Biofuels and Tribology: Pathways Toward Sustainable Engine Performance

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ABSTRACT

The rapid increase in automobile usage has accelerated the depletion of fossil fuels and contributed significantly to environmental degradation. This scenario highlights the urgent need for alternative energy resources that can meet growing energy demands while reducing harmful emissions from conventional fuels. Among the various alternatives, biofuels have emerged as a promising option for internal combustion engines. Numerous short-term engine tests using biofuels have shown encouraging results; however, challenges persist in long-term engine durability tests, which often reveal issues such as excessive carbon deposition and contamination of lubricating oils, ultimately leading to engine failure.

This review aims to evaluate the tribological feasibility of biofuels in transportation applications, as their tribological performance plays a critical role in engine reliability and efficiency. The discussion focuses on various tribological aspects, including material compatibility, long-term endurance, wear behavior, and frictional characteristics. A detailed analysis of friction and wear parameters is presented, covering both compression ignition and spark ignition engines, with particular attention to the use of biodiesels, biofuels, and bio-oils as potential lubricants.

Rather than introducing new experimental findings, this review consolidates and critically analyzes existing research, outlining past developments and highlighting future perspectives in the field of biofuel tribology.

INTRODUCTION

Tribology, a branch of engineering science, focuses on friction, wear, and lubrication of machine components in relative motion. When surfaces interact with materials and the surrounding environment, parameters such as wear, reliability, and maintenance requirements are affected—together forming the core of tribology [1]. In mechanical systems, the primary goal of tribology is to minimize both friction and wear through effective lubrication. Insufficient attention to tribological studies can lead to significant economic losses due to wasted materials, excess energy consumption, and reduced equipment reliability [2].

Tribology also emphasizes selecting suitable material films for specific applications to safeguard contact events such as rolling, sliding, and impact interactions [3]. A lack of such optimization often results in shortened equipment life, increased downtime, and energy inefficiency [4]. For instance, the U.S. Department of Energy has reported that reducing friction and wear in engines and drivetrain components could save approximately $120 billion annually [5].

The core responsibility of engine tribologists is to minimize wear and friction in sliding components through effective lubrication strategies. Improved tribological performance in engines leads to benefits such as better fuel economy, higher brake power, lower oil consumption, reduced exhaust emissions, and longer engine life with minimal maintenance [6]. A 10% reduction in mechanical losses has been shown to reduce fuel consumption by 1.5%, while nearly 48% of an engine's energy is lost as friction in components such as pistons, bearings, valve trains, crankshafts, and transmissions [7].

Hence, adequate lubrication of all tribological engine components is crucial to achieve durability, higher efficiency, and lower emissions [8]. The lubricity of a fuel plays a vital role in protecting engine surfaces by forming films that reduce wear and friction [9]. Since 6–7% of an engine's operating cost is attributed to lubricating oil consumption, the condition and compatibility of lubricants with the fuel in use must be carefully examined [10]. Before adopting any alternative fuel, its tribological suitability must be verified. Monitoring lubricating oil condition and its interaction with the fuel provides insight into engine health and helps assess the feasibility of biofuels in internal combustion (IC) engines [11].

1.1 Brief Discussion on Biofuels

The decline of fossil fuel reserves and their environmental consequences have fueled a growing global demand for biofuels [12]. Among the different options, biodiesel and bioethanol are widely accepted as alternatives for diesel and gasoline engines. Their usage has expanded rapidly in countries such as India, the USA, Europe, Indonesia, Japan, and Sweden [13].

Biodiesel, a mono-alkyl ester of long-chain fatty acids, is produced from vegetable oils, animal fats, or waste oils through transesterification [14]. Similarly, biofuels can be derived from resources like corn, wheat, sugarcane, or natural gas. Production pathways include gasification, anaerobic digestion, pyrolysis, and hydrolysis, which yield biogas, bio-oil, and syngas. These intermediate products undergo further processes such as fermentation, esterification, and purification to produce biodiesel, ethanol, methanol, and other biofuels [16–17].

The suitability of biofuels as IC engine fuels depends on their physical and chemical properties, which must meet the tribological requirements of engines.

1.2 Tribological Properties of Biofuels

The present review focuses on the impact of biofuels on engine durability and life, highlighting their tribological aspects. Extensive research has been conducted worldwide on biodiesel and bioethanol owing to their renewability and biodegradability [18]. Biodiesel has already been commercialized as a partial diesel substitute in many regions [19], while ethanol is increasingly used as a gasoline replacement [20].

