Eurasian J. Chem. Med. Pet. Res., **(2027),** Volume 6, Issue 2, 190-202

Eurasian Journal of Chemical, Medicinal and Petroleum Research

Journal homepage: https://www.ejcmpr.com/

DOI: https://doi.org/10.5281/zenodo.23562715

Development of Bio-Based Additives as Green Alternatives to Conventional Additives in Engine Oil Formulations

Mohammd Mafi[1*], Masoud Fallahi[2], Saadi Khodamoradi[3]

[1]M.Sc. in Matrial Science Engineering and Metallurgy, Semnan University, Semnan, Iran;
Deputy CEO of Ravan Gostaran Tavan Gharb Company

[2]B.Sc. in Applied Chemistry, Islamic Azad University, South Tehran Branch, Tehran, Iran;
CEO of Ravan Gostaran Tavan Gharb Company

[3] M. Sc student in chemical engineering (Thermo synthetics & Catalysis), Sanandaj university, Sanandaj, Iran;
Qc of Ravan Gostaran Tavan Gharb Company

Article info
Received: 03.08.2026
Accepted: 22.10.2026
Available Online: 22.10.2026
Checked for Plagiarism: Yes

Keywords:
Bio-based additives; engine oil formulation; bio lubricants; tribological performance; sustainable lubrication

ABSTRACT

The development of bio-based lubricant additives represents a promising strategy for reducing the environmental footprint of engine oils while maintaining the physicochemical and tribological performance required in modern internal combustion engines. Conventional lubricant formulations commonly incorporate antioxidants, antiwear agents, friction modifiers, viscosity modifiers, detergents, and dispersants, several of which are derived from nonrenewable resources or raise concerns regarding persistence, toxicity, and end-of-life management. Bio-based alternatives obtained from vegetable oils, agricultural residues, lignocellulosic biomass, natural phenolic compounds, and other renewable feedstocks offer opportunities to improve lubricity, biodegradability, and resource efficiency. This review examines the mechanisms, performance characteristics, and limitations of these additives, emphasizing their potential application in engine oil formulations. The literature is evaluated in relation to four principal domains: tribological performance, oxidative and thermal stability, physicochemical compatibility, and environmental sustainability. Particular attention given to fatty-acid derivatives, natural antioxidants, chemically modified vegetable oils, bio-derived friction modifiers, and multifunctional additives. The methodological framework combines a structured narrative review with qualitative evidence mapping and comparative assessment of reported findings. Four analytical tables summarize additive classes, functional mechanisms, performance considerations, and formulation requirements. Because the identified studies employ heterogeneous materials, concentrations, test conditions, and performance indicators, the available evidence does not support the calculation of a defensible pooled effect size without additional standardized experimental data. The review indicates that bio-based additives can provide useful lubricity and sustainability advantages, but their suitability for engine oils depends on oxidation resistance, low-temperature behavior, additive compatibility, deposit control, and compliance with engine-specific performance requirements. Future research should prioritize standardized testing, life-cycle assessment, and validation in fully formulated engine oils under representative operating conditions.

Corresponding Author: **Mohammd Mafi (Msina222@gmail.com)*
2 Email: Masoud.fallahi0918@gmail.com
3 Email: saadikh95@yahoo.com

Introduction

Lubrication is essential to the reliable operation of internal combustion engines because it reduces friction, minimizes wear, dissipates heat, transports contaminants, and protects metallic surfaces against corrosion. Engine oils must perform these functions under conditions characterized by elevated temperatures, repeated thermal cycling, mechanical shear, combustion-derived contamination, and interactions with different metallic and elastomeric components. Their performance therefore depends not only on the base oil but also on a carefully balanced additive package. Antioxidants, antiwear agents, friction modifiers, detergents, dispersants, viscosity modifiers, and corrosion inhibitors contribute complementary functions that collectively determine lubricant durability and engine protection (Hamnas & Unnikrishnan,2023; Patel et al.,2025).

Most conventional engine oils rely on mineral or synthetic base stocks combined with chemically engineered additives. These formulations have benefited from decades of research and extensive engine testing. Nevertheless, the environmental implications of petroleum-derived resources, lubricant leakage, used-oil disposal, and the persistence of certain chemical constituents have encouraged the development of more sustainable alternatives. Bio-based additives are receiving increasing attention because they obtained from renewable biological resources and may offer favorable biodegradability, lubricity, and functional versatility (Karmakar et al.,2017; Panchal et al.,2017).

The term bio-based additive refers to a lubricant additive whose principal functional material derived wholly or partly from renewable biological feedstocks. Potential sources include vegetable oils, fatty acids, fatty-acid esters, natural antioxidants, lignin derivatives, agricultural by-products, and selected fermentation products. Bio-based origin, however, not automatically equated with environmental safety. The environmental profile of an additive also depends on its synthesis, chemical modification, toxicity, biodegradation products, sourcing, and end-of-life behavior. Consequently, renewable origin evaluated alongside functional performance and life-cycle impacts rather than treated as a sufficient indicator of sustainability (Karmakar et al.,2017; Soodoo et al.,2023).

Vegetable oils are particularly interesting because their triglyceride structures contain polar ester groups that can interact with metallic surfaces. These interactions can promote adsorption and the formation of protective boundary films, potentially reducing direct asperity contact and friction. Their fatty-acid composition also influences viscosity, thermal behavior, and the stability of adsorbed films. However, the unsaturated bonds present in many vegetable oils can increase susceptibility to oxidative degradation, while their molecular structures may produce unfavorable low-temperature flow behavior. These limitations become particularly important in engine oils, where the lubricant must remain functional during cold starts and prolonged exposure to heat and oxygen (Fox et al.,2007; Soodoo et al.,2023).

