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Bio-Based Lubricants and Wear Reduction in Small Machinery

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Abstract

Small agricultural and rural machines operate under conditions characterized by repeated starts, variable loads, dust exposure, limited cooling, seasonal storage, and inconsistent maintenance. Lubricant performance therefore has a direct influence on friction, wear, temperature control, sealing, energy efficiency, and component service life. Bio-based lubricants derived principally from vegetable oils and chemically modified renewable feedstocks have attracted attention because their polar molecular structures can provide strong lubricity while offering advantages related to renewability, biodegradability, high viscosity index, and reduced environmental persistence. Their use in small machinery nevertheless requires careful formulation because unmodified vegetable oils can exhibit inadequate oxidation stability, unfavorable low-temperature flow, viscosity growth during aging, and variable compatibility with existing seals and additive packages.

This study develops a simulation-based framework for evaluating bio-based lubricant formulations for wear reduction in small machinery. Five lubricant configurations are compared: a conventional mineral-oil reference, unmodified vegetable oil, a bio/mineral blend, a chemically modified bio-ester, and an additive-enhanced bio-based formulation. A Small-Machinery Lubrication Performance Index is constructed using anti-wear performance, friction reduction, viscosity-temperature stability, oxidation resistance, and machinery compatibility. Simulated index values increase from 61.0 for the mineral reference to 84.5 for the additive-enhanced bio-lubricant.

A complementary simulation indicates wear-reduction potential ranging from 12% for unmodified vegetable oil to 46% for a properly formulated additive-enhanced bio-lubricant relative to the reference condition. The results emphasize that bio-origin alone does not guarantee superior machinery lubrication. Chemical modification, antioxidant protection, anti-wear additives, viscosity control, seal compatibility, application-specific specifications, and appropriate service intervals are critical.

Keywords: bio-based lubricants, wear reduction, vegetable oils, small machinery, tribology, sustainable lubrication, friction, agricultural machinery.

1. Introduction

Lubrication is fundamental to the reliability of small machinery because many mechanical components operate through repeated sliding, rolling, oscillating, or rotating contact. Bearings, gears, piston–cylinder interfaces, chains, shafts, cutting mechanisms, pumps, and transmission elements experience friction that

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generates heat and progressively removes or deforms surface material when an adequate lubricating film is not maintained. Lubricants reduce direct asperity contact, remove heat, protect surfaces against corrosion, transport contaminants, and influence sealing behavior. For small agricultural and rural machinery, lubrication reliability can be especially important because equipment may operate intermittently under heavy loads, dusty environments, high ambient temperatures, and limited preventive-maintenance infrastructure. Suhane and colleagues specifically identify vegetable-oil-based lubricants as potentially relevant to crop cutters and harvesting equipment, where leakage and lubricant loss can also create environmental exposure.

Conventional mineral oils provide established viscosity grades, oxidation stability, additive compatibility, and broad machinery experience, but their petroleum origin and persistence after leakage have encouraged interest in renewable alternatives. Vegetable oils contain triglyceride structures with polar ester groups that can adsorb strongly onto metallic surfaces and form lubricating boundary films. This surface affinity contributes to the favorable lubricity frequently reported for plant-derived oils. Salimon and colleagues identify high lubricity and viscosity index among the important advantages of plant oils, while Chan and colleagues show that tribological behavior is strongly influenced by the molecular structure of the bio-based stock and by the additives incorporated into the formulation.

The potential advantages of bio-based lubricants should not, however, be interpreted as evidence that crude vegetable oil can be poured into any machine without technical qualification. Natural triglycerides commonly contain unsaturated fatty-acid structures susceptible to oxidation. Oxidation can increase acidity, viscosity, sludge formation, deposits, and degradation products during extended thermal exposure. Fox and Stachowiak identify oxidative instability and poor low-temperature behavior as major limitations restricting broader industrial adoption of untreated vegetable oils. McNutt and He similarly describe chemical modification through transesterification, estolide formation, and epoxidation as important pathways for improving the stability and lubrication characteristics of renewable feedstocks.

