

Effects of Soybean and Olive Oil Additives on the Physical and Frictional Properties of Synthetic 5W/30 Oil

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Article Info

Article history:

Received January 25, 2025

Revised March 20, 2025

Accepted May 20, 2025

Keywords:

Biolubricant
Lubricant blend
SAE 5W/30
Tribology
Pin-on-disc

ABSTRACT

The growing demand for environmentally friendly lubricants has encouraged the development of bio-based additives derived from vegetable oils. This study investigates the effects of soybean oil and olive oil, tested independently as separate additives, on the physical and tribological properties of SAE 5W/30 synthetic lubricant. Lubricant blends were prepared with vegetable oil volume fractions of 0, 20, 40, 60, and 100% for each oil type. Density and kinematic viscosity were measured at room temperature to evaluate changes in physical properties, with results showing a progressive increase in viscosity of approximately 25–40% as vegetable oil content increased. Tribological performance was evaluated using a pin-on-disc friction test under a constant rotational speed of 450 rpm, a normal load of 2 kg, and a test duration of 3 minutes. The blended lubricants exhibited a reduction in friction temperature of approximately 10–20% compared to the base synthetic oil, indicating improved boundary lubrication behavior. Optical microscopy of the wear surfaces revealed smoother morphologies and reduced wear severity for the vegetable-oil-modified lubricants, particularly at intermediate blending ratios. These improvements are attributed to the polar functional groups present in vegetable oils, which enhance lubricant film stability at the contact interface. Overall, the findings demonstrate that soybean oil and olive oil can independently improve the tribological performance of SAE 5W/30 synthetic lubricant, highlighting their potential as sustainable and environmentally friendly lubricant additives.

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1. INTRODUCTION

The global energy sector remains heavily dependent on fossil fuels, which account for more than 80% of primary energy consumption worldwide and nearly 88% in Indonesia, resulting in escalating environmental degradation, greenhouse gas emissions, and resource depletion [1]. The increasing demand for energy, rising oil prices, and mounting concerns over climate change have accelerated the transition toward renewable, sustainable, and environmentally benign alternatives across various industries, including lubrication technology. Conventional petroleum-based lubricants pose significant environmental challenges due to their non-renewable origin, toxicity, poor biodegradability, and improper disposal, with nearly half of the 40 million tons of lubricants produced annually released into the environment, causing severe soil and water pollution [2]. In response, bio lubricants derived from renewable feedstocks such as vegetable oils, waste cooking oil (WCO), and other non-edible biomass have emerged as promising alternatives due to their biodegradability, low

toxicity, high lubricity, and reduced carbon footprint [3]. Moreover, bio lubricants offer superior tribological performance, including enhanced viscosity–temperature behavior, excellent lubricity, and improved wear protection, making them suitable for modern automotive applications, including internal combustion engines and electric vehicles [4]. The utilization of low-cost and abundant resources such as WCO not only reduces production costs but also addresses environmental and public health concerns associated with improper waste oil disposal. When optimized through blending strategies, advanced synthesis techniques, and performance-enhancing additives, bio lubricants can overcome inherent limitations such as oxidation instability and low viscosity, thereby offering a sustainable, high-performance, and economically viable solution that aligns with global sustainability goals and the growing demand for eco-friendly lubrication systems [5].

