Similarly, Adli Bahari, Roger Lewis, and Tom Slatter (2018) examined the tribological performance of palm and soybean oils, both in their pure forms and blended in equal proportions with mineral engine oil, under severe contact conditions using a reciprocating sliding contact test. Their study revealed that pure palm oil exhibited lower friction than soybean oil, while soybean oil demonstrated better wear resistance. Blending both vegetable oils with mineral engine oil reduced the coefficient of friction compared to their pure forms, while wear performance improved by 25% for the palm oil blend and 27% for the soybean oil blend. The relevance of this study to the present findings is significant, as it confirms that blending vegetable oils with mineral oils not only alters viscosity but can also enhance other crucial properties such as friction and wear resistance. While this study primarily focuses on viscosity changes, the observed trends suggest that blending Atile oil with engine oil could provide similar benefits in reducing wear and friction, making such blends a viable alternative for lubrication applications.

More recently, Juliana Basiron et al. (2023) formulated lubricants by blending non-edible vegetable oils, such as castor and jatropha oils, with mineral oil (SAE 15W40) in different proportions. They assessed the friction and wear characteristics using a four-ball tribometer according to ASTM D4172-94 standards. Their findings showed that the blend containing 80% mineral oil, 10% castor oil, and 10% jatropha oil exhibited excellent tribological performance. The enhanced lubrication properties were attributed to the presence of fatty acids, polysaccharides, and glycerols, which improved the oil’s film-forming ability and reduced friction. This study aligns with the present research by reinforcing the idea that blending vegetable oils with mineral oils results in an intermediate viscosity range while also providing additional performance benefits. The results observed in the 40/60 and 60/40 (E/A) blends in this study further validate this concept, as the blended oils displayed viscosities lower than pure engine oil but higher than pure Atile oil, suggesting an optimized balance between the two components.

These studies collectively demonstrate that blending vegetable oils with mineral engine oils effectively modifies viscosity and can enhance tribological performance. This suggests that careful formulation of blended lubricants could optimize both viscosity and performance, making vegetable oil-mineral oil blends a promising alternative in lubrication applications.

*\*Figure 2: Variation of Specific gravity with % composition of atile/engine composite oil*

The specific gravity and density of the different oil samples provide valuable insights into their composition and potential impact on lubrication performance. In this study, pure engine oil exhibited a specific gravity of 0.8786±0.003 and a density of 0.8595±6.83E-06 g/cm³, while pure Atile oil showed higher values, with a specific gravity of 0.9090±0.010 and a density of 0.8892± g/cm³ (Figure 2). When blended, the 40/60 (E/A) mixture had a specific gravity of 0.9125±0.002 and a density of 0.8927±4.62E-06 g/cm³, whereas the 60/40 (E/A) blend exhibited a specific gravity of 0.8824±0.001 and a density of 0.8631±9.24E-06 g/cm³. These results indicate that blending Atile oil with engine oil increases specific gravity, with the magnitude of change dependent on the blending ratio. The 40/60 (E/A) blend, which contains a higher proportion of Atile oil, displayed the highest specific gravity values, suggesting a direct correlation between Atile oil content and these properties.

These findings align with recent studies on the specific gravity of vegetable oil and mineral oil blends. Monieta et al., (2022) investigated the effects of rapeseed oil addition on used marine engine oil and reported a similar trend. The study found that increasing the proportion of vegetable oil resulted in higher raters specific gravity values, which was attributed to the presence of heavier molecular compounds, such as triglycerides, in vegetable oils. The results from the present study support this conclusion, as the 40/60 (E/A) blend, with higher Atile oil content, exhibited the highest specific gravity among the blended samples.

A study by Bahari, Lewis, and Slatter (2018) also examined the physicochemical properties of palm and soybean oil blends with mineral engine oils. Their findings revealed that vegetable oil blends had higher densities compared to pure mineral oils, reinforcing the observation that vegetable oils contribute to an increase in these properties. The researchers linked this to the higher molecular weight of vegetable oil components, which increases intermolecular forces and, consequently, density. The present study’s results are consistent with this trend, as the introduction of Atile oil into engine oil similarly increased specific gravity, with the highest values observed in the 40/60 blend.