Experimental tribology provides evidence that properly selected plant-oil formulations can reduce friction and wear. Shahabuddin and colleagues found that a relatively low Jatropha-oil concentration blended with SAE 40 reduced both friction and wear-scar diameter under their test conditions, whereas increasing the vegetable-oil proportion beyond the favorable range increased wear. Suhane and colleagues likewise examined castor-oil-based lubricant under low-speed conditions and showed that load, speed, and blend ratio interact significantly in determining wear behavior. These studies demonstrate a central engineering principle: optimum bio-based formulation is conditional on operating regime rather than proportional to the percentage of renewable oil in the lubricant.

The present study therefore evaluates bio-based lubricants specifically from the perspective of wear reduction and service suitability in small machinery. No original four-ball testing, engine-bench experiment, viscosity measurement, or component-wear dataset is represented as collected evidence. Instead, a transparent simulation framework integrates findings from tribology, bio-lubricant chemistry, thermal aging, and machinery compatibility research. The study compares raw, blended, chemically modified, and additive-enhanced formulations while explicitly considering the limitations created by oxidation, cold flow, material compatibility, and application-specific lubricant specifications. The central proposition is that bio-based lubrication can support both wear reduction and environmental performance when renewable feedstocks are engineered as complete lubricants rather than treated simply as substitutes for mineral base oil.

2. Objectives of the Study

2.1 To Assess the Wear-Reduction Potential of Bio-Based Lubricants

The first objective is to examine how bio-based lubricant formulation influences friction and wear in representative small-machinery contact conditions. Particular attention is given to boundary and mixed lubrication, where metal surfaces approach closely and the adsorption characteristics of polar vegetable-oil molecules can materially influence tribological behavior.

The assessment differentiates unmodified vegetable oil from mineral/bio blends, chemically modified bio-esters, and formulations containing anti-wear or friction-modifying additives. This distinction is important because published experiments demonstrate that changes in blend ratio, molecular modification, and additive concentration can substantially alter wear outcomes.

2.2 To Examine Stability and Machinery Compatibility Constraints

The second objective is to evaluate whether favorable short-duration lubricity can be retained under realistic machinery conditions. Oxidation stability, viscosity change during aging, low-temperature fluidity, hydrolytic behavior, thermal stability, and interaction with sealing materials are therefore considered alongside friction and wear.

The study treats compatibility as a prerequisite for adoption. A lubricant that produces low friction in a laboratory tribometer may remain unsuitable for a specific engine, gearbox, hydraulic circuit, or pump if its viscosity grade, additive chemistry, seal interaction, or thermal performance conflicts with equipment requirements.

2.3 To Develop an Application-Oriented Bio-Lubricant Selection Framework

The third objective is to establish a framework through which bio-based lubricants can be evaluated for small machinery according to operating severity rather than environmental characteristics alone. The framework considers light-duty mechanisms, low-speed machinery, small gear drives, agricultural cutters, pumps, and engine-related applications as distinct lubrication environments.

The intended result is a balanced selection strategy in which renewable content, tribological performance, component protection, material compatibility, maintenance intervals, and manufacturer specifications are considered simultaneously.

3. Review of Literature

3.1 Molecular Basis of Bio-Lubricant Friction and Wear Performance

Vegetable oils differ structurally from conventional hydrocarbon mineral oils because their triglyceride molecules contain polar ester groups. These polar groups have a relatively strong affinity for metallic surfaces, enabling the formation of adsorbed molecular layers that can reduce direct surface contact in boundary-lubrication conditions. Salimon and colleagues describe this inherent lubricity as one of the primary functional advantages of plant oils, while Chan and colleagues show that fatty-acid chain length, molecular polarity, and chemical structure influence friction and wear behavior.

