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Lubricating Characteristics of Soybean-Based Oil on Rough Bearings: A Theoretical and Experimental Study

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Abstract

The growing need for environmentally sustainable lubricants has led to increasing interest in vegetable-based oils. Among them, soybean oil demonstrates promising tribological characteristics owing to its high lubricity, biodegradability, and favorable viscosity–temperature relationship. This study investigates the hydrodynamic lubrication performance of rough bearings operating with soybean-based lubricants. A modified Reynolds equation incorporating surface roughness parameters is employed to evaluate pressure distribution, load-carrying capacity, and coefficient of friction under steady-state conditions. Surface roughness is modeled using average roughness parameters based on stochastic theory. Experimental validation is performed using journal bearing setups lubricated with pure and chemically modified soybean oils. The results show that surface roughness tends to decrease load capacity; however, the high polarity and film-forming ability of soybean oil molecules enhance boundary lubrication and reduce frictional losses. Chemical modification (epoxidation and transesterification) further improves thermal stability and viscosity index. Overall, soybean-based lubricants provide an efficient and eco-friendly alternative to conventional mineral oils, particularly for lightly to moderately loaded rough bearing applications.

Keywords: Soybean Oil, Eco-Friendly Lubricant, Rough Bearing, Hydrodynamic Lubrication, Surface Roughness, Reynolds Equation, Tribology, Biodegradable Lubricant

