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REVIEW ARTICLE

A REVIEW OF BLENDED NON-EDIBLE GREEN OIL-BASED LUBRICANTS FOR ENHANCED PERFORMANCE IN TWO-STROKE ENGINES

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ABSTRACT

The increasing environmental concerns associated with petroleum-based lubricants and growing demand for environmentally friendly solutions have spurred research into non-edible green oil-based lubricants, particularly for their application in two-stroke engines. Two-stroke engines, while offering advantages in power-to-weight ratio, pose environmental challenges due to their inherent design of the oil-fuel mixture. By utilizing non-edible sources, these lubricants help avoid competition with food crops, ensuring that edible oils remain available for human consumption, while non-edible oils present a promising solution. Study have shown green oil enhances mechanical and thermal braking efficiency by 13% and 27%, while it reduces emission of CO, CO_2 and HC approximately by 62%, 54% and 44% respectively compared to conventional lubricants. This review explores the properties of various non-edible green oils, including their physicochemical characteristics and potential as base stocks for lubricants production. Furthermore, it explores the challenges and opportunities associated with these non-edible green oil-based lubricants. Furthermore, it analyses previous research on the application of green oil-based lubricants in two-stroke engines, focusing on their impact on engine performance, emissions, and wear. The review also discusses the role of additives and blending in improving the overall performance of these lubricants and highlights the need for further research to optimise their application in two-stroke engines. Finally, the review identifies key research gaps and future directions, emphasizing the need for systematic investigation of blend ratios, exploration of environmentally friendly nano-additives, and rigorous engine testing to unlock the full potential of blended non-edible green oil-based lubricants for sustainable two-stroke engine applications. This review underscores the potential of blended non-edible green oil-based lubricants as viable solutions for enhancing performance in two-stroke engines and encourages further research into their long-term effects and commercial viability.

1.0 Introduction

Environmental anxiety and regulatory measures to control carbon emissions and ecologically detrimental activities have, therefore, resulted in an enormous transformation toward sustainable practices in the automotive and industrial sectors in recent decades. This change of thinking fostered lots of research and development to discover alternative lubricant solutions that perform even better than conventional lubricants with no or minimal harm to the environment.

Lubricating oils play an important role in both automotive and industrial applications by minimizing wear and friction between the moving parts so as to maximize efficiency and increase equipment lifespan (Ng *et al.*, 2022). Lubricants, in fact, happen to have a pivotal role in the smooth operation of internal combustion engines, particularly two-stroke engines; they enhance performance and longevity (Musa and Omisanya, 2021). The properties of lubricants required by two-stroke engines, which mix petrol and oil in one cycle, are that they resist high temperatures and have good wear-and-tear resistance. This particularity highlights the importance of selecting lubricants and formulating them such that engine life will be fully maximized.

Two-stroke engines are lighter than other engines, and they are also simple to make and use (Krishna *et al.*, 2016; Alturki, 2017). At the same time, however, they add environmental problems by not burning the oil completely and running on oil-fuel mixtures (Orman, 2023). Though outlawed, two-stroke engines are in use for certain cases and when policies are made, the impact on the low-income earners and rural areas is usually ignored by lawmakers. All those applications where two-stroke engines are still popular are giving some motorcycles, especially off-road and dirt bikes, outboard motors for small boats, lawn mowers, small electric generators, and in small engines such as chainsaws, leaf blowers, and brush cutters (Mang and Dresel, 2007; Zulfattah *et al.*, 2019; Ng *et al.*, 2022; Orman, 2023). Two-stroke engines provide specific lubrication needs and issues due to their widespread application in anything from very small power tools to everyday motorbikes (Mang and Dressel, 2007; Singh, 2011; Zulfattah *et al.*, 2019; Ng *et al.*, 2022).

Therefore, two-stroke engine needs a lubricant to provide essential lubrication at varying operating conditions and would withstand high temperatures (Zulfattah *et al.*, 2019) due to simplification in combustion cycle that has only two basic strokes. Figure 1 shows working principle of two-stroke engine, it completes a power cycle in two piston strokes by using the piston's movement to control intake, compression, power, and exhaust through a system of ports and crankcase compression. This results in a simpler and often more power-dense engine for its size and weight, but typically with lower fuel efficiency and higher emissions compared to a four-stroke engine (Ng *et al.*, 2022). This cycle repeats with each rotation of the crankshaft, allowing for more power strokes per cycle.