This molecular behavior is especially relevant to small machinery because many mechanisms operate intermittently at speeds too low to maintain a thick hydrodynamic lubricant film continuously. At start-up, under oscillating load, or during speed reduction, lubrication can shift toward mixed or boundary conditions. In these regimes, surface-active lubricant molecules and anti-wear additives become increasingly important.

Shahabuddin and colleagues provide useful experimental evidence through their investigation of Jatropha-oil blends. Their tribological tests showed that adding a suitable proportion of Jatropha oil to a mineral base could reduce coefficient of friction and wear scar, but that excessive proportions did not continue to improve performance. The authors reported a maximum friction reduction of approximately one third and wear-scar reduction approaching thirty percent within their tested conditions.

Castor oil has also attracted interest because the hydroxyl functionality of ricinoleic acid contributes unusual viscosity and polarity. Suhane and colleagues studied castor-oil-based lubricant in a four-ball arrangement for low-speed applications and demonstrated that wear behavior depends strongly on operating load, sliding speed, and blending ratio. This reinforces the need to match bio-lubricants to actual operating conditions rather than evaluate them solely from base-oil identity.

3.2 Chemical Modification, Additives, and Performance Enhancement

The major challenge for untreated vegetable oils is that the molecular unsaturation supporting desirable fluid characteristics can also create sites vulnerable to oxidative attack. Fox and Stachowiak explain that vegetable-oil oxidation can generate degradation products and viscosity changes that affect long-duration lubrication. Poor cold-flow characteristics represent a parallel constraint because some plant oils become excessively viscous or crystallize at temperatures where machinery may still be expected to start and circulate lubricant.

Chemical modification can alter these limitations while retaining much of the favorable ester-based lubricity. McNutt and He describe esterification and transesterification, epoxidation, and estolide formation among the principal methods used to improve oxidative, thermal, and low-temperature properties of vegetable-oil feedstocks. Nagendramma and Kaul similarly identify synthetic and vegetable-derived esters as important foundations for environmentally compatible lubricant formulation in applications including gears, hydraulic systems, transmission fluids, and other machinery systems.

Additives provide a second route to performance improvement. Practical lubricants are rarely composed solely of a base stock; they commonly contain antioxidants, anti-wear additives, friction modifiers, corrosion inhibitors, dispersants, viscosity modifiers, and pour-point depressants. Syahir and colleagues review the broad application range of bio-based lubricants and emphasize that formulation must address both environmental properties and engineering performance. Chan and colleagues similarly identify plant-derived additives, particulate materials, layered solids, and other additive classes capable of modifying friction and wear.

Bhaumik, Pathak, and Datta provide an instructive example of additive-enhanced castor oil. Their optimized formulation containing multiple friction modifiers demonstrated substantial reductions in both friction coefficient and wear scar compared with the tested commercial mineral-oil samples. The magnitude of their laboratory improvement should not be generalized directly to machinery service, but

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the study demonstrates that renewable base stocks can provide a strong tribological platform when formulation chemistry is optimized rather than left in crude form.

3.3 Thermal Aging, Seal Compatibility, and Machinery Application

Short-duration tribological performance does not guarantee long service life. Farfan-Cabrera and colleagues investigated thermal aging of Jatropha oil and demonstrated substantial oxidative thickening of the straight vegetable oil under severe thermal exposure. Their bio/mineral blend showed more stable behavior than the pure vegetable oil while retaining favorable lubricity. The study illustrates that long-term viscosity evolution can become as important as initial friction performance when bio-based lubricants are applied to engines or other heated mechanisms.

Compatibility with elastomeric seals is another practical consideration. Farfan-Cabrera, Gallardo-Hernández, and Pérez-González evaluated several common sealing elastomers in contact with Jatropha oil, mineral engine oil, and a mixed formulation. Their standardized tests showed generally favorable compatibility with pure Jatropha oil, although creep behavior and surface characteristics varied among elastomers. Their findings highlight why lubricant substitution should include seal-specific testing rather than assuming chemical compatibility from biodegradability or plant origin.