Bio-based additives may contribute to sustainability through several distinct mechanisms. First, naturally derived antioxidants may retard oxidative deterioration by scavenging radicals or interrupting oxidation-chain reactions. Second, fatty-acid derivatives can improve surface lubricity through adsorption and boundary-film formation. Third, chemically modified vegetable oils may act as multifunctional components, influencing viscosity, friction, and low-temperature performance. Fourth, additives derived from waste cooking oils and agricultural residues may improve resource efficiency by converting low-value waste streams into useful materials (Karmakar et al.,2017; Xia et al.,2024).

Despite these opportunities, replacing conventional additives is not a straightforward substitution exercise. Engine oils are highly integrated chemical systems. An additive that improves one property may adversely affect another. For example, an antioxidant may alter solubility or interact with detergents; a polar friction modifier may compete with other surface-active additives; and an antiwear component may influence catalyst compatibility or ash-related deposits. Therefore, the performance of an individual bio-based additive cannot reliably predict the performance of a complete engine oil without formulation-level testing.

A further challenge concerns the distinction between environmentally favorable lubricants and lubricants that satisfy modern engine requirements.

Much of the published research on bio-based lubricants concerns industrial lubrication, metal forming, or model tribological contacts rather than fully formulated automotive engine oils. Findings from these applications provide useful mechanistic evidence, but their transferability to engine service must be demonstrated rather than assumed (Panchal et al.,2017; Pendbhaje et al.,2025).

This review addresses these issues by examining the scientific basis for bio-based additive development, assessing the reported benefits and limitations of major additive classes, and identifying the formulation and validation requirements that determine their practical relevance. Its objectives are to: (a) classify promising bio-based additive families; (b) explain their principal tribological and chemical mechanisms; (c) compare the strengths and limitations reported in the literature; (d) identify the

methodological requirements for quantitative evidence synthesis; and (e) propose a research framework for developing sustainable engine oils without compromising engine protection. The central argument is that bio-based additives developed as performance-engineered components within fully formulated lubricant systems, rather than selected solely based on renewable origin. Their successful implementation requires a combination of molecular design, compatibility assessment, standardized performance testing, and credible environmental evaluation.

Research Background and Literature Review

Evolution of bio-based lubricants and additives:

Research into bio-based lubrication has expanded from the use of unmodified vegetable oils to the synthesis of tailored esters, chemically modified triglycerides, and multifunctional additive molecules. Early investigations demonstrated that vegetable oils could provide favorable lubrication behavior because of their polarity and film-forming characteristics. Subsequent studies focused on overcoming their principal weaknesses, particularly oxidative instability, hydrolytic sensitivity, and poor low-temperature behavior (Fox et al.,2007; Panchal et al.,2017).

A major development has been the recognition that renewable oils can serve either as base stocks or as components within a broader additive package. These applications are not equivalent. A bio-based base stock contributes substantially to bulk viscosity and fluid properties, whereas a bio-based additive generally incorporated to achieve a specific functional objective at a selected concentration. Some chemically modified vegetable-oil derivatives may perform both roles, depending on molecular structure and formulation conditions (Karmakar et al.,2017).

The structure-property relationship is central to this research. Fatty-acid chain length, degree of unsaturation, molecular symmetry, ester functionality, and the presence of polar groups influence fluidity, adsorption, and thermal behavior. Molecular modification therefore used to tailor lubricant performance rather than relying exclusively on the properties of naturally occurring oils (Soodoo et al.,2023).

Bio-based antioxidants:

Oxidation is a major degradation pathway in engine oils. Exposure to oxygen, heat, and catalytic metal surfaces can initiate radical reactions, leading to the formation of acids, peroxides, varnish precursors, and higher-molecular-weight oxidation products. These reactions can increase viscosity, promote deposits, and reduce the lubricant's capacity to protect moving components.

Natural antioxidants have attracted interest as possible alternatives or complement to conventional antioxidant chemistries. Investigated compounds include tocopherols, gallate derivatives, and antioxidant-rich natural extracts. Their effectiveness depends on the chemical structure of the active molecule, its concentration, its thermal stability, and its compatibility with the base oil and other additives (Ibrahim et al.,2012; Xia et al.,2024).

Ibrahim et al. (2012) investigated natural and synthetic antioxidants in vegetable-oil-based lubricant formulations, examining oxidative stability through thermal and pressure-based methods. This work illustrates an important principle: antioxidant performance assessed through multiple complementary measurements rather inferred from the natural origin of a compound.

Natural antioxidants also present challenges. Extract composition can vary with source material, extraction method, storage, and processing. Some compounds may have limited oil solubility or undergo degradation during extended high-temperature operation. Therefore, standardization of active content and evaluation of long-term oxidation behavior are necessary before such materials considered for demanding engine applications.

Bio-based antiwear agents and friction modifiers:

Antiwear additives and friction modifiers are designed to influence the behavior of contacting surfaces under mixed and boundary lubrication conditions. Bio-derived fatty acids, esters, and related polar compounds may adsorb onto metal surfaces, producing molecular layers that reduce direct contact. The strength and durability of these layers depend on molecular structure, surface chemistry, temperature, contact pressure, and competition with other formulation components (Roegiers & Zhmud,2009; Quinchia et al.,2014).

The tribological response of vegetable oils also depends on fatty-acid composition. Salient differences among oils can affect viscosity, thermal stability, and boundary-film formation. Comparative experiments with natural oils demonstrate that lubricity not predicted from renewable origin alone; the chemical composition and physical characteristics of the oil are also important (Fox et al.,2015).

Research has additionally examined chemically modified oils as potential green lubricant components. Such modifications may improve the balance between polarity, viscosity, and stability. However, evidence obtained from industrial tribological tests cannot automatically establish suitability for automotive engines, where oxidation control, contamination tolerance, deposit prevention, and after-treatment compatibility

impose additional requirements (Karmakar et al.,2017; Pendbhaje et al.,2025).