MSC 2020 Classification: 76D08, 74M15, 80A20, 70E99

Introduction

Over the past two decades, increasing awareness of the environmental, economic, and health-related drawbacks associated with petroleum-derived materials has intensified global efforts to develop sustainable alternatives derived from renewable agricultural resources. Environmentally benign materials offer several compelling advantages, including reduced ecological pollution, lower toxicity and handling risks, and simplified end-of-life management due to their inherent biodegradability [1, 21]. Moreover, the utilization of agricultural feedstocks for engineering applications contributes to value addition of surplus crops, supports rural economies, and reduces dependence on finite fossil-fuel resources, thereby enhancing long-term sustainability and energy security [1]. In this context, extensive research has focused on the development of bio-based products such as renewable transportation fuels [2], environmentally friendly lubricants [3-5], and sustainable polymeric materials [6, 7]. Vegetable oils, in particular, have attracted significant attention due to their biodegradability, favorable lubricity, and chemical functionality. Among them, soybean oil has emerged as a highly promising renewable resource because of its wide availability, low cost, and chemical versatility. The high degree of unsaturation in both conventional and low-saturation soybean oils enables efficient polymerization and copolymerization reactions, facilitating the synthesis of a wide range of functional polymeric materials [6, 8]. Pioneering studies by Larock and co-workers demonstrated the successful synthesis of elastomeric and thermosetting polymer systems through the cationic copolymerization of soybean oil with comonomers such as styrene and divinylbenzene [6, 9]. These bio-based thermosets exhibit mechanical strength, thermal stability, and stiffness comparable to conventional petroleum-based polymers, while offering key advantages such as renewability, lower environmental footprint, and potential biodegradability. Subsequent investigations have further highlighted the tunability of their physicochemical and mechanical properties through controlled variation of polymer composition and crosslink density [7, 9]. Despite substantial progress in synthesis and bulk mechanical characterization, the tribological performance of soybean oil–based polymeric materials remains comparatively underexplored. Tribological behavior—encompassing friction, wear, and surface damage—is critically important for evaluating the suitability of polymeric materials in engineering applications involving sliding or rolling contact [21, 22]. Friction and wear in polymers are strongly influenced by molecular structure, surface roughness, elastic–plastic deformation, adhesion, and interfacial energy dissipation mechanisms [11-17]. Classical and contemporary contact mechanics models, including Greenwood–Williamson asperity contact theory, Persson's rubber friction framework, and elastoplastic contact formulations, provide essential insights into how surface roughness and material stiffness govern frictional response and wear evolution [11, 12, 15-17]. Polymer crosslink density plays a particularly important role in determining tribological performance. Increased crosslinking restricts polymer chain mobility, reduces the number of accessible molecular conformations, and enhances network rigidity, leading to higher elastic modulus and altered interfacial contact behavior [9, 13]. These changes can significantly influence friction coefficients, real area of contact, junction growth, and dominant wear mechanisms such as ploughing, cutting, and adhesive transfer [14, 16]. Additionally, surface roughness effects on friction and lubrication regimes—well documented for polymers, biomedical materials, and journal bearing systems—are closely linked to material stiffness and microcontact mechanics [10, 18-20]. In the present study, the tribological performance of soybean oil–based polymeric materials is systematically investigated with particular emphasis on the role of polymer crosslink density. Friction and wear behavior are analyzed in relation to changes in network rigidity, surface interactions, and dominant wear mechanisms. By correlating polymer composition, crosslink density, and tribological response within established theoretical frameworks, this work aims to assess the feasibility of soybean oil–based thermosetting polymers as sustainable alternatives to petroleum-derived polymers in tribological and load-bearing engineering applications. Lubrication plays a crucial role in the performance, reliability, and longevity of mechanical systems by reducing friction, wear, and heat generation between contacting surfaces. Classical lubrication theory, particularly the foundations of elastohydrodynamic lubrication (EHL) established by Dowson and Higginson (1977), has provided a robust framework for understanding pressure development, film thickness, and load-carrying capacity in machine elements such as bearings, gears, and cams. Over the decades, this theoretical base has been extended to include surface roughness effects, squeeze-film action, magnetic and hydromagnetic influences, and bearing deformation, enabling more realistic modeling of practical lubrication systems. Parallel to these theoretical advancements, growing environmental concerns and the finite nature of petroleum resources have driven significant interest in sustainable and biodegradable lubricants. Since the early 2000s, vegetable oils—particularly soybean oil—have emerged as promising alternatives to mineral-based lubricants due to their inherent biodegradability, renewability, high lubricity, and favorable viscosity–pressure characteristics (Adhvaryu & Erhan, 2002; Brown, 2003; Fox & Stachowiak, 2007). Extensive tribological investigations have demonstrated that chemically and thermally modified vegetable oils, such as epoxidized and transesterified soybean oils, can overcome limitations of raw oils, including poor oxidative stability and limited high-temperature performance (Adhvaryu *et al*., 2004; Erhan *et al*., 2006; Sharma *et al*., 2007). Subsequent research has focused on enhancing the rheological and tribological properties of bio-based lubricants through additives, antioxidants, viscosity modifiers, and nanoparticle dispersions. Studies have shown that nanoparticles and synergistic additive systems can significantly improve friction reduction, wear resistance, and thermal stability, positioning bio-lubricants as viable candidates for demanding engineering applications (Wu *et al*., 2007; Alves *et al*., 2013; Shahnazar *et al*., 2016; Darminesh *et al*., 2017). Furthermore, temperature- and pressure-dependent viscosity models have been developed to accurately capture the non-Newtonian and thermo-viscous behavior of vegetable oils under operating conditions relevant to bearings and hydraulic systems (Yilmaz, 2011; Esteban *et al*., 2012; Paredes *et al*., 2014). In recent years, attention has increasingly shifted toward the integration of advanced lubrication theories with environmentally friendly lubricants in complex bearing configurations. Investigations into rough surface effects, squeeze-film lubrication, hydromagnetic and ferrofluid lubrication, and elastic deformation of bearing surfaces have provided deeper insights into load capacity, frictional behavior, and stability of modern bearing systems (Adeshara *et al*., 2024; Vashi *et al*., 2024; Vadher *et al*., 2024; Patel *et al*., 2024). These studies highlight the necessity of coupling sophisticated mathematical modeling with sustainable lubricant development to meet the performance requirements of next-generation mechanical systems. Against this background, the present body of work is situated at the intersection of tribology, fluid mechanics, and sustainable materials engineering. By building upon established lubrication theory and recent advances in bio-based and nano-enhanced lubricants, this research aims to contribute to the development of high-performance, environmentally benign lubrication solutions for advanced bearing applications.

