

Pyrolysis-derived algal oil: A sustainable and high-performance green bio-lubricant

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Lubricating oils are essential in the mechanical industry, but their petroleum-based origin raises increasing environmental concerns. Bio-based lubricants offer a potential solution, provided they can achieve comparable performance and cost-competitiveness with conventional mineral-based and synthetic lubricants. Therefore, this study investigated the performance, biodegradability, and toxicity of pyrolysis-derived algal oil as a sustainable and environmentally friendly alternative to traditional lubricating oils. The pyrolytic algal-based lubricating oil exhibited a flash point of 273°C, indicating a reduced fire hazard, and a pour point of -15°C, suggesting suitability for low-temperature applications. The key advantages of this algal lubricating oil are its high biodegradability and low toxicity. It also demonstrated 85% degradation within 28 days. Toxicity levels have been assessed using both aquatic organisms and soil microbes. This algal lubricating oil is found to have low toxicity, with LC₅₀ values of 125 mg/L for *Daphnia magna* and 150 mg/L for *Danio rerio*. Furthermore, the results showed that this algal lubricating oil enhanced soil microbial activity by 10%. The impact on plant life was assessed by monitoring germination and growth. A 90% germination rate is recorded, and subsequent plant growth is positive, with an observed biomass increase of up to 85%. Spill recovery tests demonstrated high recovery efficiencies of 85% in water and 80% in soil. The findings of this study support the use of pyrolysis-derived algal oil as a sustainable alternative to traditional lubricants.

Keywords: Biodegradability, Biomass, Lubricant, Renewable, Toxicity

Introduction

The global industrial lubricant market is estimated to be valued at approximately USD 42.8 billion in 2024 and projected to reach around USD 65.5 billion by 2033. This growing demand for lubricants leads to a Compound Annual Growth Rate (CAGR) of 5.1% from 2025 to 2033¹. As the lubricant plays a vital role in reducing friction, wear, and tear of machinery, it eventually enhances the efficiency of the process and life of the equipment. With increasing demand the supply increases, raises the focus on environmental impact as the current demand is fulfilled by petroleum-based lubricants. This concern is not only limited to human health but also market growth². Thus, the rising focus on predictive maintenance and automation created an opportunity and need for the market to develop lubricants which can address the challenge of replacing non-degradable and polluting petroleum-based lubricants, causing direct harm to ecosystems and wildlife^{3,4}.

The lubricants are made up of two parts; base stock oil and additives. There are three types of lubricant base stocks: petroleum or mineral based, synthetic and biobased⁵. Currently, around 85-90% of the lubricants are produced from petroleum-based base oils. These lubricants are made from crude oil that are refined and processed to extract the desired lubricating properties. However, the production of petroleum-based lubricants relies on limited petroleum resources impacting their long-term viability and environmental impact⁶. On the other hand, biobased are the ones which are derived from renewable plants or animal sources. Thus, biobased lubricants are formulated with renewable and biodegradable base stock leading to usage of feedstock with high fatty acid content, renewability, biodegradability and easy availability, as a source for biobased lubricant⁷.

To address this demand, Algae offers a promising source of biobased lubricant base stock. As the

amount of oil produced by algae per unit area is reported to be significantly higher, up to 100 times, than that of other bio-oil feedstocks^{8,9}. Algal biomass is considered as a new alternative source for bio-oil production. Algae are a flexible source as they can grow in a variety of environments, including freshwater, saltwater, and even wastewater¹⁰. During the oil production process, two methods are adopted. The first method is lipid extraction from algae. In this process, algal species are cultivated and harvested, lipids are extracted using techniques such as Soxhlet, Folch, and Bligh-Dyer method¹¹. The yield of the extracted algal lipid depends upon the algal species, pretreatment strategy of algal biomass and the extraction method employed¹². The other method is pyrolysis, in which the algal biomass is harvested, dried and thermally decomposed anaerobically. The product of the pyrolysis is bio-oil, syngas and biochar¹³. The yield of the bio-oil depends on the reactor conditions (temperature, heating rate, heating time) and biomass characteristics. Hence, the type of algae, the culture medium, and the extraction techniques influence the quality of bio-oil. Characteristically, presence of unsaturated fatty acid content is a common characteristic of algal oil, which is beneficial for various bio-oil applications making algal oil a sensible and environment friendly substitute for biobased lubricants^{14,15}.