Recent studies have demonstrated substantial progress in the development and application of bio lubricants derived from renewable and waste-based resources, with a strong focus on enhancing tribological performance and environmental sustainability [6]. Plant oil-based bio lubricants, such as those derived from non-edible jatropha oil, have shown comparable wear resistance and friction behavior to commercial lubricants when blended at optimal concentrations, supported by surface morphology analyses confirming reduced material damage under mixed lubrication conditions [6]. Blending strategies involving biodiesel and commercial lubricants have further revealed that ester-rich bio-components significantly improve lubricity, reduce wear scar diameter, and lower coefficients of friction, particularly when combined with performance-enhancing additives such as nanoparticles [7]. Polyol ester bio lubricants synthesized from *Calophyllum inophyllum* oil have been reported to synergistically interact with conventional lubricant additives, resulting in enhanced load-bearing capacity, improved extreme pressure performance, and superior anti-wear characteristics [8]. Moreover, waste cooking oil-based bio lubricants, especially when blended with *Calophyllum inophyllum* oil, have exhibited notable reductions in friction and wear, highlighting their potential as effective lubricant additives while addressing waste management challenges [9]. Recent advancements also emphasize the incorporation of nanoparticles into palm oil-based bio lubricants, which significantly enhances thermal stability, friction reduction, and wear resistance, making them particularly suitable for high-demand applications such as electric vehicle drivetrains [10]. Additionally, innovative synthesis approaches, including infrared-assisted polyesterification and process optimization via response surface methodology, have enabled the production of high-quality bio lubricants with physicochemical and tribological properties surpassing those of conventional mineral lubricants [11]. Collectively, these studies underscore the growing viability of bio lubricants as sustainable, high-performance alternatives to petroleum-based lubricants for both internal combustion engines and emerging electric vehicle technologies.

A growing body of literature highlights the strong potential of soybean oil–based bio lubricants due to their excellent lubricity, high ester content, and ability to significantly reduce friction and wear compared to conventional mineral oils. Chemically modified soybean oil derivatives, such as esterified and oxirane ring–opened structures, have been shown to outperform hydrotreated mineral oils under varying loads, sliding speeds, and temperatures, producing lower coefficients of friction and smoother wear surfaces [12]. These favorable tribological characteristics are primarily attributed to the polar functional groups and long-chain fatty acid esters present in soybean oil, which promote the formation of a stable lubricating film on metal surfaces. However, despite these advantages, soybean oil–based lubricants still face limitations related to oxidation stability, thermal resistance, and long-term durability, particularly under high-temperature and high-load operating conditions typical of modern engines. In contrast, olive oil is rich in oleic acid, which offers superior oxidative stability and thermal endurance, making it a promising complementary bio-component [13]. To date, limited studies have explored the synergistic blending of soybean oil and olive oil as bio-additives in synthetic lubricants, particularly for improving both tribological performance and physicochemical stability simultaneously. Therefore, investigating the combined effects of soybean–olive oil blends in synthetic lubricants represents a critical research gap, with the potential to develop a high-performance, sustainable lubricant that balances excellent friction reduction with enhanced thermal and oxidative stability.

2. METHOD

In this study, a commercial SAE 5W/30 synthetic lubricant was blended separately with soybean oil and olive oil at volume fractions of 0, 20, 40, 60, and 100% to evaluate the influence of bio-oil concentration on physicochemical and tribological properties. Soybean oil and olive oil were tested independently as separate additives to clearly distinguish their individual effects across the concentration range investigated. The prepared lubricant blends were homogenized under control stirring conditions to ensure uniformity prior to testing. The kinematic viscosity and density of each blend were measured at room temperature following standard testing procedures. Tribological performance was evaluated using a pin-on-disc tribometer under controlled operating conditions, where the motor rotational speed was maintained at a constant 450 rpm, the friction test duration was fixed at 3 minutes, and a normal load of 2 kg was applied. Friction tests were

conducted at controlled temperatures, and the coefficient of friction was continuously recorded throughout the tests. Following tribological experiments, the worn surfaces of the pin and disc specimens were analyzed using optical microscopy to investigate surface morphology.

To facilitate clarity and consistency in the discussion, each lubricant formulation was identified using a specific sample code that reflects its composition. The notation OS100Z0 denotes a blend consisting of 100% synthetic oil (OS) and 0% olive oil (Z), which served as the reference sample without bio-oil addition. In this coding system, the letters OS, Z, and S represent synthetic oil, olive oil, and soybean oil, respectively, while the numerical values indicate the corresponding volume percentage of each component in the blend. Accordingly, formulations such as OS80Z20, OS60Z40, and OS40Z60 represent synthetic oil blended with olive oil at 20%, 40%, and 60% volume fractions, respectively, whereas OS0Z100 corresponds to pure olive oil. Similarly, blends containing soybean oil were designated using the same convention, for example OS80S20, OS60S40, OS40S60, and OS0S100, indicating increasing soybean oil content at the expense of synthetic oil. This systematic coding approach enables straightforward identification of lubricant compositions and supports clear comparison of physicochemical and tribological performance across all tested formulations.