Benefits of biodiesel in tribology:

- Better scuffing protection compared to petroleum diesel.
- Ester molecules in biodiesel act as surfactants on metal surfaces.
- Improved film-forming ability for surface protection.
- Oxygen content helps reduce metal-to-metal friction.
- Functional groups (C–C, –OH, –COOH) contribute to friction reduction.
- Fatty acids (e.g., stearic acid) enhance lubrication film formation.
- Protective films reduce thermal effects during sliding contact.
- Unsaturated fatty acids further improve lubricity

Limitations of biodiesel in tribology:

- Oxidation over long-term use causes degradation, poor lubricity, and corrosion.
- Property instability due to environmental exposure and metal interactions.
- Moisture absorption and auto-oxidation accelerate wear.

- Low volatility contributes to oil contamination and deposits.
- Operational problems such as filter plugging, injector coking, and sticking of moving parts.
- Impurities (free fatty acids, unused catalysts, glycerides, moisture) reduce compatibility with automotive materials.
- Aggressive catalysts and acidic nature cause corrosion.
- Higher viscosity increases fuel injector deposits.

Thus, lubricity plays a decisive role in evaluating the tribological performance of biofuels as alternate IC engine fuels.

1.3 Necessity of Lubricity in Biofuels for IC Engine Applications

Before biofuels are adapted for routine use, their lubricity characteristics must be evaluated through tribological testing. These tests examine wear, frictional behavior, corrosive potential, and effects on lubricating oil contamination. Since fuel passes through pumps, injectors, and other critical components, inherent lubricity is essential for reliable operation [21]. Tribological assessment tools include four-ball testers, pin-on-disc testers, high-frequency reciprocating tribometers, and wear testers, under varied loads, speeds, temperatures, and frequencies [22]. Biofuel performance is strongly influenced by factors such as corrosiveness, hygroscopicity, auto-oxidation, viscosity, and volatility. Storage conditions and metal interactions further affect degradation [23]. Corrosion studies, typically conducted on copper, aluminum, stainless steel, zinc, brass, and bronze, employ immersion tests to measure corrosion rates, surface morphology changes, and weight loss [24–25]. Furthermore, the physical and chemical characteristics of biofuels influence both lubrication and wear in engine components. Tribological studies of lubricating oils are therefore essential to evaluate chemical interactions between biofuels and engine lubricants [26–27]. Condition monitoring of lubricating oils is widely used to assess engine performance under real operating conditions [28–29]. Two main approaches are followed [30]:

1. **Lubricant property evaluation** – monitoring viscosity, density, ash content, moisture, flash point, and insolubles to determine lubricant life and contamination levels.
2. **Debris monitoring** – analyzing wear particles in oils through methods such as ferrography [32–33], atomic absorption spectrometry, X-ray fluorescence, and ICP-OES [34–35]. Microscopic examination, dimensional analysis, and weight measurement are also employed to quantify wear debris.

2. Novelty and Objective of the Present Work

The primary objective of this review is to examine the tribological behavior of biofuels under different operating conditions, based on a comprehensive analysis of technical literature from the past few decades. Special emphasis is placed on their influence on engine durability and service life.

While biodiesel has shown promising performance in short-term engine tests, several tribological challenges—such as increased wear, carbon deposits, and lubricant contamination—arise during long-term usage. To mitigate these issues, researchers have proposed blending biodiesel with petroleum fuels in various proportions, thereby enhancing tribological performance in terms of friction, wear, and lubrication. Such improvements are typically assessed through long-term endurance tests conducted on both constant-speed and variable-speed IC engines under standardized operating conditions.

In addition to being used as fuels, vegetable oils and biodiesels have also been tested as lubricating oils using standard tribological apparatus before application in engines. However, no comprehensive review is currently available in the literature that systematically addresses the use of bio-oils as lubricants in IC engines and evaluates their friction and wear characteristics using tribological testing methods.

This paper attempts to fill that gap by:

- Summarizing the latest developments in the tribological evaluation of biofuels.
- Providing insights into friction, wear, and corrosion aspects associated with their use.
- Serving as a basic guide for future research on the tribological feasibility of biofuels.

It must be noted that this paper does not present new experimental results; instead, it consolidates findings from various studies on the tribological testing of biofuels and their application in IC engines.

The paper is structured as follows:

- Methodology and test cycles for long-term endurance tests on constant-speed and variable-speed IC engines.
- Material compatibility studies of compression ignition (CI) engines using biofuels and biodiesels.

3. Long-Term Endurance Test

Endurance testing evaluates the ability of an IC engine to sustain prolonged operation under load while maintaining performance. Tests are conducted as per IS: 10,000 (Part VIII & IX) – 1980 standards [36–37].