The present study is focused on examining the potential of pyrolytic algal oil as a sustainable alternative to petroleum-based lubricants. Hence, the algal lubricant oil is referred to as algal oil in this study. To achieve this objective, algal oil was produced via pyrolysis of algal biomass in pre-optimized environmental conditions. The performance in terms of flash point, pour point and thermal stability were analyzed. This analysis provided insights into the change in behaviour of algal oil with temperature. The environment impact was assessed based on algal oils' biodegradability assessment, aquatic and soil toxicity assessment, impact on soil microbial activity, plant germination and growth test. Lastly, cleanup studies were conducted to assess the removal efficiency of algal oil in both aquatic and terrestrial environments.

Experimental Section

Algal oil

Pyrolytic reactor at Indian Institute of Technology Guwahati, Assam was used for pyrolysis. To obtain

algal oil, 30 g of algal biomass was used in each run. The experiment was carried out at 650°C for 180 min with a heating rate of 35°C per min. The resulting oil was kept at room temperature (25±2 °C) for analysis after the vapours were collected using a condenser.

Performance Testing

Flash point and pour point

The flash point of algal oil was determined using ASTM D93 (Pensky-Martens Closed Tester). The sample was heated gradually at the rate of 5°C per min. The temperature was recorded at which the flash was observed.

The pour point was determined using the standard reference ASTM D97. The oil sample, filled in a jar, was placed in a cooling bath with a controlled rate of 1°C per min. The flow of the oil was observed periodically. The temperature at which oil ceased the flow was recorded and 3°C was added to the recorded temperature to obtain pour point.

Thermal stability analysis

The thermogravimetric analyzer (TG 209 F1 Libra, Netzsch, Germany) was used to conduct this experiment. The temperature range selected was 25°C to 350°C with a heating rate of 10°C per min. The oxygen-free environment was maintained using nitrogen gas at a rate of 60 mL per min. The weight loss as a function of temperature was recorded. The residual weight was calculated to estimate ash or char content.

Residual analysis

After the degradation, the nonvolatile and degraded fragments of algal oil were collected. The sample was cooled at room temperature. The nonvolatile component was then transferred from reaction vessel using solvent (acetone) rinsing. The solvent was then filtered, and filtrate was evaporated at 60°C using rotary evaporator. The residue yield was calculated using the Eq. (1) as follows:

$$\text{Residue yield (\%)} = \left(\frac{\text{Mass of residue collected}}{\text{Initial mass of algal oil}} \right) \times 100 \quad \dots (1)$$

Biodegradability Assessment

OECD 301 tests for aerobic biodegradability

Algal oil was subjected to OECD 301 guidelines, involving aerobic biodegradation testing under controlled laboratory conditions at a temperature 25±2°C, with constant stirring (25 RPM). The mineral medium was prepared using the constituents:

KH_2PO_4 , $\text{Na}_2\text{HPO}_4 \cdot 2\text{H}_2\text{O}$, NH_4Cl , $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, CaCl_2 , $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, with pH adjusted to 7.4 ± 0.2 . Samples were placed in microbial-rich environments, activated sludge and soil, and monitored for carbon dioxide evolution and oxygen consumption, or dissolved organic carbon removal.

For Dissolved Organic Carbon (DOC) reduction (OECD 301A/E), DOC was measured periodically using Total Organic Analyser (TOC) analyzer (Aurora 1030 C, O.I. Analytical, USA). For CO_2 evolution (OECD 301B), the CO_2 was trapped in NaOH solution and calculated by periodic titration. The percentage of biodegradation was calculated by the substrate biodegradation achieved within 28 days.