Though traditionally dominant in this industry, petroleum-based lubricants are coming under more scrutiny for their potential environmental effects which drives research into more environmentally friendly options (Kok and Abdullah, 2019). When they burn in two-stroke engines, petroleum-based lubricants produce toxic hydrocarbons and particulate matter figures, which further contribute to air pollution and human health impacts (Ng *et al.*, 2022). Therefore, there is an urgent need for more environmentally friendly lubricant solutions that could ideally deliver the same or even better performance and not have the detrimental adverse effects on the environment. While research into green oil-based lubricants has shown some promise, issues of food security and competition for resources come into the picture when edible oils are considered.

This review examines the existing literature of non-edible green oil as base stock for biolubricant, blend of non-edible green oil-based and green oil-based lubricant for two-stroke engine applications, identifying the potential of such lubricants to improve performance and the environment, as well as the most prominent research gaps and future directions in terms of development and implementation.

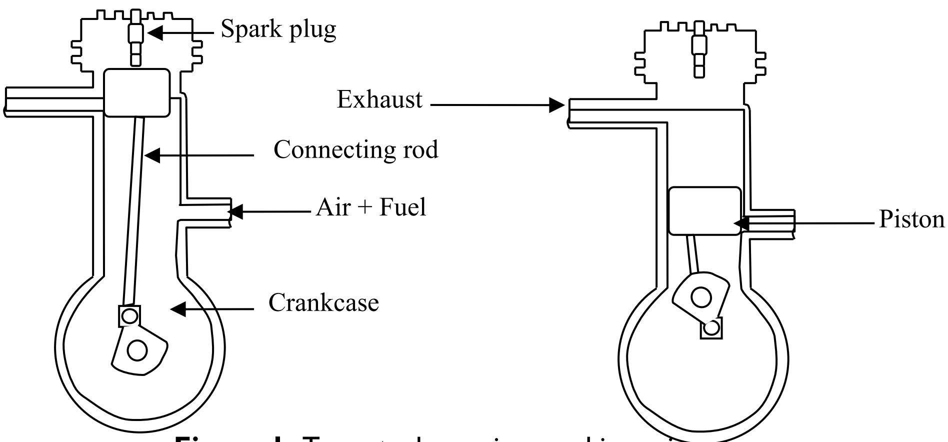

Figure 1: Two-stroke engine working principle

2. Non-edible Green Oil as Base Stocks

The most attractive prospective attributes of non-edible green oils are being renewable source and eco-friendly quality (Kumar *et al.*, 2022). Green oil-based lubricants are renewable materials derived from plant and animal fats. Compared to standard petroleum-based lubricants, which are limited due to finite fossil fuel resources and are heavily environmentally negative from their life cycles, green oil-based lubricants are more resourceful in various ways. Such renewable materials are relatively abundant and biodegradable. They can be sourced from various plants that do not compete with food crops, thereby addressing the food versus energy debate. Such oils would be relatively much cheaper to manufacture than edible oils, thereby making them a godsend for the case that seeks production of green oil-based lubricants without competition with food sources (Popoola & Jibatswen, 2024; Rockson-itiveh *et al.*, 2024). Table 1 presents examples of non-edible green oils such as: Algae oil, jojoba oil, neem seed oil, karanja oil, castor oil, mahua oil, *Thevetia peruviana* seed oil, and jatropha oil (Patil *et al.*, 2021), and their key physicochemical properties as applicable for the suitability assessment of the oils for lubricant applications. The current utilization of such non-edible oil seeds is extremely low, and their incorporation in lubricant formulations is expected to be a global move towards decreasing dependency on fossil fuels and for mitigating the negative environmental effects of dependency on such fuels (Gheidan *et al.*, 2022).

They have proved exceedingly high in lubricity and renewability combined with availability, economy, biodegradability, high viscosity index, and flash point (Ruggiero *et al.*, 2016). Suitable for different industrial applications, they can be grown in wastelands and forests and are much less environmentally friendly than mineral oils. For example, jatropha oil is well suited for high-temperature applications due to its high viscosity and oxidative stability (Islam *et al.*, 2018). Also, yellow oleander oil has potential because of its favourable high viscosity index and good cold-flow properties, which make it suitable for industrial applications (Choudhury and Saha, 2022). Selection of base oils does directly influence the performance of lubricant as well as its ability to meet certain application requirements.