3.1 Constant-Speed Internal Combustion Engines

3.1.1 Methodology

- Conducted after initial performance tests (IS: 10,000 Part VIII – 1980).
- Total test duration: 32 hours, divided into two 16-hour cycles.
- After each 16-hour cycle → engine stopped for servicing/adjustments.
- Lubricating oil temperature must return to ambient conditions before restarting [38].

3.1.2 Test Cycle (16 hours)

Step	Load Condition	Duration	Remarks
1	100% load	4 h (incl. 0.5 h warm-up)	Initial full-load run
2	50% load	4 h	Reduced load run
3	110% load	1 h	Overload testing
4	No load (idle)	0.5 h	Engine cooling/idle
5	100% load	3 h	Standard full-load run
6	50% load	3.5 h	Final reduced load run

- Cycle duration: 16 h
- Total test duration: 32 h (two cycles)

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3.2 Variable-Speed Internal Combustion Engines

3.2.1 Methodology

- Conducted after initial performance test + governor/speed limiter check.
- Total test duration: 100 hours, divided into 10-hour running periods.
- Between running periods → minimum 2-hour stoppage.
- Lubricating oil: manufacturer-recommended; oil temperature must return to ambient before restarting [39].

3.2.2 Test Cycle (2 hours)

Step	Load Condition	Duration	Remarks
1	75% full load @ max speed	50 min	Partial load check
2	100% load @ max torque speed	45 min	Peak torque condition
3	Idle condition	5 min	Stabilization
4	100% full load @ max speed	20 min	High-load verification

- Cycle duration: 2 h
- One running period: 5 cycles (10 h total)
- Total test duration: 100 h

4. Material Compatibility of CI Engines

Material compatibility is a critical concern whenever there is a change in the fuel composition used in compression ignition (CI) engines. Engine designers carefully select materials for the fuel system based on extensive laboratory testing methods [40]. However, the use of alternative fuels, such as biodiesel, often introduces challenges related to the long-term durability and reliability of engine components. Biodiesel’s interaction with engine materials has drawn significant attention from tribologists, as they aim to minimize wear, friction, and corrosion caused by fuel–material interactions.

Research findings suggest that both diesel and biodiesel can lead to corrosion and wear of engine components, although the severity varies. Biodiesel tends to create a more corrosive environment compared to conventional diesel. Nonetheless, it offers superior lubricating properties, which help reduce friction and wear [19,20,23,24,40].

4.1. Biodiesel in CI Engines

Evaluating the tribological behavior of biodiesel is essential for its sustainable use in automotive applications [66]. Although biodiesel helps mitigate fossil fuel depletion and environmental concerns, its compatibility with engine materials remains a major challenge. Critical components such as the cylinder, piston, piston rings, and bearings are especially vulnerable when biodiesel is used.

Tribologists therefore focus on identifying, analyzing, and overcoming the adverse effects of biodiesel on fuel systems and engine components. Since fuel interacts with parts like the fuel tank, fuel filter, cylinder liner, piston, piston rings, and connecting rod, researchers have performed endurance tests with different biodiesel blends to assess wear and lubrication mechanisms [67].

The results are categorized as follows:

- Section 4.1.1: Effects of biodiesel on engine components
- Section 4.1.2: Effects of biodiesel on corrosion behavior of engine materials

In general, biodiesel's higher oxygen content compared to diesel tends to accelerate wear and friction, but simultaneously contributes to a reduction in particulate emissions [68].

4.1.1 Effect on Engine Components

Wear metals commonly detected in lubricating oil samples from CI engines include iron, molybdenum,

aluminium, copper, lead, tin, and nickel. These elements originate from two primary sources:

1. **Engine component wear** – cylinder head, piston, piston rings, bearings, valve seats, etc.
2. **Environmental sources** – fuel oil contaminants, coolant additives, and lubricant additives [72].

The concentration of these metals in lubricating oil increases with operating time due to the accumulation of wear debris. Monitoring such concentrations provides a reliable **indicator of engine wear**. Once the concentration of any element exceeds its warning limit, severe wear is likely occurring in the engine. Table lists the warning levels of common wear metals in diesel engines [55].

Table . Warning levels of trace metals in diesel engines

Element	**Warning level (ppm)**
Iron (Fe)	100
Aluminium (Al)	25
Copper (Cu)	50
Lead (Pb)	50
Tin (Sn)	20
Chromium (Cr)	20
Silicon (Si)	25
Boron (B)	25

Studies have shown that biodiesel can reduce wear in several key engine components due to its inherent lubricity-enhancing properties. For instance:

- Piston top deposits and injector coking were reduced, and ash content in lubricating oil was lower in biodiesel-fueled engines compared to diesel [55].
- Durability tests revealed improved piston ring wear resistance with higher biodiesel concentrations compared to diesel [57].
- Lower wear was reported in components such as pistons, valves, piston rings, and liners, whereas higher wear was observed in main bearings and crank pins with biodiesel use [49].