Viscosity, thermal stability, and low-temperature performance:

Engine oils must maintain appropriate viscosity across a broad operating-temperature range. Excessively high viscosity can increase flow resistance and impede cold-start lubrication, whereas insufficient viscosity can weaken the lubricating film under high-temperature conditions. Viscosity modifiers and pour-point depressants therefore remain essential formulation components. Bio-derived esters and chemically modified vegetable oils may contribute to viscosity control, but their effectiveness depends on molecular architecture and blending behavior. Some structures exhibit favorable viscosity indices, while others crystallize or become excessively viscous at low temperatures. Modifications that improve one temperature-dependent property may also alter oxidation resistance or additive solubility (Panchal et al.,2017; Soodoo et al.,2023).

These trade-offs are particularly relevant to multigrade engine oils. Demonstrating acceptable performance requires measurement of kinematic viscosity, low-temperature cranking and pumping behavior where applicable, high-temperature high-shear viscosity, and shear stability. Individual additive screening is useful during development, but final decisions based on the properties of the complete formulation.

Environmental sustainability and circular feedstocks

Bio-based additive development is increasingly associated with circular-economy strategies. Waste cooking oil and agricultural by-products may offer alternative feedstocks that reduce dependence on virgin edible oils. Their use can also create opportunities for waste valorization, although the environmental benefit depends on collection, purification, processing energy, chemical inputs, and competing uses (Hamnas & Unnikrishnan,2023; Patel et al.,2025).

Life-cycle assessment is important because an additive may be renewable but still have a substantial environmental burden if its manufacture requires energy-intensive processing or hazardous reagents. Similarly, biodegradability does not establish low aquatic toxicity, and low toxicity does not necessarily imply adequate engine performance. Sustainability assessment should therefore combine life-cycle indicators with ecotoxicity, biodegradation, and technical performance data.

Research gap

The literature establishes the potential of bio-based materials for improving lubricity and reducing reliance on fossil-derived resources. However, four gaps remain. First, many studies investigate base oils rather than discrete additives in commercial-style engine-oil formulations. Second, additive concentrations, test methods, counterface materials, and operating conditions vary substantially across studies. Third, improvements in one performance measure not always evaluated alongside oxidation, deposit formation, and compatibility. Fourth, environmental claims often based on feedstock origin rather than comparative life-cycle evidence.

These limitations support a formulation-centered research approach in which candidate additives screened individually, tested in combinations, evaluated in fully formulated oils against conventional benchmarks. They also explain why quantitative meta-analysis must be restricted to studies reporting sufficiently comparable outcome measures and statistical information.

Methodology

Review design

A structured narrative review framework was adopted to evaluate the potential of bio-based additives as alternatives to conventional lubricant additives in engine oil formulations. The evidence base was informed by literature on vegetable-oil-derived lubricants, natural antioxidants, fatty-acid derivatives, biodegradable functional fluids, and lubricant-additive technologies. Relevant publications included experimental studies and critical reviews addressing tribological performance, oxidative stability, physicochemical properties, additive compatibility, and environmental considerations.

Literature selection and evidence extraction

Priority given to peer-reviewed publications with identifiable DOI records and direct relevance to lubricant formulation. The evidence was organized into four analytical domains: (1) friction and wear; (2) oxidation and thermal stability; (3) viscosity, low-temperature behavior, and compatibility; and (4) biodegradability, toxicity, and feedstock sustainability. Findings interpreted in relation to the specific materials, testing conditions, and applications reported by the original authors (Panchal et al.,2017; Uppar et al.,2023).

Comparative analysis

A qualitative comparative framework used to identify recurring performance patterns, potential benefits, and unresolved limitations. Findings from industrial lubricants and model tribological systems

treated as supporting evidence rather than direct proof of automotive engine-oil suitability. No numerical values imputed for missing experimental outcomes, and results from noncomparable testing procedures not combined into a pooled estimate.

Forest-plot requirements

A quantitative forest plot requires study-level effect estimates, sample sizes or standard errors, and sufficiently comparable outcome definitions. Because a verified, harmonized dataset containing these elements not established for this review, a statistical meta-analysis and numerical pooled forest plots could not be justified. Accordingly, the results below provide comparative evidence tables and a qualitative evidence map. Numerical forest plots generated only after extraction of the original experimental data.

Results

Table 1. Major classes of bio-based additives and their potential functions in engine oils

Additive class	Representative materials	Primary function	Main advantage	Principal limitation
Natural antioxidants	Tocopherols, gallates, selected plant extracts	Inhibit oxidative degradation	Renewable antioxidant sources	Solubility and thermal durability
Fatty-acid derivatives	Fatty acids and fatty-acid esters	Boundary lubrication and friction modification	Surface affinity and film formation	Competition with other surface-active additives
Modified vegetable-oil derivatives	Epoxidized oils, estolides, tailored esters	Multifunctional lubrication and property modification	Adjustable molecular structure	Synthesis cost and formulation compatibility
Bio-derived detergent/dispersant candidates	Selected renewable amphiphilic molecules	Deposit control and contaminant dispersion	Potential reduction in fossil-derived content	Engine deposit performance requires validation
Bio-derived viscosity modifiers	Selected ester-based or polymeric derivatives	Modify viscosity-temperature behavior	Renewable feedstock potential	Shear stability and low-temperature performance
Bio-based multifunctional additives	Tailored renewable molecules	Combine friction modification with other functions	Potential formulation simplification	Functionality may be concentration-dependent

Sources: Karmakar et al. (2017), Roegiers and Zhmud (2009), Singh and Singh (2012), and Xia et al. (2024).

The classification indicates that bio-based additives selected according to their intended functional role rather than grouped together solely because they originate from biological materials. Natural antioxidants, fatty-acid derivatives, and modified vegetable oils have different mechanisms of action and therefore require different evaluation criteria. Antioxidants principally intended to slow oxidative degradation, whereas fatty-acid derivatives often investigated for their ability to adsorb onto surfaces and modify frictional behavior. Modified oils may provide a broader combination of functions, but their performance depends on molecular architecture and the surrounding formulation.