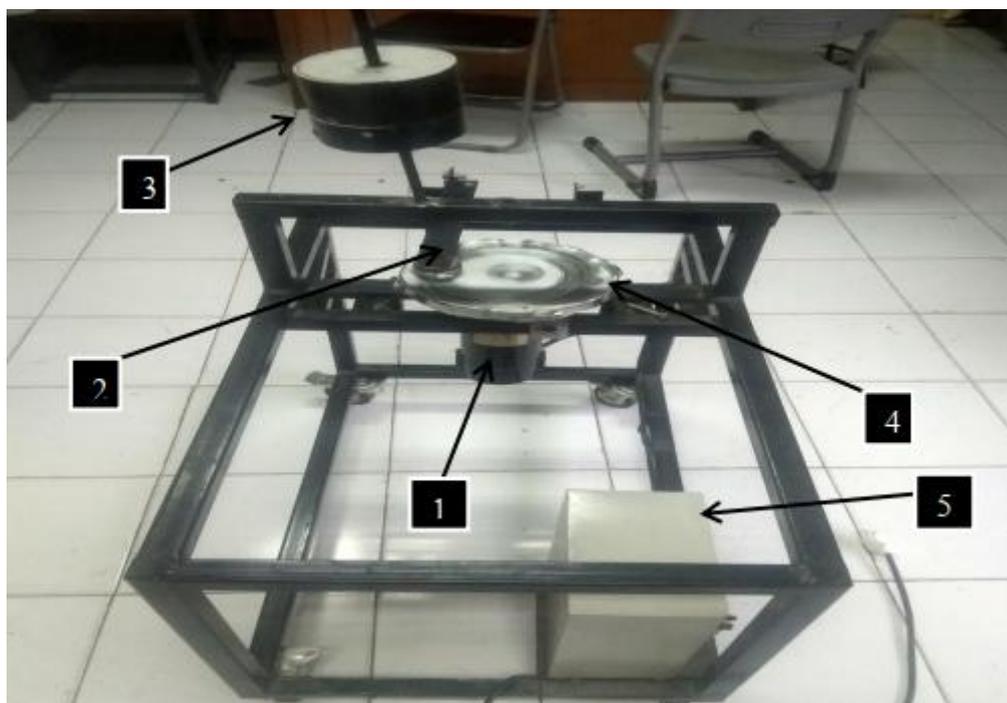


Figure 1. pin on disc friction test apparatus

Figure 1 illustrates the pin-on-disc friction test apparatus used to evaluate the tribological behavior of the lubricant samples. The AC motor (1) serves as the driving unit, providing rotational motion to the system at a constant speed throughout the test. The specimen holder (2) accommodates the test specimen (pin), which remains in direct contact with the rotating disc during operation. A normal load of 2 kg (3) is applied vertically to the specimen to ensure a consistent contact pressure between the mating surfaces. The disc plate (4) acts as the counter face material and rotates under the applied load, enabling the generation of friction and wear under lubricated conditions. The entire testing process is regulated through the control panel (5), which allows adjustment and monitoring of operational parameters such as motor speed and test duration. This configuration enables controlled and repeatable friction testing for assessing the tribological performance of lubricant blends.

3. RESULTS AND DISCUSSION

3.1 Properties of lubricant

Based on Table 1, the basic physicochemical properties of the lubricant blends show a clear dependence on oil composition, particularly on the proportion of vegetable oil mixed with the synthetic base oil. The density values increase progressively with higher contents of soybean oil (S) and olive oil (Z), reflecting the inherently higher density of vegetable oils compared to synthetic oil. For instance, pure synthetic oil (OS100) exhibits the lowest density (0.861 g/cm^3), while pure soybean oil (S100) and pure olive oil (Z100) show higher densities