- Structural changes were observed in injection system components, such as injector nozzles and pump pistons, when neat biodiesel was used [48].

Overall, increasing biodiesel concentration in blends reduces friction and wear, attributed to the presence of free fatty acids, oxygenated moieties, and unsaturated molecules [73]. Worn surface distortion also decreases with higher biodiesel content. However, increased rotational speeds can reduce lubricity, leading to higher friction and wear [74].

Biodiesel's lubricity, though beneficial, is influenced by several factors:

- Enhancing lubricity: free fatty acids, unsaturated compounds, glycerides, long-chain molecules, and high viscosity [80–82].
- Reducing lubricity: oxidation, moisture absorption, auto-oxidation, and corrosiveness [83].

While biodiesel blends enhance lubricity compared to ultra-low-sulfur diesel, their high viscosity may impair fuel atomization and injector performance [83]. Studies also indicated that oxidation products in biodiesel can interact with anti-wear additives such as ZDDP, reducing overall lubricant effectiveness [85–86]. Glycerin and water contamination in lubricating oil further influence wear behavior [87]. Moreover, biodiesel-fueled engines showed greater oxidative degradation and polymerization of lubricating oil compared to diesel engines [88].

4.1.2 Effect of Corrosion on Engine Components

The oxidation of biodiesel results in the formation of mono-carboxylic acids, which significantly increase corrosion risk [89]. At elevated temperatures, biodiesel oxidizes more rapidly, producing water and other by-products that accelerate tribo-corrosion—a combined effect of wear and corrosion [90–91].

Although biodiesel generally provides better lubricity than diesel, its higher oxidation tendency contributes to material degradation. Methyl esters react with atmospheric oxygen to form ketones, aldehydes, and carboxylic acids [93]. The presence of metals such as copper catalyzes oxidation, further accelerating degradation, as confirmed by FTIR spectroscopy [94]. Other metal impurities and unsaturated fatty acids also reduce the oxidation stability of biodiesel [95–96].

Biodegradation studies indicate that biodiesel degrades between 77–89% within 28 days, compared to only ~18% for diesel, due to enzyme-catalyzed oxidation [97]. While this biodegradability offers environmental advantages, it also impacts long-term fuel stability and tribological performance [98].

Research findings include:

- Higher biodiesel blends experience increased wear due to acidic constituents formed during combustion [99].
- Copper alloys corrode more severely in biodiesel compared to ferrous alloys [100–101].
- Prolonged exposure to biodiesel not only corrodes engine metals but also degrades fuel properties due to unsaturated molecules and compositional effects [102–105].

Thus, the dual nature of biodiesel—providing enhanced lubricity yet promoting tribo-corrosion—presents a major challenge in ensuring material compatibility of CI engines.

CONCLUSIONS

This review has examined the tribological implications of biofuels with specific attention to wear behavior, lubrication mechanisms, frictional response, corrosion effects, and long-term endurance testing in IC engines. A comprehensive assessment of existing studies indicates that:

- Biodiesel generally enhances lubricity due to its polar ester groups and oxygenated molecular structure.
- However, long-term durability concerns persist, including oxidative instability, lubricating oil degradation, and corrosive wear, especially on copper-containing alloys.
- Condition monitoring techniques such as ferrography, spectrometric analysis, and wear debris evaluation remain effective diagnostic tools for detecting early-stage engine wear.
- Material compatibility challenges continue to limit widespread implementation, particularly due to biodiesel's hygroscopic nature, auto-oxidation, and the formation of acidic by-products.

Overall, while biodiesel demonstrates promising tribological performance in controlled short-term tests, achieving reliable long-term engine operation requires deeper understanding of corrosion mechanisms, material interactions, and fuel–lubricant chemistry.

Future Scope

Based on current research gaps and reviewer recommendations, future studies should focus on:

- Experimental validation under real engine conditions to verify summarized tribological findings and support practical implementation.
- Integration of modern analytical techniques, such as 3D surface topography, wear debris morphology analysis, and advanced lubrication modeling, to better understand wear mechanisms.
- Development of hybrid bio-lubricant formulations and nano-additive packages to improve anti-wear, anti-friction, and anti-corrosion characteristics of both fuels and lubricating oils.
- Assessment of long-term economic and environmental trade-offs, including life-cycle analyses for various biofuel blends.
- Comparative case studies on long-duration endurance tests using blended and pure biofuels to evaluate durability, component degradation, and lubricant condition over extended operation.

These future research directions will strengthen the scientific understanding of biofuel tribology and support the transition toward cleaner, more sustainable engine technologies.

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