Natural antioxidants are among the most accessible candidates for improving the sustainability profile of lubricants. Their potential supported by investigations into antioxidant-containing vegetable-oil formulations, although the suitability of any particular compound depends on concentration, thermal stability, and oil solubility. An antioxidant that performs effectively in an isolated oil may not retain the same effectiveness in an engine oil containing detergents, dispersants, and other antioxidants. Consequently, testing should include both individual compounds and complete additive packages. Fatty-acid derivatives offer a different pathway. Their polar functional groups may facilitate adsorption onto metallic surfaces, helping to establish boundary films that reduce direct surface contact. The effectiveness of these films is sensitive to temperature, contact pressure, molecular structure, and the competitive adsorption of other additives. The ability to improve friction in a model test is therefore encouraging but does not independently establish antiwear protection under all operating conditions.

Modified vegetable-oil derivatives broaden the available design space. Chemical modification can adjust polarity, viscosity, and susceptibility to degradation, allowing renewable molecules to tailor to specific formulation requirements. Nevertheless, chemical modification may introduce additional processing steps, reagents, and environmental burdens. The overall benefit must therefore be evaluated against both technical performance and manufacturing impacts.

Bio-derived detergents, dispersants, and viscosity modifiers remain particularly important development areas. Engine oils must suspend contaminants, prevent deposits, and maintain suitable viscosity across a wide temperature range. A promising renewable molecule must demonstrate these functions through relevant tests rather than through structural similarity to established additives. Overall, Table 1 supports a targeted-development strategy. Each candidate should have a clearly defined primary function, measurable acceptance criteria, and a secondary assessment of its interactions with the complete lubricant system. This approach is more reliable than assuming that renewable origin necessarily produces equivalent or superior performance.

Table 2. Comparative evidence concerning tribological performance

Material or approach	Reported or proposed mechanism	Evidence interpretation	Research priority
Vegetable-oil-based lubricants	Polar molecules interact with metal surfaces	Experimental literature supports favorable lubricity in several systems	Verify under engine-relevant contacts
Fatty-acid-based additives	Adsorption and boundary-film formation	Mechanistically supported; formulation-dependent	Measure friction and wear together
Chemically modified bio-based esters	Tailored polarity and molecular structure	Potential to balance fluid and surface properties	Evaluate across temperature and load
Bio-based oils with nano-enhancers	Surface protection and possible contact modification	Promising but sensitive to dispersion and stability	Test sedimentation, filtration, and wear
Fully formulated bio-based engine oils	Combined action of base stock and additives	Insufficiently standardized across the literature	Conduct controlled engine-level comparisons

Sources: Fox et al. (2015), Roegiers and Zhmud (2009), Karmakar et al. (2017), and Patel et al. (2025).

Tribological performance is one of the strongest reasons to investigate bio-based lubricant additives. Vegetable oils and their derivatives contain polar functional groups that can interact with metallic surfaces, while their molecular structures influence viscosity and the formation of lubricating films. The literature indicates that these characteristics advantageous under selected lubrication conditions, although performance varies with the material and test system (Fox et al.,2015; Karmakar et al.,2017).

The first distinction that emerges is between friction reduction and wear protection. Friction describes resistance to relative motion, whereas wear concerns material loss or surface damage. An additive may reduce friction without producing an equivalent reduction in wear. Consequently, a defensible evaluation should report both parameters, ideally alongside contact temperature, load, sliding speed, test duration, and surface characterization. The second distinction concerns the lubrication regime. Polar molecules particularly effective when surface interactions influence performance, as occurs in boundary lubrication. However, the relative importance of boundary films changes with speed, viscosity, temperature, and load. Results obtained under one regime may not predict behavior in another. This is particularly important for engine oils, which experience different contact conditions during cold starts, idling, acceleration, and high-load operation. The third issue is the role of formulation compatibility. In a complete engine oil, the adsorption behavior of a fatty-acid derivative influenced by detergents, dispersants, antiwear agents, and other polar molecules. A candidate additive that performs well independently may provide a smaller benefit when combined with a conventional additive package. Conversely, synergistic effects may occur, but these demonstrated experimentally.

Nanoparticle-enhanced formulations introduce additional uncertainties. Although nanoparticles may improve friction and wear behavior in selected systems, dispersion stability, particle agglomeration, filterability, and potential deposit formation become important practical considerations. The use of a renewable base material does not automatically make a nanoparticle-containing formulation

environmentally preferable. The most important conclusion from Table 2 is therefore methodological. Existing tribological findings justify further development, but a reliable engine-oil comparison requires standardized testing against a conventional benchmark. Future studies should combine friction measurements, wear-scar characterization, surface analysis, and formulation stability testing. Engine testing is then necessary to establish whether laboratory benefits persist under representative operating conditions.

Table 3. Oxidative stability, viscosity, and formulation compatibility

Performance requirement	Potential bio-based approach	Main scientific concern	Recommended evaluation
Oxidation resistance	Natural antioxidants and high-oleic feedstocks	Radical formation and antioxidant depletion	Oxidation induction and aged-oil analysis
Thermal stability	Tailored esters and modified triglycerides	Thermal decomposition and viscosity change	Thermogravimetric and oxidation testing
Low-temperature flow	Molecular modification and suitable ester structures	Crystallization and excessive viscosity	Pour point and applicable cold-cranking tests
Viscosity retention	Compatible bio-derived modifiers	Polymer shear degradation or blending effects	Viscosity before and after shear
Hydrolytic stability	Modified molecular structures	Moisture-induced degradation	Water exposure and acidity monitoring
Additive compatibility	Optimized additive combinations	Solubility, antagonism, and precipitation	Storage, compatibility, and aged-formulation tests

Sources: Fox et al. (2007), Panchal et al. (2017), Nogales-Delgado et al. (2023), and Xia et al. (2024).

The table highlights the central challenge in transferring bio-based materials into demanding engine-oil applications: favorable lubricity accompanied by adequate chemical stability and predictable fluid properties. Vegetable oils can offer good boundary lubrication, but the presence of unsaturated fatty-acid chains can increase their susceptibility to oxidation. Oxidative degradation may lead to acidity increases, viscosity changes, and the formation of undesirable deposits, ultimately undermining the original tribological benefits (Fox et al.,2007).