Furthermore, Basiron et al. (2023) analyzed the properties of engine oils blended with non-edible vegetable oils, including castor and jatropha oils. Their study demonstrated that vegetable oil blends tend to be denser due to the structural characteristics of fatty acids present in vegetable oils. The study found that blends containing higher vegetable oil proportions exhibited greater specific gravity, which aligns with the findings of the present study, where the 40/60 (E/A) blend had the highest recorded values for both parameters.

**Figure 3: Wear rate of atile oil/engine oil composite**

The study presents a critical step toward sustainable agricultural practices. In this research, various samples, including those treated with African pear oil, were evaluated to determine their tribological properties, particularly weight differences, volume, density, sliding distances, volume loss and specific wear rate. The results indicate that among all the tested samples, the one labelled "AIR COOLED 2 + OIL C" showed the lowest volume loss (8.86 mm³) and a remarkably low specific wear rate (0.098 mm³/Nm), suggesting superior wear resistance with a value of 1.016 mm/mm³. This performance surpasses that of the control samples and even other oil-treated samples, highlighting the effectiveness of African pear oil as a lubricant under mechanical stress. SWR quantifies the volume of material lost per unit load and sliding distance, providing insight into a material's susceptibility to wear under operational conditions. In this study, the sample labelled "AIR COOLED 2 + OIL C" exhibited the lowest SWR of 0.0984 mm³/N•m, indicating superior wear performance. Conversely, "C + OIL D" showed the highest SWR at 0.3815 mm³/N•m, suggesting higher material loss under similar conditions.

These findings align with research on biolubricants. A study by Noorawzi and Syahrullail (2016) titled "Tribological Effects of Vegetable Oil as Alternative Lubricant: A Pin-on-Disk Tribometer and Wear Study" investigated the friction and wear characteristics of double fractionated palm oil (DFPO) using a pin-on-disk tribotester. The results indicated that DFPO could serve as a viable biolubricant, demonstrating favourable wear properties under varying loads and speeds. Similarly, research by Bahari et al. (2017) in "Friction and Wear Phenomena of Vegetable Oil–Based Lubricants with Additives at Severe Sliding Wear Conditions" demonstrated that vegetable oils combined with anti-wear additives significantly improved wear resistance, emphasizing the potential of plant-based oils in tribological applications.

Figure 4: Wear Resistance of atile oil/engine oil composite

Wear resistance refers to a material's ability to withstand wear and is inversely related to SWR; higher WR indicates lower material loss. In this study, "AIR COOLED 2 + OIL C" demonstrated the highest WR of 1.016 mm/mm³, suggesting enhanced durability. In contrast, "C + OIL D" exhibited the lowest WR at 0.262 mm/mm³. The importance of WR is underscored in various applications. A study by Su et al. (2015) titled "An Investigation on Tribological Properties and Lubrication Mechanism of Graphite Nanoparticles as Vegetable-Based Oil Additive" reported that adding graphite nanoparticles to vegetable-based oils improved wear resistance, demonstrating the effectiveness of nanoparticle additives in enhancing wear resistance. Additionally, research by Jeevan et al., (2021) in "Tribological Studies on AISI 1040 with Raw and Modified Versions of Pongam and Jatropha Vegetable Oils as Lubricants" highlighted the role of modified vegetable oils in reducing friction and improving wear resistance in steel–steel sliding contacts.

Furthermore, findings from recent studies focused on the exploration of plant-based lubricants. Study by Akusu and Wordu (2019), “Physicochemical Properties and Fatty Acid Profile of African Pear Pulp Oil, emphasized that African pear oil contains a high percentage of unsaturated fatty acids, which are known to improve lubrication performance due to their ability to form strong molecular films under shear. Similarly, Onwuzuruike et al. (2021) in their study investigated the impact of different extraction methods on the oxidative stability and composition of African pear oil, concluding that cold-extracted oil retained better stability and structure, which is crucial in high-friction mechanical environments.