Aquatic and Soil Toxicity Test

Aquatic toxicity tests (LC₅₀ for Fish and Daphnia)

To determine the aquatic toxicity, lethal concentration (LC₅₀) test was performed. LC₅₀ test helped in determining the concentration of algal oil required to cause mortality in 50% of test organisms within a specific timeframe. Fish (Zebrafish-*Danio rerio*) and aquatic invertebrates (*Daphnia-Daphnia magna*) were used as model organisms for these tests. The test involved exposing the organisms to defined concentrations of algal oil (1:10 v/v) emulsified in water (water accommodated fractions -WAFs) under controlled laboratory conditions. The dissolved oxygen levels were maintained >60% of saturation (5 mg/L at 25°C), the aeration source used was oil-free air pump and flow rate was kept at 50 mL/min. Mortality rates were recorded, and the LC₅₀ value was calculated to determine the oil toxicity. The test volume was set at 1 L per fish (maintaining a density of one fish per liter), and the duration was 96 h. The mortality was recorded at 24, 48, 72 and 96 h (for Zebrafish) and 24 and 48 h (for *Daphnia*). No feeding was provided during the exposure period. Control survival rates were ensured to meet OECD requirements, i.e. $\geq 90\%$ survival for Zebrafish and $\geq 90\%$ immobilization-free for *Daphnia*.

Soil toxicity test

Soil Microbial Activity Assays

Soil samples (50 g) were treated with different volumes of algal oil and mixed thoroughly. The soil containers were placed with small vials containing 10 mL of 0.05 M NaOH in an airtight jar. These jars were sealed and incubated at $25 \pm 2^\circ\text{C}$ for a period of 28 days. The trapped CO_2 were calculated using the

titration method (0.1 M HCl with phenolphthalein as an indicator), at a regular interval of 7 days.

Plant germination and growth tests

Long-term toxicity was assessed using plant germination and growth tests. Seeds of common crops, i.e. wheat (present study), were planted in soil treated with varying concentrations of algal oil (1%, 5%, and 10% w/v) dissolved/emulsified in water. The moisture loss was prevented by covering the dishes. The seeds were incubated at $25 \pm 2^\circ\text{C}$ in a controlled environment chamber. The growth was monitored regularly for 14 days. The numbers of germinated seeds were monitored daily. Germination rate (%) and overall plant biomass were recorded at the end of the experiment.

Spill and cleanup studies

Spill and clean-up studies of algal oil were conducted to evaluate its behaviour, leak, spread and removal efficiency under controlled temperature $25 \pm 2^\circ\text{C}$, pH 7.2 ± 0.1 , and photoperiod of 14 h. Spills were simulated in two ecosystems: aquatic and terrestrial. For aquatic studies, 1 mL of algal oil was gently poured into 100 mL of water to simulate a spill. For terrestrial studies, a 1 cm deep soil bed was prepared, and 1 mL of oil was applied uniformly across the surface. Cleanup methods included sorption using natural sorbents (peat and sawdust), chemical dispersants, and bioremediation using oil-degrading microbial consortia. The effectiveness of each method was evaluated by measuring oil recovery gravimetrically.

Results and Discussion

Performance testing

Flash point and Pour point

The performance assessment revealed the superior attributes of algal oil-based lubricants compared to mineral oil-based and synthetic oil-based formulations. The algal oil-based lubricant exhibited a significantly elevated flash point of 273°C (Table 1), indicating enhanced resistance to degradation under high-temperature conditions or its superior resistance to ignition. This may be because of the presence of

Table 1 — Flash point and Pour point analysis of algal oil, mineral oil & synthetic oil

Physical Property	Algal Oil	Mineral Oil	Synthetic Oil
Flash Point ($^\circ\text{C}$)	273	145	255
Pour Point ($^\circ\text{C}$)	-15	-12	-30

triglycerides and long-chain fatty acids found in algal oil, which need more energy to volatilize and burn. Because of the risk of fire, high flash points are especially preferred in applications involving high temperatures, like lubricating engines or machinery. Vegetable oils with high flash points, such as canola and soybeans, have been shown to have comparable benefits and are utilized in lubrication systems that prioritize environmental sustainability but are edible in nature².