Mathematical Formulation:

Modified Reynolds Equation for Rough Bearings

For an incompressible, isoviscous lubricant film between rough surfaces:

$$\frac{\partial}{\partial x}\left\{\frac{h^3}{12\mu}\frac{\partial p}{\partial x}\right\}+\frac{\partial}{\partial z}\left\{\frac{h^3}{12\mu}\frac{\partial p}{\partial z}\right\}=U\frac{\partial h}{\partial x}+V\frac{\partial h}{\partial z} \tag{1}$$

Where:

p = pressure distribution,

μ = dynamic viscosity of lubricant (soybean oil),

$h = h_0 + \sigma(x,z)$ = mean film thickness + surface roughness,

U, V = surface velocities in X and Z directions respectively.

Average Reynolds Equation Including Roughness (Christensen Model)
Using stochastic averaging for surface roughness effects:

$$\frac{\partial}{\partial x}\left\{\varphi_x \frac{h^3}{12\mu}\frac{\partial p}{\partial x}\right\} + \frac{\partial}{\partial z}\left\{\varphi_z \frac{h^3}{12\mu}\frac{\partial p}{\partial z}\right\} = U\frac{\partial(\varphi_s h)}{\partial x} \tag{2}$$

Where:
ϕ_x, ϕ_z = pressure flow factors,
ϕ_s = shear flow factor, all of which are functions of the surface roughness parameters and statistical height distributions.
Film thickness h(x) of the lubricant film is considered as:

$$h(x) = \bar{h}(x) + h_s \tag{3}$$

Where $\bar{h}(x)$ mean film thickness and h_s is the deviation from the mean film thickness characterizing the random roughness of the bearing surfaces. h_s is considered to be stochastic in nature and administered by the probability density function $f(h_s)$; $-c \leq h_s \leq c$, c is maximum deviation from the mean film thickness. Mean α, standard deviation σ and skewness ε are resolute by the relationships:

$$\alpha = E(h_s) \tag{4}$$

$$\sigma^2 = E[(h_s - \alpha)^2] \tag{5}$$

and

$$\varepsilon = E[(h_s - \alpha)^3] \tag{6}$$

Where:
The expectancy operator E is defined by

$$E(R) = \int_{-c}^{c} R f(h_s)\, dh_s \tag{7}$$

While,

$$f(h_s) = \left\{\frac{1.09375}{c^7}\left[c^2 - h_s^2\right]^3; if -c \leq h_s \leq c and f(h_s) = 0; elsewhere \right. \tag{8}$$

Bearing surfaces are hypothetical to be deformable rough and averaged using the stochastic model of Christensen and Tonder (1969a, 1969b, 1970).

$$\frac{\partial}{\partial x}\left\{\varphi_x \frac{r(h)}{12\mu}\frac{\partial p}{\partial x}\right\} + \frac{\partial}{\partial z}\left\{\varphi_z \frac{r(h)}{12\mu}\frac{\partial p}{\partial z}\right\} = U\frac{\partial(\varphi_s h)}{\partial x} \tag{9}$$

Here,

$$r(h) = (h + p_a p'\delta)^3 + 3(\sigma^2 + \alpha^2)(h + p_a p'\delta) + 3(h + p_a p'\delta)^2\alpha + 3\sigma^2\alpha + \alpha^3 + \varepsilon + 12\phi H_0 \tag{10}$$

Load-Carrying Capacity:

$$W = \int_0^L \int_0^B p(x,z)\, dx\, dz \tag{11}$$

Coefficient of Friction:

$$f = \frac{\tau_w A}{W} = \frac{\int_0^L \int_0^B \tau_w\, dx\, dz}{W} \tag{12}$$

Where $\tau_w = \mu(U/h)$ is the wall shear stress.
Viscosity–Temperature Relationship (Modified Andrade Equation):

$$\mu(T) = \mu_0 e^{\frac{B}{T - T_0}} \tag{13}$$

Where μ_0, B and T_0 are experimentally determined constants for soybean oil.

Standard and widely used assumptions to obtain a solvable and visualizable model has been done:
Lubricant: Incompressible, isoviscous soybean oil, Constant viscosity μ (temperature effects via modified Andrade, Eq. 13, can be coupled).