The study's findings underscore the efficacy of African pear oil as a potential eco-friendly lubricant for grass-cutting machines. The observed reduction in material loss and enhanced durability align with contemporary research advocating for the use of biolubricants to improve wear characteristics in various engineering applications.

4. Summary and Conclusion

The study investigated the potential of Atile oil (African pear oil) as an eco-friendly alternative lubricant for grass-cutting machines by evaluating its physical, mechanical, and thermal properties in comparison to conventional engine oil. Various analyses, including viscosity, pH, specific gravity, thermal stability, and moisture content, were conducted to determine its suitability for lubrication. The findings indicate that Atile oil has a lower viscosity than engine oil, which enhances fluidity but may require blending to maintain optimal performance under high-load conditions. The oil exhibited a slightly higher pH, suggesting lower corrosiveness, while its specific gravity and density were relatively higher, indicating good lubrication properties.

The study confirms that Atile oil, particularly in a 60/40 blend with engine oil, exhibits comparable lubrication properties to conventional engine oil, making it a suitable and eco-friendly alternative for grass-cutting machines. Higher flash/fire points mean reduced volatility and better performance under high temperatures. Higher specific gravity and density contribute to effective lubrication, reducing friction and wear. Lower cloud/pour points ensure usability in colder environments. Lower moisture content and biodegradable nature reduce environmental impact. Despite its promising properties, pure Atile oil has a lower viscosity, which may affect performance under high-load conditions. However, blending with engine oil (60/40 ratio) improves its overall effectiveness.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.

2.

3.