Table 1: Physicochemical properties summary of some key Non-Edible Oils

Oil	**Properties**					**Reference**
	Viscosity @ 40 ^{0}C (cSt)	**Viscosity @ 100 ^{0}C (cSt)**	**Viscosity Index**	**Pour Point (^{0}C)**	**Flash Point (^{0}C)**	
Algae	*	*	*	5 – 8	110	Ejim and Kamen (2013)
Jojoba	26	7.5	257	*	*	El-adly *et al.* (2012)
Neem	109	22.6	*	25	265	Idris *et al.* (2018)
Karanja	54.54	15.18	304.9	-1	220	Agrawal *et al.* (2017)
Castor	280.6	77.5	33.4	-23.2	282	Woma *et al.* (2019)
Mahua	37.18	11.66	325.6	18	210	Agrawal *et al.* (2017)
Yellow oleander	31.76	7.89	235.59	-4	344	Choudhury and Saha
Jatropha	83.2	63.5	145.5	-11.2	264	Woma *et al.* (2019)

**Not specified*

2.1 Non-edible Green Oil Lubricant

In 2013, Chauhan and Chhibber hinted that green oil-based lubricants could be formulated from non-edible oils from particular non-edible plant seeds with an oil yield of at least 30%. Oil is usually extracted from kernels or seeds using mechanical, solvent, or enzymatic extraction methods (Bilal *et al.*, 2013). Green oils from the non-edible class can find use in a variety of applications including cutting fluids for machining as well as lubricants for automotive and industrial machinery (Katna *et al.*, 2022, Trzepieciński, *et al.*, 2022). Non-edible green oil lubricants represent a sustainable choice for lubrication requirements, balancing performance and environmental consideration. The growing demand for these lubricants will most likely be boosted by the industries eager to lessen their ecological impacts.

Non-edible green oils have been said to possess qualities that are sometimes matching or even superior to traditional lubricants in performance. They exhibit good lubrication properties, reducing wear and friction (Silva *et al.*, 2013). In order to meet these performance standards some other properties such as poor cold flow and poor oxidative stability need to be improved through the use of appropriate additives or formulation or chemical modification.

Awoyale *et al.* (2011) set out to produce biodegradable grease from black date oil. Extraction of the oil with n-hexane and hydrolysis with base oil, thickener, stearic acid, and additives were conducted. The tests verified the quality of grease, biodegradability, dropping point, and workability. The observations indicated consistency and Biochemical Oxygen Demand were within acceptable limits. Oseni *et al.* (2014) investigated the alternative use of yellow oleander oil for machine lubricant. The extracted oil displays characteristics that are comparable to oil lubricants popularly used. Specifically, the oil has a free fatty acid percentage of 5.61%, specific gravity ranging from 0.89 to 0.92, and high flash and fire points of 350 ^{0}C and 375 ^{0}C respectively.

Orhevba and Attamah (2016) studied biolubricants produced from neem seed oil for agricultural machinery. Among their findings was a high fatty acid content of 3.7% which was reduced to 0.7% through methanol esterification. The viscosity index of developed lubricant is 10.9% better than the conventional lubricant. The biolubricant synthesized is used as a substitute for petroleum-based lubricants in industrial as well as agricultural machines. Agrawal *et al.* (2017) studied the physicochemical properties of crude mahua and karanja oils. The final products which is Karanja and Mahua Biolubricants were found to have higher viscosity index and lower oxidation stability compare to two stroke lubricant. These biolubricants can replace significant quantities of mineral oil as base oil. Owuna *et al.* (2018a) research use calabash seed oil to develop a motor oil lubricant. Blend of calabash seed oil, synthetic oil and additives were used to formulate a lubricant with better characteristics meeting engine oil specifications for eco-friendly lubricant with the same quality as synthetic oil. According to Idris *et al.* (2018), neem oil can acts as an efficient lubricant in both light and heavy automotive systems. The neem oil flash point was determined to be 265°C, which aligns with the SAE 30 and SAE 40 flash point values. However, given its pour point of 25 ^{0}C, it is less effective in cold climates. Jatropha Oil as a base oil for biolubricant production was assessed by Woma *et al.* (2019). Jatropha oil was studied for its physicochemical, rheological, thermo-oxidative, and corrosion properties. A comparison was drawn on these properties with that of a commercial lubricant SAE20W50. Though SAE 20W50 proved superior to that of Jatropha oil in all test parameters, Jatropha oil has a much higher viscosity index than SAE 20W50.

The physicochemical, oxidative, and tribological characteristics of chaulmoogra oil as a lubricant base stock were assessed by Salaji and Jayadas (2021). At 100°C, the oil's viscosity is 9.2 cSt, and its viscosity index is 166. According to the study, chaulmoogra oil has a higher wear scar diameter but a better coefficient of friction than commercial lubricants. Wear performance was enhanced by the use of zinc dialkyl dithiophosphate, an antiwear additive. Chaulmoogra oil is a great base stock for lubricants because of its non-edible nature and environmental benefits.

Bulus and Odetoye (2022) studied the use of parinari and neem seed oils as environmentally friendly biolubricants. The seed oils were processed by double transesterification method with trimethylolpropane. From the physicochemical properties of the resultant biolubricants, it shows that they have potential as sustainable alternatives to petroleum-based lubricants.