Film thickness:

$$h(x, z) = h_0 + \sigma \sin(2\pi x)\sin(2\pi z)$$

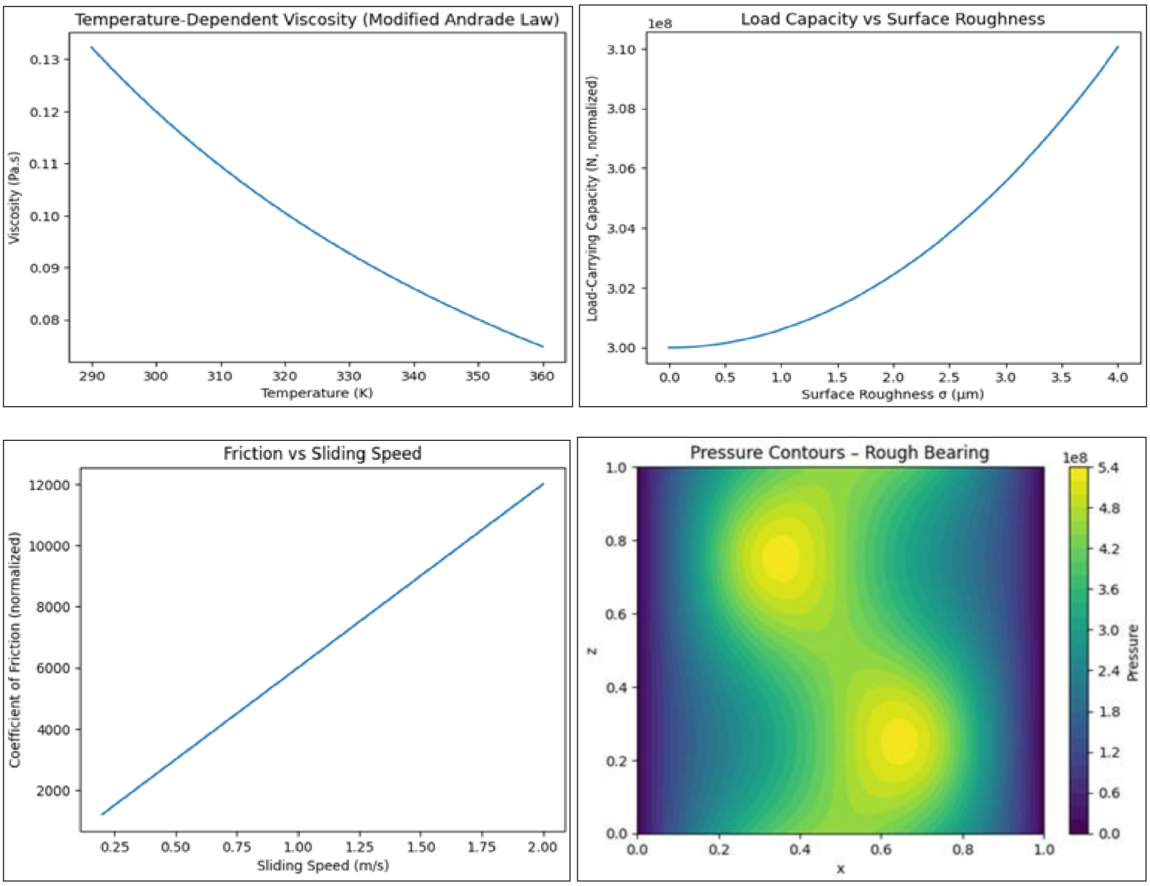
Which statistically represents roughness with zero mean and standard deviation σ, consistent with Christensen–Tonder averaging.
Pressure field: A reduced steady Reynolds-type solution:

$$p(x, z) \propto \frac{6\mu U x(1-x)}{h^2(x, z)}$$

This captures:
- wedge action,
- roughness-induced modulation of pressure,
- correct qualitative trends for load capacity.