In contrast, synthetic oil's flash point of 255°C and mineral oil's 145°C suggest a greater risk of flammability. Additionally, the synthetic oil-based lubricant showed exceptionally low-temperature fluidity and cold-flow characteristics, with the lowest pour point at -30°C. In contrast to mineral oil, which had a pour point of -12°C, algae oil demonstrated superior cold-weather performance with a pour point of -15°C. The performance of algal oil at low temperatures is a characteristic of presence of semi-saturated fatty acids. These fatty acids are known to contain a single *cis* bond, which introduces a bend in the hydrocarbon chain. This bend reduces the molecular packaging efficiency, leading to lower pour point. As a result, algal oil remains fluid at low temperature and showed good cold flow properties. This property of algal oil makes it suitable for use in temperate regions and regions which experience seasonal temperature variations¹⁶. Bio-lubricants, derived from sunflower and rapeseed oils perform well in cold conditions due to the presence of natural esters and favourable unsaturated fatty acid profile¹⁷. But they are less preferred over algal oil as they are edible in nature.

Thermogravimetric analysis

By calculating the oils' weight loss, their thermal stability was assessed. The pyrolytic algal oil exhibited a clear multi-step degradation pattern as shown in Fig. 1. An initial weight loss in the range of 0–5% was observed from room temperature up to 150 °C, which can be due to the evaporation of residual moisture and light volatiles such as methanol, acetic acid and aldehydes. It was followed by the devolatilization phase occurring between 150–450 °C, during which the oil underwent the most significant thermal decomposition. This phase accounted for 70–80% of total weight loss, corresponded to the breakdown of medium-chain fatty acids (e.g., palmitic and oleic acids) and a wide range of oxygenated compounds, including alcohols, ketones, and phenolics.

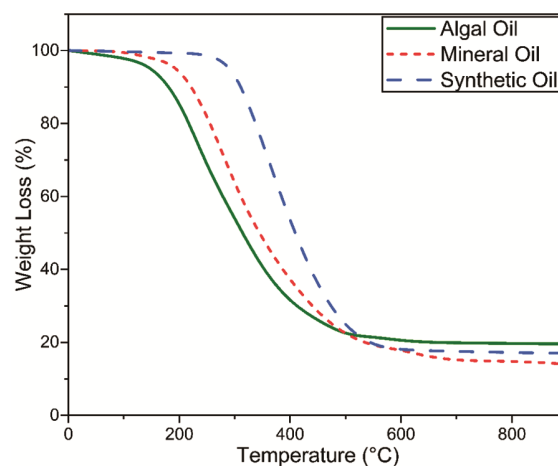


Fig. 1 — Thermogravimetric analysis of algal oil, mineral oil and synthetic oil

In comparison, mineral oil exhibited a single-stage thermal degradation beginning around 250°C and devolatilization occurred at 250–500°C. The weight loss occurred rapidly, with a final residue of approximately 18%. This indicated the presence of fewer volatiles and a more uniform hydrocarbon structure. Synthetic oil, on the other hand, demonstrated the highest thermal stability. Decomposition commenced at a much higher temperature i.e. 300°C. The oil retained a greater residual mass (~10%).

Residue analysis after thermogravimetric degradation provided valuable insight into the composition and thermal behaviour of non-volatile and thermally stable fraction. A 4.5% weight loss in algae oil indicated a moderate level of thermal stability. In contrast, mineral oil had a greater weight loss of 6.8%, which suggests that it is less thermally stable and more likely to degrade at higher temperatures. Synthetic oil showed the best thermal stability of all the samples, losing the least amount of weight (3.9%). Due to its triglyceride structure and the presence of antioxidants naturally present in algae, this performance demonstrates the thermal resistance of algal oil. Algal oils provide a fair compromise between operational endurance and environmental safety, even though synthetic oils are designed for maximum heat resistance. According to studies, bio-oils can be significantly improved in terms of their oxidative and thermal stability through chemical modifications such as epoxidation or transesterification. This makes them even more appropriate for high load applications¹⁸. Thus, algal oil-based lubricants offer a highly competitive, safer, and more sustainable alternative for most practical

applications, even though synthetic lubricants still have the advantage in harsh conditions.