Choudhury and Saha (2022) evaluated the use of *Thevetia peruviana* oil (TPO) as a biolubricant after analysis of its physicochemical, rheological and tribological properties. The values reported were as follows for TPO: acid value 1.383± 0.015 mg KOH, pour point -4 ±0.231 ^{0}C, and flash point 344±0.04 ^{0}C. Its viscosity index was 235.59. Meanwhile, the wear scar diameter was found to be 0.462±0.001 mm. For all intents and purposes, TPO is 50% better than expensive commercial lubricants on account of its viscosity index despite very marginal pour point temperature while TPO exhibit a lowest friction coefficient and wear scar diameter than sunflower and jatropha oil. However, conventional lubricant has lower wear scar diameter due to present of strong anti-wear additives. TPO has good thermo-oxidative stability. These findings make TPO an excellent candidate for a base stock as a bio-lubricant.

Bindra *et al.* (2023) investigated the tribological performance of a novel bio-lubricant blend composed of Castor Oil as the base fluid with a 20% addition of Neem Oil as base fluids for bio-based lubricants. The results indicate a substantial improvement in tribological properties with the inclusion of Neem Oil, demonstrating approximately a 70% reduction in wear rate under specific conditions.

Using the sonification approach, Basiron *et al.* (2023) developed environmentally friendly lubricants by blending non-edible castor and jatropha oils with a mineral oil (SAE 15W40). They next assessed the lubricants' tribological performance. A four-ball tribometer was used to evaluate their wear and friction characteristics in accordance with ASTM guidelines. Superior tribological qualities were obtained by the optimal formulation as 80% mineral oil, 10% castor oil, and 10% jatropha oil.

Prasanth and Rahul (2024) presented and discussed the test of the physicochemical, rheological, and tribological properties of transesterified grape seed oil, neem oil, and waste cooking oil as potential green oil-based lubricants. The results show that transesterification improves the properties of oils, but the sudden change may cause them to perform poorly tribologically. The requirement now is to optimally numerically balance these properties in the lubricant compositions.

2.2 Blends of Non-edible green oils lubricant

Blending of other green oils, which have better properties, into the base oil to improve its properties is another viable option (Ting and Chen, 2011). Blending different vegetable oils is said to also modify the chemical composition of the oil, which in turn modifies the physicochemical properties of the oil (Wahyudi *et al.*, 2018). Such plant oil blending can result in oils with sustainable viscosity that do not require the use of any external additives (Siddique *et al.*, 2010). According to Salimon *et al.* (2010); Sharma *et al.* (2017); Owuna *et al.* (2018b); and Jeevan and Jayaram (2018) revealed that blending has been proven to improve on the flash point, pour point, viscosity and oxidative stability of lubricants based on green oils. Blend of green oils can enhance tribological performance compared to mineral oil, as shown in Table 2.

According to Jain and Suhane (2014), tribological properties of Castor and Mahua oils blend was analyzed. A castor and mahua oil on 80:20 mixture was confirmed as a candidate for maintenance, especially gear applications. The properties of mixed neem oil and mineral oil followed by their effects on engine emission were studied by Sharma *et al.* (2017). The blended oil had better anti-wear properties and lesser viscosity as compared to normal mineral oil.

Bahari *et al.* (2018) investigated the friction and wear behavior of the lubricants being based on mineral and vegetable oils at high-pressure and high-temperature environments. Results of the investigations indicated that even if the friction coefficient of soybean oil was greater than that of pure palm oil, the tribological characteristics of green oils were far superior over that of mineral oil. In a comparison of coconut oil and mustard oil, Sajeeb and Rajendrakumar (2019) found that a 50% blend of mustard oil and coconut oil exhibited superior performance in tribological and cold flow properties, thereby becoming a biodegradable alternative for mineral oil production.

Pathmasiri *et al.* (2022) studied Palm-Castor oil blend for industrial lubricant application. They studied kinematic viscosity, flash point, demulsibility, pour point, copper corrosion, and total acid number. The findings showed that with the blending of 40% castor oil to 60% palm oil, the properties were similar to SAE30. Araujo *et al.* (2022) studied the production of biolubricants using vegetable oil blends without any chemical modifications. The biolubricant formulation utilizes castor oil, jatropha curcas, macauba pulp, and macauba kernel oil. The findings showed that Macauba pulp oil performs better than the chemically modified oil and can serve as a potential base oil for biolubricant and biodiesel.