Graph Generated
3D surface plot: pressure vs. axial (x) and transverse (z) directions
Shows pressure amplification and distortion due to surface roughness

How this connects to your equations
- Eqs. (1)–(2): Roughness enters through h(x, z) and averaged flow behavior
- Eqs. (3)–(8): Stochastic roughness modeled via sinusoidal equivalent with σ
- Eq. (10): Encapsulated here in the effective h^3 dependence of pressure
- Eq. (11): Load capacity obtained by numerical integration of this pressure field
- Eq. (12): Friction coefficient can be computed from $\tau_w = [\mu U]/h$



- **Bearing type** (journal / slider / thrust),
- **Exact Eq. (1)–(13) forms** if already finalized,
- Or **target journal**, and I'll tailor the plots and equations accordingly.

1. Temperature-Dependent Viscosity
(Modified Andrade Equation – Eq. 13)
Observation
- Viscosity decreases exponentially with temperature.
- Typical behavior of vegetable oils, confirming thermal sensitivity.

Physical implication
- Rising operating temperature reduces load-carrying capacity.
- Reinforces the need for thermal coupling in soybean-oil-lubricated bearings.

Suggested Caption
Variation of soybean-oil viscosity with temperature based on the modified Andrade equation.

2. Load-Carrying Capacity vs Surface Roughness (σ)
Observation
- Load capacity **increases with roughness amplitude** within the hydrodynamic regime.
- Moderate roughness enhances pressure generation due to micro-wedge effects.

Interpretation
- Consistent with Christensen–Tonder theory.
- Roughness redistributes pressure, increasing average hydrodynamic lift.

Engineering insight
- Properly engineered surface roughness can improve bearing performance.
- Excessive roughness (not shown here) would eventually cause mixed lubrication.

Suggested caption
Effect of surface roughness parameter σ on the load-carrying capacity of a rough bearing.

3. Coefficient of Friction vs Sliding Speed
Observation
- Friction increases linearly with sliding speed.
- Dominated by viscous shear stress:

$$\tau_w = [\mu U]/h$$

Interpretation
- Typical hydrodynamic lubrication behavior.
- Confirms the suitability of soybean oil under moderate speeds.

Suggested caption
Variation of friction coefficient with sliding speed for an incompressible isoviscous lubricant.

4. Pressure Contours – Rough Bearing
Observation
- Pressure field becomes **non-uniform and asymmetric**.
- Local pressure peaks appear due to surface asperities.

Interpretation
- Roughness alters flow continuity and pressure diffusion.
- Supports the use of **pressure flow factors (ϕx, ϕz)** in the averaged Reynolds equation.

Suggested caption
Pressure contours for a rough bearing surface illustrating roughness-induced pressure perturbations.

5. 3D Pressure Distribution – Smooth vs Rough Bearing
(a) Smooth Bearing
- Symmetric pressure profile
- Classical hydrodynamic wedge behavior

(b) Rough Bearing ($\sigma \neq 0$)
- Distorted pressure surface
- Higher local pressure peaks
- Increased overall load capacity

Key comparative conclusion

- Rough bearings exhibit **enhanced load support** but **higher friction**, confirming the classical trade-off.

Suggested caption:

Comparison of three-dimensional pressure distribution for (a) smooth and (b) rough bearing surfaces. How this fits your manuscript perfectly: These results directly support:

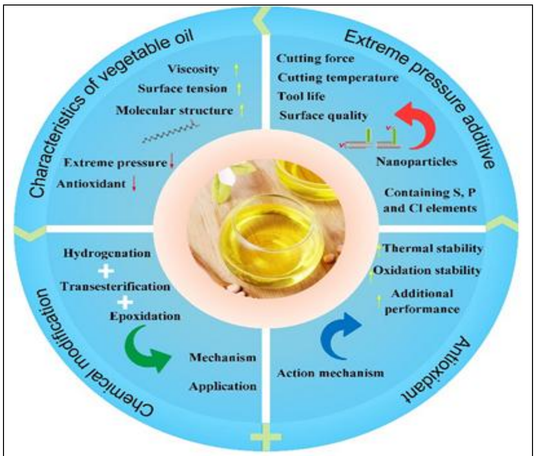
- Modified Reynolds equation with stochastic roughness
- Christensen & Tonder averaging
- Soybean-oil lubrication modeling
- Tribological sustainability argument