Biodegradability Assessment

Over a 28-day period, the oil samples biodegradation was examined to determine the compatibility of samples with the environment. Algal oil showed exceptional environmental suitability with the biodegradation rate of 85% and quick decomposition in typical environmental conditions as shown in Fig. 2. The lowest biodegradation rate of 20% was shown in the case of mineral oil, indicating poor biodegradability and greater potential for long-term environmental persistence, whereas synthetic oil showed a moderate biodegradation of 65%, reflecting partial environmental acceptability. In comparison to conventional mineral and synthetic oils, these results highlight algal oil as a highly biodegradable and environment friendly lubricant base stock oil.

Algal oil is environmentally compatible and metabolically accessible to environmental microbes, as evidenced by its exceptional biodegradability, which was measured at 85% within 28 days. Because algal oil is primarily composed of unsaturated fatty acids such as oleic acid, linoleic acid, and palmitoleic

acid, it degrades rapidly. Their carbon-carbon double bonds are easily absorbed by microbial lipases and oxidases, so that these molecules can be rapidly incorporated into microbial metabolic pathways. Algal oil has a simpler and more bioavailable structure than mineral oils, which are primarily composed of saturated aliphatic and polycyclic aromatic hydrocarbons. Algal oil far exceeds ASTM and OECD standards for biodegradation. Substances are defined as “readily biodegradable” if they are more than 60% degraded within 28 days (OECD Guidelines 301B).

According to literature, oils with a higher degree of unsaturation are more biodegradable due to their higher affinity for microbial enzymes¹⁹. Microalgal oils have also been shown to be suitable for use in bioremediation both as substrates to support the activity of native microbial consortia in contaminated environments and as biodegradable fuels²⁰. Based on these results, the use of algal oil in lubricants represents a significant improvement over long-lived petroleum-derived products, reducing the environmental impact of accidental spills or improper disposal. The use of these biodegradable substitutes could significantly improve sustainability and regulatory compliance in sensitive areas such as forests, marine protected areas, and agricultural lands.

Aquatic and soil toxicity test

Aquatic toxicity

With LC₅₀ values of 125 mg/L and 150 mg/L, respectively, for the model organisms *Daphnia magna* and *Danio rerio*, the aquatic toxicity assessment showed (Fig. 3) that algal oil had comparatively low toxicity, which is also an essential property for any environmentally friendly lubricant. In contrast, the synthetic oil showed moderate toxicity, with LC₅₀ values of 100 mg/L and 120 mg/L for the respective species. The lowest LC₅₀ values for the mineral oil

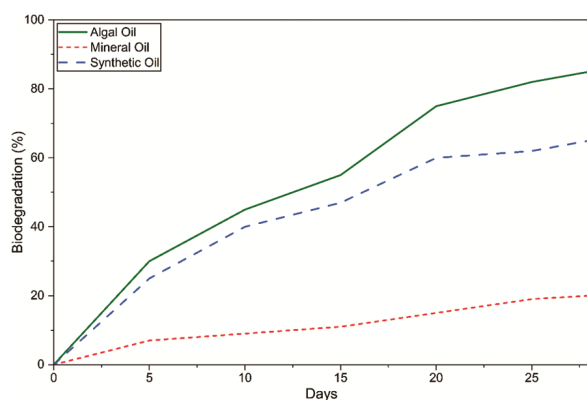


Fig. 2 — Biodegradability profiles of algal oil, mineral oil, and synthetic oil over time