Table 2: Performance comparison of green oil blends

Lubricant blend	Friction coefficient	Wear resistance	Comparison to conventional lubricants	Reference
Castor Oil + Neem Oil	Reduced friction coefficient	Improved (70% reduction in wear rate)	Superior to conventional lubricant	Bindra *et al.* (2023)
Coconut oil + Mustard	friction reduction	Superior wear performance	Superior to conventional lubricant	Sajeeb and Rajendrakumar (2019)
Palm Oil + Mineral oil	lowest coefficient of friction	Lower wear scar diameter	Better than mineral oil	Zulfattah *et al.* (2019)
35% Mahua Oil + 65% castor oil	Lower the friction coefficient by 24%	Reduced wear scar diameter	The blend shows superior tribological characteristics over mineral oil	(Khalid and Ali, 2020)
Palm Oil - Castor Oil (60:40)	Properties similar to SAE30	Properties similar to SAE30	Properties comparable to standard lubricant	Pathmasiri *et al.* (2022)
Neem Oil + Mineral Oil	Better anti-friction	Better anti-wear properties	Blended oil had better anti-wear properties	Sharma *et al.* (2017)
Mineral Oil + Castor Oil + Jatropha Oil (80:10:10)	Superior tribological qualities	Superior tribological qualities	Optimal formulation shows better performance	Basiron *et al.* (2023)

3. Strategies for Improving Performance of Lubricant

Lubricants durability along with its superior quality and usefulness need improvement depending on the type of additives used to meet certain performance standards. Additives are meant to address various operational challenges and enhance the service life of the lubricant. Additives are also important for improving the performance of nonedible green oil-based lubricants (Garba *et al.*, 2019). Viscosity index improvers are one class of additives employed to improve lubricants by assuring a reliable performance in a wide range of working temperatures by checking their tendency to thin out at higher temperatures and to thicken at lower ones (Del Río *et al.*, 2022).

Friction modifiers are essential in industrial and automotive applications for reducing surface interaction, energy losses, and direct metal-to-metal contact; thus, increasing the efficiency of the system within which they find their application (Ameh *et al.*, 2021). Anti-wear and extreme pressure additives essentially protect surfaces from wear and damage when high loads and stresses are present, especially in applications such as gearboxes, hydraulic systems, and high-performance engines (Omrani *et al.*, 2019). Antioxidants deter the oxidation of lubricants to avoid varnish and sludge. They also enhance thermal stability and prolong lifespan with relatively good performance at high temperatures (Wang *et al.*, 2020). Antioxidants become more important in cases where lubricants are exposed to high temperature and oxidative stress. Rust and corrosion inhibitors shield the metal surfaces from moisture and other corrosive agents to lengthen the lifespan of the machinery and to prevent repair costs, particularly in adverse weather conditions (Puhan, 2021).

Most of these additives are toxic heavy metals, such as zinc, antimony, sulfur, and phosphorus, which help in upgrading the performance of lubricants for greater endurance. Some oil additives pose environmental threats (Vazquez-Duhalt, 1989; Henry, 1998; Madanhire *et al.*, 2016). However, the environmental effects of some additives need serious attention. A possibly promising research area will be an exploration of bio-based additives from renewable resources and nanotechnology.

4. Nanotechnology and Lubricants

This is the end of the main introduction and it describes- nano-technology in lubricant properties via manipulating substances at nanoscale, thermal stability enhancement, friction reduction, wear protection (Wang *et al.*, 2020). Therefore, these developments owe their uniqueness to the three physical and chemical properties of nanoparticles, different from those of bulk materials (Abdullah *et al.*, 2019; Abdel-Rehim *et al.*, 2021). Nanoparticles like boron nitride or molybdenum disulphide get into sliding contact surfaces and act as wear-resisting agents by virtue of their small sizes and larger surface areas that minimize wear and maximize wear resistance (Azman and Samion, 2019). Nanoparticles like graphene, carbon nanotubes, and fullerene increase the performance of lubricants by aiding the formation of a smooth sliding surface, thereby minimizing friction loss with energy.

Liu *et al.* (2020) add that reducing friction in any application will lower operating temperature, conserve energy, and hence create an efficient mechanical system. Nanoparticles of metal oxides such as zinc oxide and titanium oxide improve thermal stability of lubricants, allowing them to perform at higher temperatures without degrading. Enhanced thermal stability will stabilize the lubricant's performance and viscosity by preventing oxidation and deterioration, which in turn might decrease effectiveness (Liu *et al.*, 2020).

Additives for nanolubricants, including inorganic oxide nanoparticles and carbon-based nanomaterials, are characterized by unique functionalities that increase the performance of standard lubricants. Metal oxides including cerium oxide, zinc oxide, and titanium oxide are widely used in lubricants as nanoscale additives. These additives enhance several properties of lubricants, such as wear resistance, friction reduction, load-bearing, oxidative stability, thermal stability, and thermal conductivity (Binu *et al.*, 2014; Ali and Salam, 2020; Abdullah *et al.*, 2020).