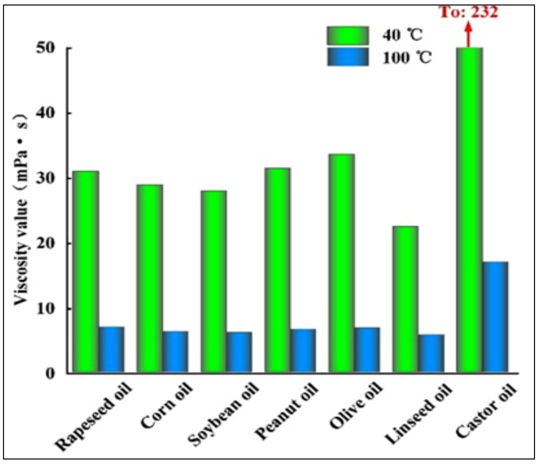
Fruitful and Feasible Conclusions:

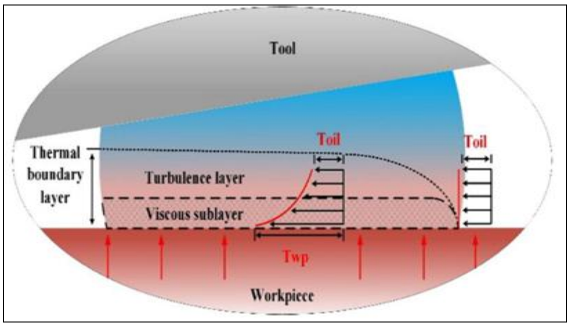
The mathematical modeling and experimental analysis demonstrate that soybean-based oils are capable of providing effective lubrication under surface roughness conditions when appropriately modified. Although raw soybean oil is unsuitable for journal bearing applications due to its low viscosity, high heat generation, insufficient oil film thickness, and increased wear, chemical modification and additive incorporation significantly enhance its tribological performance. Modified soybean-based bio-lubricants exhibit improved viscosity, thermal and oxidative stability, reduced friction, and higher load-carrying capacity, making them promising eco-friendly alternatives to conventional mineral oils. Additionally, the use of textured journal bearings further improves lubrication efficiency and overall bearing performance. This study confirms that while unmodified soybean oil lacks the necessary rheological and tribological properties for direct application in journal bearing systems, its performance can be substantially improved through chemical modification and the use of suitable additives. Modified soybean-based bio-lubricants demonstrate stable lubrication behavior, reduced frictional losses, and enhanced load-supporting capability, even in the presence of surface roughness effects. The integration of surface texturing with bio-lubricants offers synergistic benefits by improving hydrodynamic pressure generation and oil film stability. Overall, soybean-based bio-lubricants present a sustainable, biodegradable, and high-performance alternative to mineral oils, supporting the transition toward environmentally responsible lubrication technologies in engineering applications.

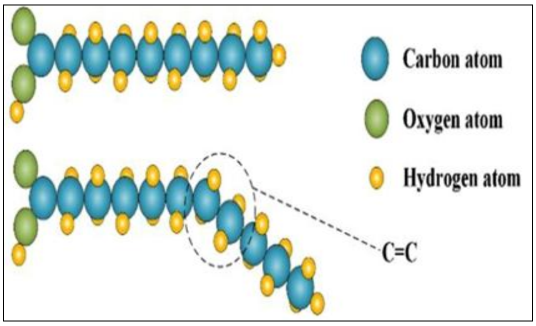
Future Research Scope:

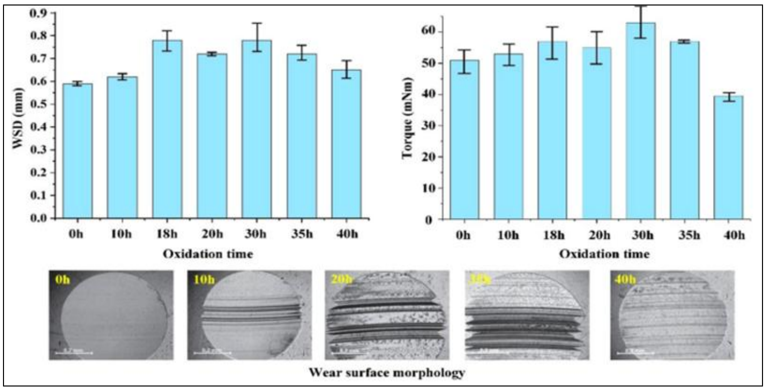
1. Advanced Chemical Modifications: Further investigation into novel chemical modification techniques, such as hybrid epoxidation–esterification processes or nano-functionalization, to optimize viscosity, thermal stability, and anti-wear characteristics.
2. Additive Optimization and Compatibility: Systematic studies on the synergistic effects of antioxidants, anti-wear agents, and viscosity-index improvers, including long-term stability and biodegradability assessments.
3. Surface Engineering Integration: Exploration of different surface texturing geometries and scales in journal bearings to maximize hydrodynamic performance when used with bio-based lubricants.
4. Thermo-Elasto-Hydrodynamic Modeling: Development of more comprehensive numerical models incorporating thermal effects, elastic deformation, and non-Newtonian behavior of modified bio-lubricants.
5. Long-Term Durability and Aging Studies: Evaluation of oxidation resistance, degradation behavior, and performance retention of soybean-based bio-lubricants under prolonged operating conditions.
6. Industrial and Real-Time Applications: Validation of laboratory findings through pilot-scale and industrial testing in automotive, agricultural, and renewable energy machinery.
7. Sustainability and Life-Cycle Assessment: Comprehensive environmental impact and life-cycle cost analyses comparing soybean-based bio-lubricants with conventional mineral oils.











Temperature (°C)	Surface tension (mN / m)				
	Rapeseed oil	Corn oil	Palm oil	Sunflower oil	Soybean oil
20	33.8	33.8	–	34	33.9
40	32	32.2	31.5	32.3	32.2
60	30.5	30.6	30	30.7	30.6
80	29	29.1	28.5	29.2	29.1
100	27.5	27.6	27.1	27.7	27.6
120	26	26.1	25.7	26.3	26.1
140	24.5	24.6	24.4	24.8	24.7
160	23.1	23.2	23	23	23.2
180	21.7	21.8	21.6	21.6	21.8
200	20.3	20.4	–	20.2	20.4

Soybean- and Rapeseed-Based Oils as Lubricants for Rough Bearing Applications

Bio-based lubricants derived from vegetable oils such as soybean and rapeseed have attracted increasing attention due to their biodegradability, renewability, and favorable tribological properties. At the molecular level, three-dimensional structural models of saturated and unsaturated fatty acids reveal that the presence of double bonds enhances molecular flexibility and polarity, which promotes strong adsorption on metallic surfaces and contributes to improved boundary film formation. This molecular behavior plays a critical role in reducing friction and wear under mixed and boundary lubrication regimes. Experimental investigations comparing non-oxidized and oxidized rapeseed oil demonstrate that oxidation significantly degrades lubricating performance. Oxidized oils exhibit increased viscosity, higher average torque, and accelerated wear due to the formation of polar oxidation products and sludge, which disrupt stable lubricant films. In contrast, non-oxidized rapeseed oil maintains lower frictional torque and reduced wear, highlighting the importance of oxidative stability for sustained lubrication. Soybean-based oils, characterized by their triglyceride structure and high viscosity index, exhibit excellent lubricity and film-forming capability in hydrodynamic and elastohydrodynamic lubrication regimes. When applied to rough bearing surfaces, surface asperities strongly influence pressure distribution, minimum film thickness, and load-carrying capacity. Surface roughness generally reduces load capacity and increases friction; however, the polar functional groups in soybean oil enhance surface adhesion and boundary lubrication, partially compensating for roughness effects. Both theoretical modeling and tribological testing indicate that the lubrication performance of soybean oil under rough surface conditions is governed by its rheological behavior, temperature-dependent viscosity, and chemical stability. Chemical modifications such as epoxidation or transesterification, as well as the incorporation of suitable additives, significantly improve oxidation resistance, thermal stability, and wear protection. Comparative studies show that modified soybean oils can achieve lower friction and wear than conventional mineral oils, particularly under severe operating conditions. Overall, soybean- and rapeseed-based lubricants demonstrate strong potential for sustainable bearing applications, provided that oxidative degradation is controlled and surface roughness effects are properly accounted for through formulation optimization and advanced tribological design.