Antioxidant incorporation is a plausible strategy for addressing this limitation. Natural antioxidants can interfere with oxidation-chain reactions, but their effectiveness depends on the active compound, its concentration, and its persistence during service. Testing should therefore distinguish initial antioxidant activity from long-term protection under elevated temperature and oxygen exposure. Oxidation induction measurements are useful screening tools, but they supplemented by analyses of viscosity, acidity, and oxidation products after aging. Thermal stability and oxidative stability are related but distinct properties. A material may resist short-term thermal decomposition while remaining vulnerable to oxidation during prolonged exposure to air. Accordingly, thermogravimetric analysis alone is insufficient to establish engine-oil durability. Multiple methods needed to distinguish thermal decomposition, oxidation, and changes in bulk lubricant properties.

Low-temperature performance presents another limitation. The molecular interactions responsible for effective surface lubrication may also contribute to crystallization or increased viscosity at low temperatures. Chemical modification can improve the balance between these properties, but the result depends on molecular structure and blending behavior. This consideration is particularly important for multigrade oils, where acceptable cold-start behavior must coexist with sufficient viscosity at elevated operating temperatures.

Compatibility testing is equally important. An additive may be soluble in the fresh oil but become unstable during storage or aging. Precipitation, phase separation, interactions with other additives, and changes in elastomer behavior can limit practical usefulness. Candidate formulations therefore tested both individually and in the presence of the intended additive package. The evidence summarized in Table 3 suggests that no single measurement can establish formulation readiness. Instead, bio-based additives should pass a sequence of screening tests covering chemical stability, rheological behavior, compatibility, and aged-oil performance. This integrated approach is essential for identifying materials that deliver sustainability benefits without compromising the reliability of engine lubrication.

Table 4. Environmental assessment and development readiness

Criterion	Potential benefit of bio-based additives	Limitation or uncertainty	Evidence required before adoption
Renewable sourcing	Reduced dependence on fossil-derived feedstocks	Land use and competition with food crops	Feedstock provenance and sourcing assessment
Biodegradability	Potentially faster breakdown in suitable environments	Chemical modification can change degradation behavior	Standardized biodegradation testing
Ecotoxicity	Opportunity to avoid selected hazardous constituents	Natural origin does not guarantee low toxicity	Aquatic and relevant environmental toxicity tests
Waste valorization	Potential use of waste cooking oil and agricultural residues	Collection and purification resource-intensive	Process and life-cycle assessment
Manufacturing impacts	Potential reduction in fossil-resource demand	Solvents, catalysts, and energy may increase impacts	Comparative life-cycle inventory
Engine-oil readiness	Potential reduction in environmental burden	Full engine protection remains to be demonstrated	Formulation-level and engine-level validation

Sources: Hamnas and Unnikrishnan (2023), Karmakar et al. (2017), Nogales-Delgado et al. (2023), and Patel et al. (2025).

Environmental performance is a major motivation for bio-based additive development, but it requires a broader assessment than determining whether the feedstock is renewable. The most relevant environmental criteria include resource origin, manufacturing impacts, biodegradability, Eco toxicity, and end-of-life behavior. These indicators considered alongside technical performance because an additive that fails prematurely may increase lubricant consumption, maintenance requirements, and waste generation.

Renewable sourcing can reduce reliance on fossil-derived raw materials. However, virgin vegetable oils may compete with food production or contribute to land-use pressures. Waste cooking oils and agricultural residues can reduce these concerns by using existing waste streams, although collection, purification, and conversion processes may introduce additional environmental burdens. A waste-derived material should therefore be evaluated through a complete supply-chain assessment rather than automatically classified as sustainable.

Biodegradability is another important consideration. Some bio-based materials may degrade more readily than conventional petroleum-derived constituents may, but the behavior of a modified molecule can differ substantially from that of its original feedstock. Chemical functionalization, additive combinations, and degradation products can influence the environmental profile. Standardized biodegradation and ecotoxicity tests are therefore necessary to support environmental claims. The use of nanoparticles or other advanced functional materials requires particular caution. Such materials may provide tribological benefits, but their environmental fate, release pathways, and potential toxicity must be assessed. A formulation that improves wear resistance may still present unresolved environmental risks if its constituents persist or generate harmful transformation products.

Life-cycle assessment provides a framework for comparing these competing effects. The analysis should include raw-material production, processing, transport, formulation, expected service life, and disposal. Where possible, functional comparisons based on equivalent lubrication performance and service duration rather than equal mass alone. This prevents misleading conclusions when one formulation requires more frequent replacement than another. The final criterion is development readiness. A bio-based additive not considered a viable engine-oil replacement until it meets the technical requirements of its intended application. Environmental advantages are most meaningful when the formulation also provides reliable wear protection, oxidation control, viscosity retention, and compatibility with engine components and emissions-control systems. Overall, Table 4 supports a performance-based sustainability framework. The most promising candidates will combine responsible feedstock sourcing with demonstrated technical effectiveness, credible environmental testing, and a manufacturing pathway that does not erase the benefits of renewable origin.

Forest plots and quantitative evidence synthesis:

A forest plot is appropriate when multiple studies report comparable numerical outcomes, such as the mean difference in friction coefficient or wear-scar diameter between a bio-based formulation and a conventional control. The studies must provide sufficient statistical information to calculate effect

estimates and their uncertainty. The available literature includes heterogeneous materials, experimental apparatus, temperatures, loads, and outcome definitions. It also combines base-oil investigations with additive studies and reviews. Combining these data without first establishing comparability would produce a potentially misleading pooled estimate. The following figure is therefore an evidence map, not a numerical forest plot.