Graphene, carbon nanotubes (CNTs), and fullerene are carbon-based nanomaterials with excellent lubricating properties. Graphene develops a strong, low-shear-strength layer on contact surfaces mixed with lubricants, thereby reducing wear and friction. Due to their unique cylindrical nanostructure, CNTs augment load transport and friction reduction of lubricants by ensuring smooth surface contact, while fullerenes serve as nano-ball-bearings that reduce wear and friction (Htwe *et al.*, 2024). Heat-conductive nanoparticles including metal oxides and graphene may optimize the performance and efficiency of lubricants through improved heat dissipation and prevention of overheating and breakdown in higher temperature conditions in mechanical systems (Kumar and Upadhyay, 2021).

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The search for high-performance environmentally friendly lubricating system with the introduction of nano additives in lubricants has been gaining momentum (Suresha *et al.*, 2020). The introduction of nano lubricants additives with the aid of nanotechnology creates a wider horizon in lubricating technology as it enhances the properties of wear, friction, and thermal stability.

5. Green oil-based Lubricant for Two-Stroke Engine

Two-stroke engines necessarily require specific lubricants that mix with the fuel to ensure proper internal distribution and lubrication (Zulfattah *et al.*, 2019). High power-to-weight ratio running two-stroke engines evidently require lubricants that can resist high pressures and temperatures (Dangayach *et al.*, 2021). Specialized two-stroke engine lubricants aim to cut down on exhaust emissions, fuel consumption, and engine wear (Orman, 2023).

Green oils derived from plant and animal fats have advantages such as less toxicity, biodegradability, and possible parameter modification to reach performance standards for two-stroke engines. Lubricants based on green oils help to minimize carbon emissions and environmental destruction, thus enhancing the life of the engine and its efficiency, essentials for sustainable industrial operations (Galgat *et al.*, 2021). On account of their exceptional lubricity and thermal durability, non-edible green oils contain natural esters and fatty acids suitable for high-performance applications like two-stroke engines. The use of non-edible green oil for lubricants in two-stroke engines represents a significant advancement towards a cleaner and more sustainable future for small engine applications with higher demands.

Life Cycle Assessments (LCAs) by Methes Energies International Ltd., reveal that biolubricants have a carbon footprint 29-67% lower than their mineral based counterparts, meaning biolubricants demonstrate a significant reduction in emissions and overall environmental impact compared to traditional, mineral based lubricants.

Singh (2011) developed a biodegradable two-stroke lubricant based on castor, coconut and palm oils blend with a performance additive and fatty acid derived from acetylated castor oil. The oil was observed to reduce smoke by 50–70%, being in compliance with product specifications. Taguchi's analysis for optimization of the transesterification process for the synthesis of sunflower methyl ester was done by Senthilkumar *et al.* in 2015. The study revealed that a blend of 20% sunflower methyl ester reduced unburned hydrocarbons and nitrogen oxides in comparison with commercial 2T oil.

Dehghani *et al.* (2015) evaluated biolubricants made from castor oil, palm oil, and waste cooking oil in a two-stroke gasoline engine, under an environmentally friendly alternative program. These materials were analyzed for engine performance and emissions using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method and found that palm oil-based biolubricants offered the most promising option. The study found that biolubricants performed better than two-stroke lubricants.

Iresh *et al.* (2016) developed a green oil-based lubricant from a blend of sunflower, soybean, palm, and castor oils and compared it with conventional synthetic lubricants 2T oil. The result demonstrates that the green oil enhances mechanical and thermal braking efficiency by 13% and 27% respectively, while it reduces emission of CO, CO_2 and HC approximately by 62%, 54% and 44% respectively compared to synthetic MAK 2T engine oil.

Zulfattah *et al.* (2019) studied the effect of bio-lubricants on the emissions and engine failures due to spark plug fouling in a two-stroke engine. Different lubricant samples were made by Trimethylolpropane Trioleate (TMPTO) Blends made from palm oil and mineral oil. 20% TMPTO, mineral oil blend showed better performance in emissions and engine performance while 15% TMPTO blend had the lowest coefficient of friction and wear scar diameter among. Ng *et al.* (2022) reported the use of palm fatty acid distillate (PFAD) as a base oil for biolubricants intended for two-stroke engine oils. Neopentyl glycol was chemically modified using PFAD in an 84% yield and 82% conversion. The base oil was in agreement with Japanese Automotive Standards Organization (JASO) M345:2018 requirements for two-stroke engine lubricants.