of 0.927 g/cm³ and 0.938 g/cm³, respectively. This trend is consistently observed in blended samples, where increasing vegetable oil concentration from 20% to 60% results in gradual density increments, indicating good miscibility and homogeneous blending behavior. When vegetable oils are blended with mineral-based lubricants, the gradual increase in density observed as the vegetable oil concentration rises from 20% to 60% reflects how well the two fluids mix at the molecular level. Good miscibility means that the triglyceride molecules from the vegetable oil distribute evenly within the hydrocarbon matrix of the base lubricant, preventing phase separation or layering. This homogeneous blending behavior is crucial in lubrication because it ensures consistent viscosity, stable film formation, and uniform load-bearing capacity across the contact surfaces. In practice, such density increments confirm that the blend behaves as a single fluid rather than two immiscible phases, which enhances reliability in tribological applications by maintaining smooth flow, predictable rheology, and stable lubrication performance under varying operating conditions.

Table 1. basic properties of lubricant blends

Lubricant	Density	Viscosity
OS100	0.861	50.707
S100	0.927	31.862
Z100	0.938	40.1
OS80S20	0.868	41.459
OS60S40	0.889	35.633
OS40S60	0.902	34.193
OS80Z20	0.871	42.226
OS60Z40	0.896	41.930
OS40Z60	0.909	38.782

In terms of viscosity, the synthetic oil demonstrates the highest value (50.707 cSt), while the vegetable oils exhibit lower viscosities, with soybean oil showing the lowest (31.862 cSt). The incorporation of vegetable oils into the synthetic base oil leads to a noticeable reduction in viscosity, which becomes more pronounced as the vegetable oil fraction increases. For example, OS80S20 and OS60S40 display viscosities of 41.459 cSt and 35.633 cSt, respectively, while further reduction is observed at higher blend ratios. A similar trend is evident for olive oil blends, although olive oil-based mixtures generally maintain slightly higher viscosity values than soybean oil blends at equivalent proportions. This behavior can be attributed to differences in fatty acid composition and molecular structure between soybean and olive oils. The differences in fatty acid composition and molecular structure between soybean and olive oils directly influence their lubrication behavior, where soybean oil, being rich in polyunsaturated fatty acids, provides higher reactivity and better film-forming ability but suffers from lower oxidative stability, while olive oil, dominated by monounsaturated oleic acid, offers greater thermal and oxidative stability, reduced volatility, and longer-lasting lubricating films; thus, soybean oil tends to enhance boundary lubrication and wear reduction through chemical modification, whereas olive oil contributes to consistent viscosity, resistance to degradation under high temperature, and improved long-term tribological performance. Overall, the results indicate that blending synthetic oil with controlled amounts of vegetable oils can effectively tailor density and viscosity characteristics, which are critical parameters influencing lubrication performance and tribological behavior.

3.2 Friction test.

Table 2. friction temperature

Lubricant blend	Temperature
OS100	40.4
S100	48.9
Z100	41.6
OS80S20	40
OS60S40	42.7
OS40S60	47.2
OS80Z20	46
OS60Z40	39.6
OS40Z60	36

The friction temperature results of the lubricant blends indicate a clear influence of lubricant composition on heat generation during the pin-on-disc test. Pure synthetic oil (OS100) exhibited a moderate friction temperature of 40.4 °C, reflecting its stable thermal behavior under the applied operating conditions. In contrast, pure soybean oil (S100) produced the highest friction temperature (48.9 °C), suggesting increased frictional heat generation, which can be attributed to its lower oxidative stability and higher polarity, leading to stronger surface interactions during sliding. Pure olive oil (Z100) showed a friction temperature (41.6 °C) comparable to that of synthetic oil, indicating better thermal performance than soybean oil when used alone.

For the blended lubricants, soybean oil–synthetic oil mixtures demonstrated a gradual increase in friction temperature with higher soybean oil content. The OS80S20 blend recorded the lowest temperature (40.0 °C), like the synthetic base oil, while OS60S40 and OS40S60 showed increased temperatures of 42.7 °C and 47.2 °C, respectively. This trend suggests that moderate soybean oil addition can maintain acceptable thermal behavior, whereas higher concentrations may intensify frictional heating. Conversely, olive oil–based blends exhibited a different pattern, where OS80Z20 presented a relatively high friction temperature (46.0 °C), followed by a reduction at higher olive oil contents, with OS60Z40 and OS40Z60 reaching 39.6 °C and 36.0 °C, respectively. This behavior implies that higher olive oil fractions may contribute to improved heat dissipation and reduced frictional interaction due to the formation of a more stable lubricating film.