Agricultural applications are especially relevant because leakage or total-loss lubrication can release oil directly into soil and vegetation. Suhane, Sarviya, and Siddiqui identify crop-cutting and harvesting machinery as promising targets for vegetable-oil-derived lubrication precisely because such equipment combines mechanical wear with the possibility of environmentally exposed lubricant loss.

The literature therefore indicates that the strongest candidates for small machinery are not necessarily untreated vegetable oils but purpose-formulated renewable esters, compatible blends, or additive-enhanced bio-lubricants. Successful adoption requires integration of tribological performance with viscosity control, oxidation resistance, additive chemistry, materials compatibility, and the specific lubrication regime of the machine.

4. Research Methodology

4.1 Simulation-Based Comparative Research Design

The study adopts a simulation-based comparative methodology. No lubricant was synthesized or physically tested as part of the present analysis. Five hypothetical formulation classes were defined to represent progressively greater levels of formulation engineering.

The first condition is a conventional mineral-oil reference meeting the assumed machinery viscosity requirement. The second represents an unmodified vegetable oil possessing favorable polarity but limited oxidation control. The third is a bio/mineral blend in which renewable oil provides additional lubricity while the conventional fraction improves stability. The fourth consists of a chemically modified renewable ester with improved low-temperature and oxidation characteristics. The fifth represents a complete additive-enhanced bio-based formulation containing suitable antioxidant, anti-wear, viscosity, and corrosion-control chemistry.

All numerical results are explicitly simulated and are intended to illustrate a decision framework rather than report laboratory evidence.

4.2 Small-Machinery Lubrication Performance Index

A Small-Machinery Lubrication Performance Index (SMLPI) was developed using five criteria. Tribological protection receives substantial emphasis, but formulation stability and compatibility are incorporated so that short-term wear performance does not dominate long-term suitability.

Table 1: Criteria and weights used in the Small-Machinery Lubrication Performance Index

Criterion	Engineering interpretation	Weight
Anti-wear capability	Ability to reduce material loss and wear-scar development under representative contact conditions	0.25
Friction reduction	Capacity to reduce sliding resistance and associated heat generation	0.20
Viscosity-temperature stability	Ability to maintain appropriate lubricant film formation across operating temperatures	0.20
Oxidation and aging resistance	Resistance to excessive viscosity growth, sludge, acidity, and thermal degradation	0.20
Machinery compatibility	Compatibility with seals, additives, metals, lubricant circulation, and application requirements	0.15

This weighting structure intentionally prevents environmental origin from appearing as an independent performance score. Biodegradability and renewability are important sustainability advantages, but machinery protection must first satisfy the functional requirements of the lubrication point.

4.3 Simulated Wear Assessment and Engineering Constraints

Illustrative relative reductions of 12%, 24%, 34%, and 46% were assigned to the unmodified oil, bio/mineral blend, modified bio-ester, and additive-enhanced formulation respectively. The values were selected to demonstrate realistic ranking behavior informed by experimental literature rather than to reproduce any single published experiment.

The analysis assumes equal machinery load and correct viscosity selection. No formulation is considered acceptable merely because it produces lower simulated wear.

5. Analysis

5.1 Comparative Lubrication Performance

The mineral-oil reference produces an SMLPI of 61.0. Its principal strengths are oxidation stability, viscosity control, established additive technology, and compatibility. Because it serves as the comparison condition, it receives moderate friction and wear scores rather than being treated as a technically poor lubricant.

Unmodified vegetable oil achieves a slightly higher simulated index of 63.4 because its strong molecular polarity provides favorable friction and wear behavior. This improvement is moderated by weak oxidation and low-temperature scores. The result illustrates why favorable bench lubricity cannot be interpreted automatically as superior long-duration machinery performance.