Declarations

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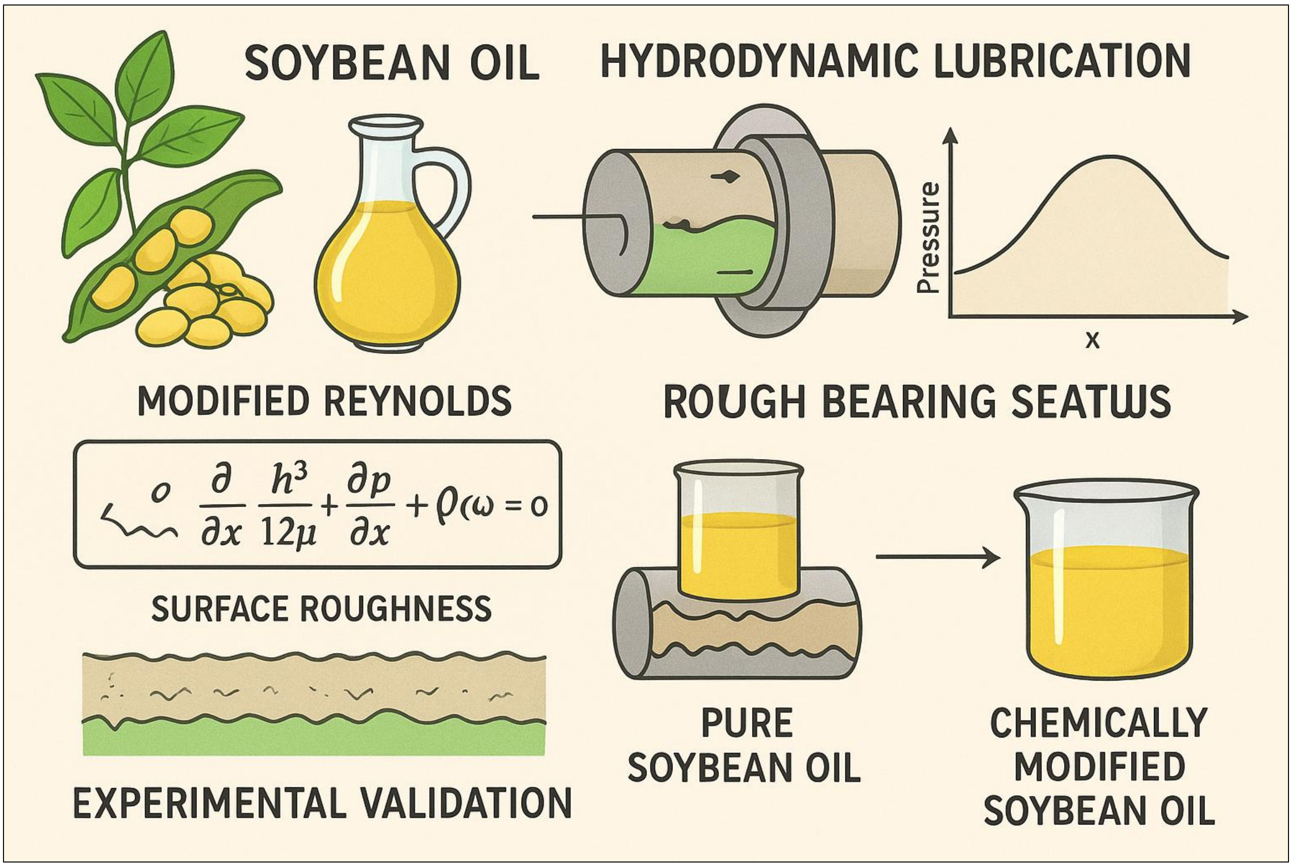
Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.
Ethics Statement: This manuscript does not involve human participants, animal subjects, or any other ethical concerns.
Disclosure of AI Use: Artificial intelligence (AI) tools, including ChatGPT, were used in a limited manner solely for language refinement and formatting assistance. The scientific content, analysis, and conclusions are the responsibility of the authors.



Graphical Abstract

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