Overall, the results demonstrate that lubricant composition significantly affects friction-induced temperature. Soybean oil tends to increase friction temperature at higher blend ratios, while olive oil shows potential for lowering friction temperature when blended at higher concentrations with synthetic oil. These findings highlight the importance of optimizing vegetable oil content to achieve balanced thermal and tribological performance in synthetic–biolubricant blends.

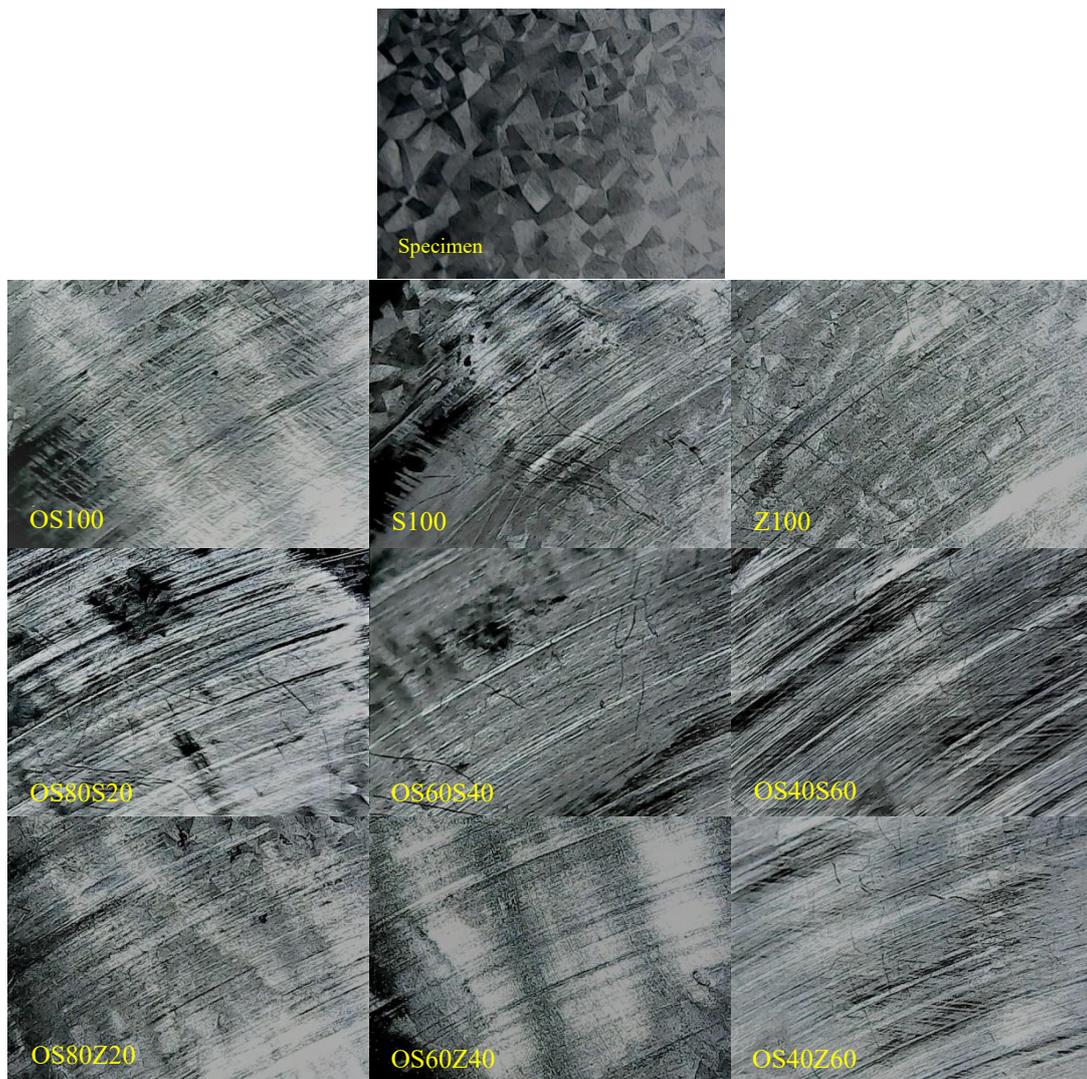


Figure 2. Surface morphology before and after pin-on-disc tests for different lubricant blends