The bio/mineral blend reaches 71.6, reflecting a compromise between renewable-oil surface activity and conventional lubricant stability. Experimental Jatropha-blend research supports this general formulation concept, with selected low-concentration blends demonstrating reduced friction and wear under tested conditions.

Table 2: Simulated performance of alternative lubricant formulations

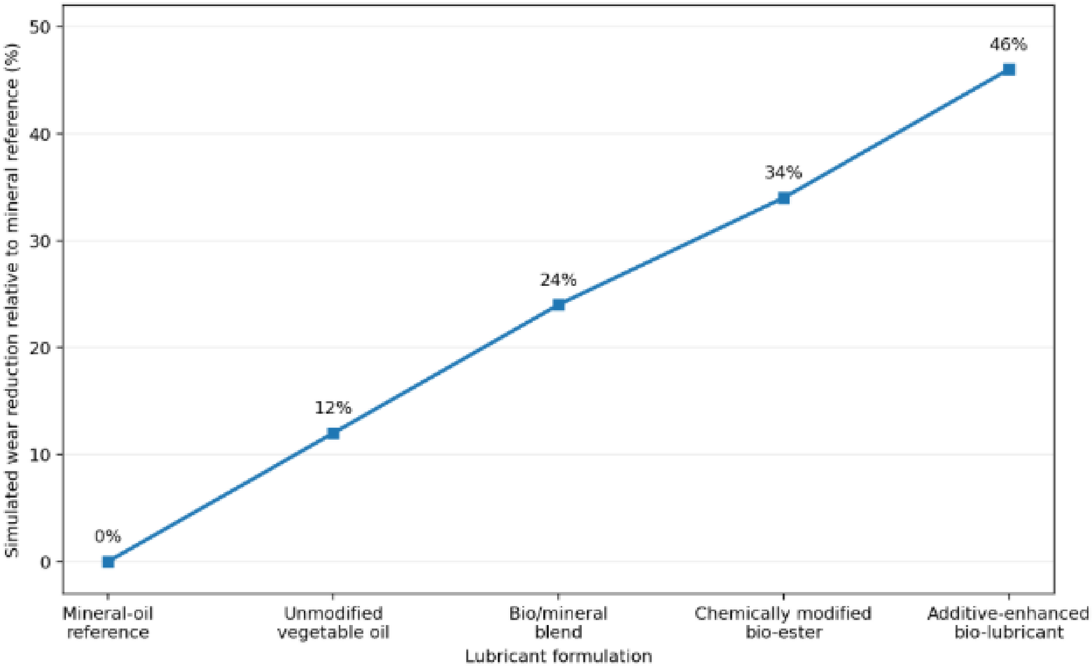
Lubricant formulation	Anti-wear	Friction control	Viscosity stability	Oxidation resistance	Compatibility	SMLPI
Mineral-oil reference	62	60	78	80	78	71.0
Unmodified vegetable oil	70	75	62	42	68	64.2
Bio/mineral blend	76	75	76	70	80	75.4
Chemically modified bio-ester	84	82	84	79	82	82.4
Additive-enhanced bio-lubricant	91	88	86	84	85	87.2

The chemically modified bio-ester achieves 82.4, while the additive-enhanced formulation produces the highest simulated SMLPI of 87.2. These results reflect the central finding that bio-based lubricant performance becomes increasingly competitive when molecular modification and a complete additive system correct the weaknesses of raw vegetable oil.

5.2 Simulated Wear-Reduction Potential

The simulated wear comparison provides a more focused view of contact protection. Unmodified vegetable oil produces an illustrative 12% reduction in wear relative to the mineral reference. The value increases to 24% for the bio/mineral blend, 34% for the chemically modified bio-ester, and 46% for the additive-enhanced bio-lubricant.