5.1 Benefits of Green oil-based lubricant for two-stroke engine

i. Green oil-based lubricants are one of the solutions available to wet the promoters of noise and hazardous exhaust emissions from two-stroke engines (Khalid and Ali, 2020), where they add at least 250 grams to a relatively high amount of air pollution. The less hazardous bio-degradable bases are relatively cleaner and emit pollutants or burn cleaner, improving the air quality and lowering the impact of these engines on the surroundings.

ii. Green oil-based lubricants increase fuel economy and are instrumental in preventing deposits and wear in two-stroke engines. This reduces friction as well as enhances efficiency in engines and prevents oxidation and thermal degradation. Its oxidative stability makes it a point of keeping the engine clean and prolongs the life of the parts (Khalid and Ali, 2020).

iii. Green oil-based lubricants prevent wear and deposits in a two-stroke engine and minimize wear because they keep the reformers from coming in contact with metallic surfaces, as they dissolve and disperse deposits in the engine, achieving agent cleanliness and peak performance (Gheidan *et al.*, 2022).

6. Challenges and Opportunities

The use of petroleum-based lubricants in two-stroke engines release harmful gases into the environment, which includes toxic gases in considerable amounts: unburned hydrocarbon, carbon monoxide, and particulate matter (Alander *et al.*, 2005; Ng *et al.*, 2022). Engine emission tests were conducted to investigate the influence of the usage of green oil-based lubricants. It was found that such lubricants were able to reduce emissions (Senthilkumar *et al.*, 2015; Zulfattah *et al.*, 2019; Ng *et al.*, 2022), while phosphate found in exhaust particles in a two-stroke engine from mineral-based oil was absent with the green oil-based lubricant (Alander *et al.*, 2005).

Non-edible green oils have a lot of promise, but many challenges still exist concerning their lubrication of engines. Non-edible oils possess lower thermo-oxidative stability compared to mineral oils, which leads to the degradation of vegetable oils at high engine operating temperatures. Furthermore, pour point and low-temperature behaviour can also be limiting. To be applicable in engine lubrication, non-edible green oils, noted for their high viscosity and poor low-temperature fluidity, need modifications, which can be carried out through chemical modifications such as esterification, transesterification, hydrogenation and epoxidation, which, although contributes to the overall costing, but helps to improve their lubricity, thermo-oxidative stability, viscosity index, and pour point thereby enhancing their suitability as lubricants (Cecilia *et al.*, 2020; Rocksonitiveh *et al.*, 2024).

Epoxidation process involves converting unsaturated fatty acids into epoxides thereby enhancing the oil's stability and suitability for applications like biolubricants, hydrogenati on reduces the unsaturation of fatty acids, improving the oil's shelf life and stability while esterification / transesterification are commonly used to produce biodiesel / biolubricant, this process transform an ester to another ester with higher thermal stability (Odi-Owei *et al.*, 2021). Some of these modifications require expensive catalysts or complex processes, which can increase production costs and limit scalability, potentially making these products less competitive in the market.

These modifications add tremendous value to crucial lubricant properties. An example of their benefits includes increasing thermo-oxidative stability, vital for efficient operation in many high-temperature engines, as well as improve low-temperature fluidity resulting in performance enhancement. The enhanced thermo-oxidative stability minimizes deposits/sludge formation, as well as wear and reduces performance degradation. The smoother and less friction-ridden engine overall naturally contributes to a longer engine life, and probably better engine performance. In addition, the changes may affect emissions, leading to harmful exhaust reduction.

Chemical modification method has been explored for the same purpose by Wagner *et al.* (2001); Bilal *et al.* (2013); Soni and Agarwal (2014); Musa *et al.* (2015); Umaru *et al.* (2016); Orhevba and Attamah (2016); Agrawal *et al.* (2017); Menkiti *et al.* (2017); Panchal *et al.* (2017); Woma *et al.* (2019); Bulus and Odetoye (2022). The chemical process is quite an energy- and water-intensive process requiring many reagents; the concomitant processes of separation and purification of the desired product generate waste and by-products leading to increased production cost (Panchal *et al.*, 2017; Araujo *et al.*, 2022). Prasanth and Rahul (2024) affirmed that transesterification improves oil properties but causes a deterioration of its tribological performance. Moreover, Cecilia *et al.* (2020) commented that chemical modification improves thermo-oxidative stability and lubricity and makes them appropriate for different applications. The drawbacks, however, are feedstock requirements, high reaction temperature, and cost. Yet, possibilities to overcome these limitations abound.