The surface morphologies of the specimens after the pin-on-disc friction test reveal clear differences in wear behavior depending on the lubricant composition, as shown in Figure X. The specimen surface before testing exhibits a relatively smooth and uniform texture with no visible grooves or damage, serving as a reference condition. After testing with pure synthetic oil (OS100), shallow and continuous wear tracks are observed, indicating mild abrasive wear and the formation of a stable lubricating film during sliding. In contrast, the specimen lubricated with pure soybean oil (S100) shows more pronounced grooves and localized dark patches, suggesting higher frictional interaction and increased material removal, which is consistent with its higher friction temperature and lower viscosity stability. The surface lubricated with pure olive oil (Z100) displays comparatively smoother wear tracks than S100, with fewer severe grooves, indicating improved boundary lubrication performance.

For the blended lubricants, the wear patterns demonstrate a strong dependence on vegetable oil concentration. The OS80S20 sample shows relatively smooth wear tracks with limited groove depth, comparable to OS100, suggesting that a low addition of soybean oil enhances surface lubrication without significantly increasing wear. However, as the soybean oil content increases (OS60S40 and OS40S60), the wear tracks become deeper and more irregular, accompanied by increased surface deformation, indicating a transition toward more severe abrasive wear. This behavior implies that higher soybean oil fractions may weaken the lubricating film under the applied load and sliding conditions.

Conversely, olive oil-based blends exhibit improved surface conditions at higher olive oil contents. While OS80Z20 presents noticeable wear marks and dark regions, the specimens lubricated with OS60Z40 and OS40Z60 show smoother surfaces with finer and more uniform grooves. The reduced severity of wear in these blends suggests that olive oil contributes to the formation of a more stable tribofilm at the sliding interface, likely due to its fatty acid composition, which promotes strong adsorption onto the metal surface. Overall, the pin-on-disc test results indicate that blending synthetic oil with an optimal proportion of vegetable oils, particularly olive oil at higher concentrations, can significantly improve wear resistance and frictional performance, whereas excessive soybean oil content may lead to increased surface damage.

4. CONCLUSION

This study evaluated the effects of blending soybean oil and olive oil with SAE 5W/30 synthetic lubricant on physical properties and tribological performance. The results showed that increasing the proportion of vegetable oils generally led to higher density and altered viscosity compared to the base synthetic lubricant, indicating changes in molecular structure and intermolecular interactions within the blends. Blends containing moderate proportions of soybean or olive oil exhibited more balanced viscosity values, which are favorable for maintaining stable lubrication films during frictional contact. Friction tests revealed that lubricant composition significantly influenced friction-induced temperature. Blends with higher vegetable oil content tended to reduce friction temperature, suggesting improved lubricity and enhanced heat dissipation, likely due to the presence of polar ester groups in the vegetable oils. Conversely, blends dominated by synthetic oil or pure soybean oil exhibited relatively higher temperatures, indicating increased frictional resistance under the tested conditions. Surface morphology analysis supported the friction temperature results. Specimens lubricated with blended oils showed smoother worn surfaces with shallower grooves and fewer severe wear marks compared to those lubricated with single-component oils. Blends containing both soybean and olive oil demonstrated reduced abrasive wear and more uniform surface textures, indicating the formation of a stable lubricating film during sliding contact. Overall, the combined results of physical property measurements, friction temperature analysis, and wear morphology observations confirm that blending soybean and olive oils with synthetic lubricant can enhance tribological performance. These findings highlight the potential of soybean-olive oil blends as environmentally friendly additives for synthetic lubricants in mechanical applications.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to all parties who contributed to the completion of this research. Special appreciation is extended to the staff of the Research Laboratory and the Metallurgy Laboratory for their valuable assistance in sample preparation, material characterization, and tribological testing.

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