Graph 1: Simulated Wear-Reduction Potential of Bio-Based Lubricant Formulations



The shape of the simulated trend is compatible with published tribological evidence showing that optimized blending and additive design can improve wear relative to either raw plant oil or conventional references under selected conditions. Shahabuddin and colleagues demonstrated wear-scar reduction from Jatropha-containing formulations, while Bhaumik and colleagues reported substantially greater reductions from an optimized castor-oil formulation containing multiple friction modifiers.

The graph should not be interpreted as a universal prediction for small machinery. A lubricant producing 46% lower wear in one tribometer condition could perform differently in a gearbox, small engine, chain drive, hydraulic pump, or bearing because lubrication regime, temperature, contaminant exposure, surface metallurgy, and additive chemistry differ.

5.3 Application Suitability for Small Machinery

Small agricultural machines encompass several distinct lubrication environments. Low-speed exposed mechanisms such as chains, cutter drives, and some harvesting components may benefit substantially from high lubricity and environmentally compatible total-loss oils because leakage can enter soil or crop residue. Suhane and colleagues specifically identify crop-cutting and harvesting equipment as promising settings for vegetable-derived lubricants.

Small gearboxes place greater emphasis on viscosity stability, extreme-pressure behavior, oxidation control, foam resistance, and seal compatibility. In these applications, a chemically modified ester or fully formulated bio-based gear lubricant is more defensible than untreated vegetable oil.

Engine lubrication is considerably more demanding. Small engines expose lubricants to thermal oxidation, combustion products, deposit formation, shear, additive depletion, and extended recirculation. Farfan-Cabrera and colleagues' thermal-aging work demonstrates why pure vegetable oil can undergo dramatic viscosity change even while maintaining low friction. For this reason, a favorable tribological test should never be treated as sufficient evidence for substituting an unapproved plant oil into an engine.

Two-stroke engines require particular caution because lubricant formulation influences fuel miscibility, deposit formation, exhaust behavior, and lubrication after the oil is carried with the fuel. Only products specifically qualified for the intended engine and fuel system should be considered.

6. Discussion

6.1 Why Vegetable Oils Can Reduce Wear but Still Fail as Long-Life Lubricants

The strongest tribological advantage of vegetable oils originates from the same molecular chemistry that creates some of their long-term limitations. Polar ester groups promote adsorption on metallic surfaces and can form effective boundary films, reducing direct asperity interaction. This explains why several studies report low friction and favorable wear performance relative to mineral oils under selected test conditions.

However, unsaturated fatty-acid chains are also vulnerable to oxidative degradation. As oxidation progresses, the lubricant may thicken, form deposits, lose low-temperature mobility, and alter its chemical interaction with machine surfaces. Fox and Stachowiak identify this trade-off as one of the central barriers to widespread use of raw vegetable oils.

The practical implication is that tribological testing should include aging rather than evaluating only fresh lubricant. An oil displaying excellent four-ball wear performance before oxidation may behave differently after exposure to thermal cycling, moisture, and long service periods. Farfan-Cabrera and colleagues' thermal-aging data on Jatropha oil demonstrate this point directly, showing dramatic viscosity changes despite continued favorable friction behavior.

For small machinery, where owners may extend oil-change intervals unintentionally, oxidative stability can therefore be as important as the initial coefficient of friction.

6.2 Chemical Modification and Additive Design as the Practical Transition Route

The simulation indicates that the strongest overall performance occurs after the renewable base oil is chemically and additively engineered. Chemical modification changes the molecular features responsible for poor stability while allowing the ester-based lubrication advantages to be retained. McNutt and He identify transesterification, estolide chemistry, and epoxidation among the principal methods used to develop more durable bio-lubricant base stocks.

Additives then address functions that the base stock cannot provide reliably on its own. Antioxidants slow oxidative chain reactions, pour-point depressants support low-temperature flow, anti-wear additives protect high-load contacts, corrosion inhibitors protect metals, and viscosity modifiers can stabilize film characteristics over a wider temperature range.