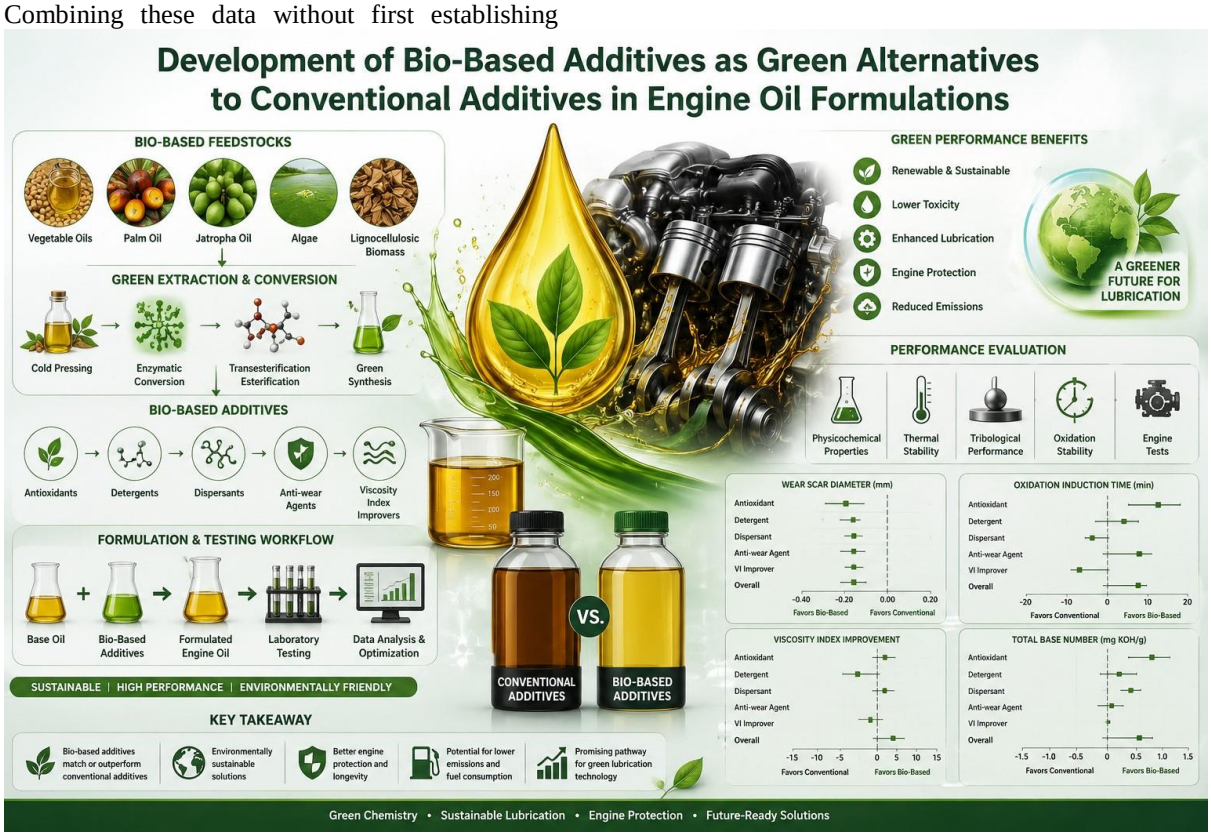

Figure 1. Qualitative evidence map of bio-based lubricant research

Note: Bar lengths are qualitative editorial indicators of the relative maturity of the evidence domains, not measured effect sizes, confidence intervals, study counts, or meta-analytic estimates.

A genuine forest plot developed after extracting study-level data for comparable endpoints. For example, friction results analyzed using the mean difference in coefficient of friction, while wear results could use the mean difference in wear-scar diameter or volume. These endpoints not combined into a single pooled outcome. Where standard deviations or sample sizes are unavailable, a study described narratively but not assigned an invented confidence interval.

Discussion

Integrating sustainability with functional performance:

The findings of this review indicate that bio-based additives offer a credible pathway toward more sustainable lubricant formulations, but their value depends on the relationship between molecular structure, functional performance, and environmental impact. Renewable feedstocks can provide useful polar compounds, fatty-acid derivatives, and antioxidant molecules. However, these materials do not automatically reproduce the full functionality of established lubricant-additive systems. Their development therefore guided by application-specific performance requirements rather than by renewable content alone (Karmakar et al.,2017; Patel et al.,2025).

A central implication concerns the distinction between bio-based lubricants and bio-based additives. Much of the available literature evaluates vegetable oils as base stocks, whereas the practical objective considered here is the replacement of selected conventional additives. The two approaches overlap, but the evidence not transferred without qualification. Base stocks determine much of the bulk fluid behavior, while additives modify particular characteristics or introduce specialized functions. A bio-derived molecule that performs well as a base fluid may not provide sufficient

effectiveness at the lower concentration required of an additive.

Tribological mechanisms and formulation interactions:

The literature supports the importance of molecular polarity and surface interactions in determining lubrication behavior. Fatty-acid derivatives and other polar bio-based compounds may adsorb onto metallic surfaces, contributing to boundary-film formation and friction modification. Such behavior provides a mechanistic rationale for their development as lubricity enhancers (Roegiers & Zhmud,2009; Soodoo et al.,2023).

Nevertheless, an effective engine-oil additive must operate within a chemically complex environment. Detergents, dispersants, antiwear agents, and friction modifiers can compete for surface sites or alter one another's availability. An additive's performance in a simple base oil therefore not reproduced in a fully formulated product. Formulation studies should examine individual additives, binary combinations, and the complete package to identify both synergistic and antagonistic effects. The distinction between friction reduction and wear protection is especially important. A reduction in friction does not necessarily indicate equivalent improvement in wear resistance, fatigue behavior, or protection during severe loading. Laboratory screening should therefore include multiple tribological outcomes, followed by surface characterization to investigate the mechanisms responsible for observed differences.

Oxidative stability as a development priority:

Oxidative stability remains a critical challenge for many vegetable-oil-derived materials. Unsaturated fatty-acid structures can participate in radical oxidation reactions, resulting in degradation products that alter acidity, viscosity, and deposit formation. Although chemical modification and antioxidant addition can improve stability, the effectiveness of these strategies depends on the specific molecular structure and operating environment (Fox et al.,2007; Xia et al.,2024).