Different chemical modification processes have varying costs associated with reagents, catalysts, energy consumption, and processing steps. The costs for heating, cooling, mixing, and other utilities during the chemical modification process and the type and amount of catalysts and chemical reagents used in the modification process contribute to the overall cost. The cost of purification and separation steps post-chemical modification is also increased. Biolubricants, including those that are chemically modified, generally have a higher initial cost compared to conventional petroleum-based lubricants. Some sources suggest they can be 30-40% or even twice as expensive (Potera, 2009). Biolubricants that are chemically modified have higher initial cost compared to conventional petroleum-based lubricants while biolubricant produced by the additive route are lower than the chemical modification route (Khan *et al.*, 2022). Techno-economic analysis by Khan *et al.,* (2022) reveals that the highest unit cost for producing 1-kg estolide among chemical modification routes, while additive-based jatropha biolubricant has lower unit cost per kilogram.

Various non-edible green oils, when blended, can contribute to the optimisation of specific lubricant properties to meet engine requirements or applications. The proper selection of the various green oil combinations can lead to the fine-tuning of viscosities, viscosity indexes, pour points, oxidation stability, and tribological properties. The blends of different non-edible green oils are synergistic and improve the overall performance of the lubricants. For instance, a balanced lubricant can be created by combining oils with high viscosity indices and low-temperature properties. State-of-the-art techniques were then engaged in optimising viscosity, thermal stability and lubrication properties to ensure reliable operation of two-stroke engines based on non-edible green oil lubricants.

Even though green oil-based lubricants have great potential, there are still major issues with using them directly because they struggle with thermo-oxidative stability and performance in cold temperatures. These shortcomings, often addressed through energy-intensive and costly chemical modifications that can even negatively impact tribological properties, necessitate future research focused on exploring blends of non-edible green oils that have not been chemically modified and environmentally friendly additives.

6.1 Economic Feasibility of Adopting Green Oils

The economic viability of moving to green oil-based lubricants is a complex matter involving several factors to be considered in terms of the cost of going green in the short term, potential long-term savings, and the positive environmental implications of the switch. Although it is the initial price point that seems to be the most daunting aspect, an extensive exploration offers a much more diverse set of economic variables.

Generally, biolubricants tend to have higher initial costs and are 30-40% more expensive compared to traditional mineral oil-based lubricants (Singh, 2022; Ilmi *et al.*, 2024). This is frequently attributed to the costs associated with sourcing, processing, and sometimes chemically modifying vegetable oils to meet performance specifications. Production costs can vary significantly depending on the specific non-edible oil source, extraction methods, and refining processes involved. In addition, additives can enhance green oil performance but also increase cost, particularly nano-additives, which offer friction reduction, wear protection, and thermal stability but can be relatively expensive.

Green oils, despite the higher initial costs, may provide some potential economic benefits in the long run, including less frequent machine maintenance for cost savings, better fuel economy due to lower friction and cost savings from waste disposal, as well as liabilities associated with dangerous mineral oil waste.

7. Research gap and Future Research Directions

Subsequent investigations should focus on mixtures of non-edible green oils that have not undergone chemical changes to cater for the environmental aspect and cost of making green oil-based lubricant base oil compositions. To fully determine the long-term effects of blends of non-edible green oil-based lubricants on engine components, overall engine performance, and emissions, further investigation is required. Useful laboratory results need wider field experiments and real-life tests to validate results and enhance end-user confidence. Improving the properties of non-edible green lubricants may involve looking into additive technologies such as nano-additives and novel base green oil sources.

Some of the important areas identified for future research motion are:

- Optimization of blend ratios: Systematic study of different non-edible green oil blends to know optimal blends combinations for specific two-stroke engine applications.

- Environment-friendly nano-additives that can reduce the drawbacks of green oils and improve lubricant performance.

- Carrying out rigorous engine tests on the blended green oil-based lubricants to evaluate performance in real-world two-stroke engine operating conditions.

8. Conclusion

The evolution from edible oil-based lubricants to non-edible oil-based lubricants, which also has potential for use in two-stroke engine applications, is a tremendous leap in the direction of green lubrication options. The study shows that potential of non-edible green oil-based lubricants to improve the performance of two-stroke engines while minimizing environmental damage. The use of non-edible sources for these lubricants helps to avoid competition with food crops, ensuring the availability of edible oils for human consumption. These lubricants have demonstrated the potential to reduce emissions and enhance engine efficiency. However, challenges such as lower thermo-oxidative stability and poor low-temperature behaviour need to be addressed. Blending different non-edible green oils and the use of additives, including nanoparticles, are identified as promising strategies to overcome these limitations and optimize lubricant properties. Further research is recommended to explore optimal blend ratios, investigate environmentally friendly nano-additives, and conduct rigorous engine tests to validate the performance of these lubricants under real-world conditions.

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