The results from Bhaumik and colleagues demonstrate how formulation can substantially improve the tribological behavior of castor-oil-based lubricant through optimized friction modifiers. Such results support the principle that renewable base oils should be developed through modern lubricant formulation science rather than evaluated only in their crude state.

This approach also avoids a misleading comparison between "mineral oil" and "vegetable oil." Commercial mineral oils are already complex additive-containing formulations, while experimental vegetable oils are sometimes tested without equivalent additive optimization. Fair comparison requires formulations designed to perform the same engineering task.

6.3 Machinery Compatibility, Maintenance, and Sustainable Use

Bio-based lubrication should be implemented through application-specific qualification. Seal compatibility is particularly relevant because some ester-based fluids can cause swelling, softening, shrinkage, or property changes in elastomeric materials. Farfan-Cabrera and colleagues found generally favorable standardized compatibility between Jatropha oil and several elastomers, but their additional tests still revealed changes in creep and surface condition for selected materials.

Compatibility therefore should be confirmed for the specific elastomers, coatings, adhesives, filters, and metals present in the machine. The same principle applies to lubricant mixing. Changing from one formulation to another can leave residual oil that interacts with the new fluid or modifies additive concentration. Flushing procedures and manufacturer guidance may be necessary.

Maintenance intervals may also require adjustment. A biodegradable lubricant that oxidizes more rapidly than the original oil can still be technically valuable if condition monitoring or shorter service intervals are economically acceptable. Conversely, a high-stability modified ester may permit intervals comparable with conventional lubricants. Maintenance policy should therefore respond to actual oxidation and contamination behavior rather than to the renewable origin of the lubricant.

Environmental benefit is greatest where leakage risk is meaningful. Crop cutters, chains, forestry-type mechanisms, pumps operating near waterways, and agricultural machinery used directly over soil can create a stronger case for biodegradable formulations than fully enclosed systems with minimal lubricant loss. Nevertheless, biodegradability should complement—not replace—sound engineering performance.

7. Conclusion

Bio-based lubricants offer a technically credible pathway toward lower-wear and more environmentally compatible lubrication in small machinery, but their success depends on formulation quality rather than renewable origin alone. Vegetable oils possess strong natural lubricity because polar molecular groups interact effectively with metal surfaces, making them attractive for boundary and mixed lubrication. Experimental literature confirms that selected vegetable-oil blends and modified formulations can reduce friction and wear under controlled conditions.

The simulation developed in this study demonstrates the advantage of progressive formulation engineering. Unmodified vegetable oil produces useful simulated wear reduction but remains constrained by oxidation resistance and viscosity stability. Bio/mineral blends improve the balance of lubrication and stability, while chemically modified esters provide a stronger foundation for long-duration service. The additive-enhanced bio-based formulation achieves the highest simulated overall performance and an illustrative wear reduction of 46% relative to the reference condition.

These findings should not be interpreted as support for uncontrolled substitution of vegetable oil into existing machines. Small engines, gearboxes, hydraulic circuits, pumps, chains, and harvest mechanisms impose different requirements concerning viscosity, temperature, anti-wear chemistry, seal compatibility, oxidation, and contamination control. A formulation should therefore meet the requirements of the specific machine and, where applicable, the manufacturer's lubricant specification.

Future empirical research should validate bio-based formulations using four-ball and pin-on-disc tribology alongside oxidation testing, viscosity aging, cold-flow evaluation, seal compatibility, corrosion assessment, and actual machinery endurance trials. Long-duration testing in power tillers, small pumps, cutter mechanisms, compact gear drives, and agricultural engines would be particularly valuable.

The strongest evidence would connect reduced laboratory wear with measurable component-life extension, stable oil condition, reliable starting performance, acceptable maintenance intervals, and reduced environmental impact. Under these conditions, bio-based lubricants can develop from promising renewable fluids into application-specific engineering lubricants capable of protecting both machinery components and environmentally sensitive operating environments.

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