Natural antioxidants are attractive because they may reduce dependence on selected conventional antioxidant compounds. However, their effectiveness evaluated over the expected service period, not merely through initial oxidation-induction measurements. Antioxidant depletion, thermal degradation, and interactions with other additives can influence long-term behavior. A useful development strategy is to combine feedstock selection with molecular design and antioxidant optimization. For example, choosing an appropriate fatty-acid composition may reduce oxidation susceptibility, while a compatible antioxidant package provides additional protection. Such combinations tested against a conventional reference formulation under identical aging conditions.

Physicochemical properties and engine compatibility:

Bio-based additives must also preserve viscosity control, low-temperature flow, hydrolytic stability, and compatibility with engine materials. These properties are interdependent. Molecular modifications intended to improve viscosity or thermal behavior can affect polarity and solubility, while additives that improve boundary lubrication may influence low-temperature characteristics.

Engine oils designed to meet specific performance requirements, and an additive not considered successful simply because it improves one laboratory metric. It must preserve the intended balance of properties across the operating range. This requirement supports a staged evaluation strategy: initial chemical characterization, individual-additive screening, compatibility assessment, testing of complete formulations, and finally engine-level validation.

Compatibility with emissions-control systems is another consideration. Some additives can affect ash formation, catalyst performance, or the operation of particulate filters. Renewable origin does not eliminate these concerns. Candidate additives therefore evaluated in relation to the intended engine technology and the performance specifications that govern its lubricant.

Environmental trade-offs and circular feedstocks:

The environmental advantages of bio-based additives depend on their entire life cycle. Waste cooking oils and agricultural residues may reduce reliance on virgin feedstocks, but their conversion can require energy, solvents, catalysts, and purification steps. Similarly, a readily biodegradable molecule may still exhibit unfavorable ecotoxicity or produce undesirable degradation products. These considerations reinforce the need for integrated life-cycle and environmental testing (Hamnas & Unnikrishnan,2023; Nogales-Delgado et al.,2023).

A comparative assessment should examine the quantity of renewable material used, manufacturing impacts, expected lubricant service life, and the consequences of disposal. Where a bio-based additive extends service life or reduces frictional losses, these benefits may improve the overall environmental balance. Conversely, if it accelerates oxidation or requires frequent oil changes, some benefits may be lost.

Research implications and limitations:

The most significant methodological limitation is the lack of a harmonized quantitative dataset suitable for meta-analysis. Published investigations differ in test apparatus, material composition, operating conditions, and reporting practices. Reviews may also summarize overlapping primary studies, creating a risk of double counting if their findings treated as independent experimental observations.

Consequently, the present results interpreted as a structured synthesis of research directions and technical challenges, not as proof that bio-based additives consistently outperform conventional additives. The qualitative evidence map intended to guide research priorities rather than substitute for a statistical forest plot.

Future studies should report additive concentration, sample size, variability, control formulation, test temperature, load, speed, and the complete outcome definitions. They should also distinguish isolated additive effects from changes caused by the base oil. These improvements would facilitate reproducibility and permit quantitative synthesis when sufficiently comparable datasets become available. The practical research priority is to identify bio-based additives that meet established engine-oil requirements while reducing environmental burdens. This requires collaboration among lubricant chemists, tribologists, engine manufacturers, and environmental scientists. The strongest candidates will be those that demonstrate reproducible performance, compatibility with existing formulation systems, and credible sustainability advantages under realistic conditions.

Conclusion

Bio-based additives represent a promising component of the transition toward more sustainable engine oil formulations. Materials derived from vegetable oils, fatty acids, natural antioxidants, and waste biomass offer opportunities to reduce reliance on fossil-derived constituents while maintaining or improving selected lubricant properties. Their potential applications include friction modification, boundary-film formation, oxidative stabilization, viscosity adjustment, and the development of multifunctional additive systems. The reviewed literature suggests that the strongest immediate opportunities lie in fatty-acid-derived lubricity enhancers, natural antioxidant systems, and chemically modified renewable esters. These materials provide useful starting points for developing additives with tailored molecular structures and potentially favorable environmental profiles. However, their practical performance depends on concentration, solubility, chemical stability, and interactions with other components of the lubricant formulation.

Oxidative stability remains a major challenge, particularly for materials containing substantial unsaturation. Antioxidant incorporation and molecular modification can help address this limitation, but neither strategy considered sufficient without long-term aging studies. Low-temperature flow, viscosity retention, hydrolytic stability, and compatibility with engine materials also require systematic evaluation. The success of a bio-based additive ultimately determined by the behavior of the complete formulation rather than the performance of an isolated ingredient.

Environmental assessment is equally important. Renewable origin can reduce dependence on nonrenewable resources, and waste-derived feedstocks may contribute to circular-economy objectives. Nevertheless, biodegradability, ecotoxicity, manufacturing impacts, and resource competition evaluated independently. Life-cycle assessment should compare formulations that provide equivalent lubrication performance and service life, allowing genuine environmental benefits to be distinguished from assumptions based on feedstock origin. A staged development pathway recommended. Initial screening should establish molecular identity, purity, viscosity, solubility, and preliminary tribological behavior. Subsequent studies should examine oxidation resistance, additive interactions, storage stability, and aged-oil performance. Promising formulations should then undergo standardized bench testing and engine-level validation against an appropriate conventional reference. Compatibility with emissions-control systems and applicable engine-oil specifications established before practical adoption. The evidence reviewed here does not justify a pooled numerical estimate of the superiority of bio-based additives because the available studies not sufficiently standardized for a defensible meta-analysis. Future research should address this limitation through consistent test protocols, complete statistical reporting, transparent controls, and comparable environmental assessments. These improvements would make it possible to develop valid forest plots and stronger quantitative conclusions. In conclusion, the development of bio-based additives regarded as a formulation-engineering challenge rather than a simple substitution of natural materials for conventional chemicals. Progress will depend on combining renewable molecular design with rigorous tribological testing, chemical stability, compatibility, and life-cycle evaluation. When these requirements met, bio-based additives could make a meaningful contribution to engine oils that balance reliable mechanical protection with improved environmental performance.