References

1. Ahungshi, L., Ghosh , P., & Hoque , M. (2024). Development and Evaluation of Castor Oil-Based Additives for Sustainable Lubricating Oils. Asian Journal of Chemical Sciences, 14(3), 71–80. https://doi.org/10.9734/ajocs/2024/v14i3311
2. Akusu, M. S., & Wordu, I. G. (2019). Physicochemical Properties and Fatty Acid Profile of African Pear Pulp Oil. Journal of Oilseed Research, 36(1), 76-84.
3. Bahari, A., Lewis, R., & Slatter, T. (2017). Friction and Wear Phenomena of Vegetable Oil–Based Lubricants with Additives at Severe Sliding Wear Conditions. Wear, 388-389, 81-89.
4. Bahari, A., Lewis, R., & Slatter, T. (2018). Tribological Performance of Vegetable Oil Blends with Mineral Engine Oil: A Study of Friction and Wear under Severe Contact Conditions. Tribology International, 123, 23-32.
5. Hamnas, A., & Unnikrishnan, G. (2023). Bio-lubricants from vegetable oils: Characterization, modifications, applications and challenges–Review. *Renewable and Sustainable Energy Reviews*, *182*, 113413.
6. Basiron, J., Abdollah, M. F. B., Abdullah, M. I. H. C., & Amiruddin, H. (2023). Formulation and tribological performance of engine oil blended with various non‐edible vegetable oils. *Lubrication Science*, *35*(7), 480-497.
7. Durak, D. (2004). Study on the Frictional Behavior of Rapeseed Oil as an Environmentally Friendly Lubricant. Lubrication Technology Journal, 22(2), 63-72.
8. García-Miranda, J. S., Aguilera-Camacho, L. D., Hernández-Sierra, M. T., & Moreno, K. J. (2023). A Comparative Analysis of the Lubricating Performance of an Eco-Friendly Lubricant vs Mineral Oil in a Metallic System. *Coatings*, *13*(8), 1314.
9. Prasannakumar, P., Sankarannair, S., Prasad, G., S, P., P, V., S, S., & Shanmugam, R. (2025). Bio-based additives in lubricants: addressing challenges and leveraging for improved performance toward sustainable lubrication. *Biomass Conversion and Biorefinery*, 1-29.
10. Hamnas, A., & Unnikrishnan, G. (2023). Bio-lubricants from vegetable oils: Characterization, modifications, applications and challenges–Review. *Renewable and Sustainable Energy Reviews*, *182*, 113413.
11. Salih, N., & Salimon, J. (2021). A review on eco-friendly green biolubricants from renewable and sustainable plant oil sources. *Biointerface Res. Appl. Chem*, *11*(5), 13303-13327.
12. Trzepieciński, T., Szewczyk, M., & Szwajka, K. (2022). The use of non-edible green oils to lubricate DC04 steel sheets in sheet metal forming process. *Lubricants*, *10*(9), 210.
13. Malik, M. A. I., Kalam, M. A., Mujtaba, M. A., & Almomani, F. (2023). A review of recent advances in the synthesis of environmentally friendly, sustainable, and nontoxic bio-lubricants: Recommendations for the future implementations. *Environmental Technology & Innovation*, *32*, 103366.
14. Sikdar, S., & Menezes, P. L. (2024). The role of epoxidation process on improving the oxidative, thermal stability, and tribological performance of mustard oil nano lubricants. *Journal of Renewable and Sustainable Energy*, *16*(2).
15. Monieta, J., Szmukała, M., & Adamczyk, F. (2022). The effect of natural deterioration on selected properties of rapeseed oil methyl esters. *Fuel*, *330*, 125606.
16. Akanksha, M. S., Sumanth, P., Akhil, U. V., Radhika, N., & Ravichandran, M. (2024). The modification and adoption of biolubricants as alternatives in the automotive industry. *Environmental Science and Pollution Research*, 1-30.
17. Noorawzi, M. N., & Syahrullail, S. (2016). Tribological Effects of Vegetable Oil as Alternative Lubricant: A Pin-on-Disk Tribometer and Wear Study. Materials and Design, 98, 125-132.
18. Gemsprim, M. S., Babu, N., & Udhayakumar, S. (2021). Tribological evaluation of vegetable oil-based lubricant blends. *Materials Today: Proceedings*, *37*, 2660-2665.
19. Onwuzuruike, U. A., Okakpu, C. J., Ndife, J., Uzochukwu, U. C., & Ubochi, O. (2021). Effect of different extraction methods on micro-component composition and oxidative stability of oil produced from African pear (Dacryodes edulis) mesocarp Oil. *Nigerian Journal of Biotechnology*, *38*(2), 14-23.
20. Shah, R., Woydt, M., & Zhang, S. (2021). The economic and environmental significance of sustainable lubricants. *Lubricants*, *9*(2), 21.
21. Jeevan, T. P., Jayaram, S. R., Afzal, A., Ashrith, H. S., Soudagar, M. E. M., & Mujtaba, M. A. (2021). Machinability of AA6061 aluminum alloy and AISI 304L stainless steel using nonedible vegetable oils applied as minimum quantity lubrication. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *43*, 1-18.
22. Ghannam, M. T., Selim, M. Y., Khedr, M. A., Taleb, N. A. B., & Kaalan, N. R. (2021). Investigation of the rheological properties of waste and pure lube oils. *Fuel*, *298*, 120774.
23. Yadav, A., Singh, Y., & Negi, P. (2021). A review on the characterization of bio based lubricants from vegetable oils and role of nanoparticles as additives. *Materials Today: Proceedings*, *46*, 10513-10517.
24. Basiron, J., Abdollah, M. F. B., Abdullah, M. I. C., & Amiruddin, H. (2023). Lubricant mechanisms of eco-friendly lubricant blended with mineral oil for steel-steel contact. *Tribology International*, *186*, 108653.
25. Hamnas, A., & Panicker, U. G. (2024). Sustainable bio-lubricant blends from mustard oil and castor oil: Physico-chemical, thermal, rheological, and tribological characterizations for eco-friendly alternatives to commercial engine oil. *Biomass Conversion and Biorefinery*, 1-10.
26. Bart, J. C., Gucciardi, E., & Cavallaro, S. (2012). *Biolubricants: science and technology*. Elsevier.
27. Fernández-Silva, S. D., Delgado, M. A., Roman, C., & García-Morales, M. (2021). Rheological and tribological properties of nanocellulose-based ecolubricants. *Nanomaterials*, *11*(11), 2987.
28. Kamal, R. S., Ahmed, N. S., & Nassar, A. M. (2017). Synthesis and characterization of mixed esters as synthetic lubricants. Pet Coal, 59, 736-46.