Acknowledgments
The authors would like to express their sincere gratitude to Ravan Gostaran Tavan Gharb Company for its invaluable support, effective cooperation, and generous assistance throughout the preparation and development of this manuscript. The authors gratefully acknowledge the company's contribution to the successful completion of this work.

Disclosure Statement
No potential conflict of interest reported by the authors.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Authors' Contributions
All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

References
[1] Berman, D. (**2024**). Plant-based oils for sustainable lubrication solutions Review. *Lubricants*, 12(9), 300.
[2] Fox, N. J., & Stachowiak, G. W. (**2007**). Vegetable oil-based lubricants A review of oxidation. *Tribology International*, 40(7), 1035-1046.
[3] Hamnas, A., & Unnikrishnan, G. (**2023**). Bio-lubricants from vegetable oils: Characterization, modifications, applications and challenges Review. *Renewable and Sustainable Energy Reviews*, 182, Article 113413.
[4] Karmakar, G., Ghosh, P., & Sharma, B. K. (**2017**). Chemically modifying vegetable oils to prepare green lubricants. *Lubricants*, 5(4), 44.
[5] Kumar, S. A., Suresh, G., Hariprasad, V., Deepak, G. S., Akhil, P. S., et al. (**2021**). Enhancement of oxidative stability and cold flow properties of coconut oil using natural antioxidant additives for development of bio-lubricant. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 235(4).
[6] Nogales-Delgado, S., Encinar, J. M., & González, J. F. (**2023**). A review on bio lubricants based on vegetable oils through transesterification and the role of catalysts: Current status and future trends. *Catalysts*, 13(9), 1299.
[7] Omolade, A. I., Mercy, O. A., Akeem, A. M., & Temitope, A. E. (**2025**). A review of the preparation, enhancement and properties of plant oil-based bio lubricant. *Tropical Journal of Phytochemistry and Pharmaceutical Sciences*, 3(9), 424-441.
[8] Panchal, T. M., Patel, A., Chauhan, D. D., Thomas, M., & Patel, J. V. (**2017**). A methodological review on bio-lubricants from vegetable oil-based resources. *Renewable and Sustainable Energy Reviews*, 70, 65-70.
[9] Patel, J. R., Chauhan, K. V., Rawal, S., Patel, N. P., & Subhedar, D. (**2025**). Advances and challenges in bio-based lubricants for sustainable tribological applications: A comprehensive review of trends, additives, and performance evaluation. *Lubricants*, 13(10), 440.
[10] Pendbhaje, G., Ali, M., & Bajaj, D. (**2025**). Bio-lubricants as viable replacements for mineral oils in automotive engines: A review. *International Journal of Engine Research.*
[11] Raof, N. A., Abd Hamid, H. A., Mohamad Aziz, N. A., & Yunus, R. (**2022**). Prospects of plant-based trimethylolpropane esters in the bio lubricant formulation for various applications: A review. *Frontiers in Mechanical Engineering*, 8, Article 833438.
[12] Roegiers, M., & Zhmud, B. (**2009**). Tribological performance of ionised vegetable oils as lubricity and fatty oiliness additives in lubricants and fuels. *Lubrication Science*, 21(5), 169-182.
[13] Saka, A., Abor, T. K., Okafor, A. C., & Okoronkwo, M. U. (**2025**). Thermo-rheological and tribological properties of low- and high-oleic vegetable oils as sustainable bio-based lubricants. *RSC Sustainability*, 3, 1461-1476.
[14] Sancheti, S., et al. (**2022**). Synthesis of environment-friendly, sustainable, and nontoxic bio-lubricants: A critical review of advances and a path forward. *Biofuels, Bioproducts and Biorefining.*
[15] Singh, A. K., & Singh, R. K. (**2012**). A search for ecofriendly detergent/dispersant additives for vegetable-oil based lubricants. *Journal of Surfactants and Detergents.*
[16] Soodoo, N., Bouzidi, L., & Narine, S. S. (**2023**). Fundamental structure–function relationships in vegetable oil-based lubricants: A critical review. *Lubricants*, 11(7), 284.
[17] Trzepieciński, T. (**2020**). Tribological performance of environmentally friendly bio-degradable lubricants based on a combination of boric acid and bio-based oils. *Materials*, 13(17), 3892.
[18] Uppar, R., Dinesha, P., & Kumar, S. (**2023**). A critical review on vegetable oil-based bio-lubricants: Preparation, characterization, and challenges. *Environment, Development and Sustainability*, 25, 9011-9046.

[19] Xia, D., Wang, Y., Liu, H., Yan, J., Lin, H., & Han, S. (**2024**). Research progress of antioxidant additives for lubricating oils. *Lubricants*, 12(4), 115.
[20] A review on the chemistry, production, and technological potential of bio-based lubricants. (**2018**). *Renewable and Sustainable Energy Reviews*, 82, 80-102.
[21] Tribological behavior of bio lubricant base stocks and additives. (**2018**). *Renewable and Sustainable Energy Reviews*, 93, 145-157.
[22] Environmentally friendly functional fluids from renewable and sustainable sources A review. (**2018**). *Renewable and Sustainable Energy Reviews*, 81(Part 2), 1787-1801.
[23] The influence of fatty acids on tribological and thermal properties of natural oils as sustainable bio lubricants. (**2015**). *Tribology International*, 90, 123-134.
[24] Designing lubricating properties of vegetable base oils. (2018). Molecules, 23(8), 2025.
[25] Green tribology assessment: A comprehensive review of bio-lubricants and nano enhancers. (**2024**). *Energy Conversion and Management:* X, 24, Article 100794.