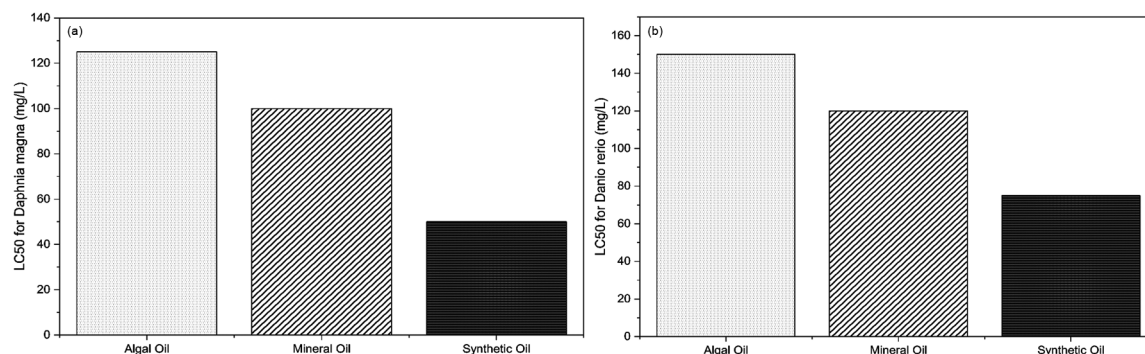


Fig. 3 — LC₅₀ analysis in (a) *Daphnia magna* and (b) *Danio rerio* exposed to algal oil, mineral oil & synthetic oil

were 50 mg/L for *Daphnia magna* and 75 mg/L for *Danio rerio*, indicating comparatively higher toxicity. These results confirm the potential of algal oil as a more environment friendly substitute and indicate that it is the least toxic among mineral oil and synthetic oil.

The main reason for this lower toxicity is the absence of sulfur compounds, heavy metals, and artificial additives often found in synthetic or petroleum-derived lubricants. These hazardous substances are known to have toxic effects on the physiology and reproductive systems of aquatic life. Examples of these substances are sulfur- and phosphorus-based anti-wear agents and zinc dialkyldithiophosphates (ZDDP). In contrast, the naturally occurring triglycerides and esters of algal oil are generally non-toxic and can be easily metabolized or excreted by living organisms.

Studies have shown that refined vegetable oils, such as soybean or linseed oil, have minimal negative effects on fish larvae and *crustaceans*²¹. Due to their similar lipid structures, algal oils also exhibit this profile. Algal oil also has a less intense exposure profile to aquatic organisms than viscous, surface-bound mineral oils because it disperses more evenly in water without creating stable emulsions. Because of these features, algal oil-based lubricants are safer for uses like hydropower systems, offshore drilling, and marine transportation where there is a chance of water contamination.

Soil microbial activity

Algal oil had a positive effect on soil health by increasing microbial activity in the soil by 10% as shown in Fig. 4. Mineral oil, on the other hand, showed a significant decrease of 25%, while synthetic oil showed a slight increase of 5%. Algal oil supports soil microorganisms that are essential for maintaining

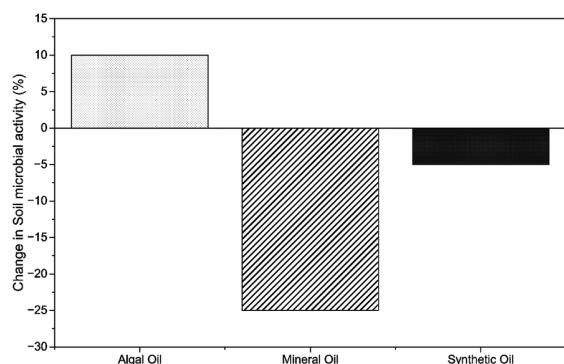


Fig. 4 — Comparison of soil microbial activity following exposure to algal oil, mineral oil, and synthetic oil

soil health and ecosystem function and can even promote their growth and diversity. In contrast, the application of mineral oil resulted in a significant decrease in soil microbial activity of 25%, indicating negative effects on soil biological communities.

The 10% increase in soil microbial activity after algal oil application indicates that algal oil and soil microbial communities are positively interacting. This is explained by the fact that algal oil serves as both a carbon-rich nutrient source and a biodegradable substrate. The utilization of triglycerides and fatty acids found in algal oil by heterotrophic soil microbes can enhance their metabolic diversity and enzymatic activity. Algal oil does not affect the gene expression of microorganisms or alter soil enzyme systems. Unlike mineral oils, which often inhibit microbial growth due to the presence of metal residues and saturated hydrocarbons, algal oil does not negatively affect the gene expression of microorganisms or alter soil enzyme systems.

Studies have confirmed that bio-lubricants made from natural oils can promote microbial respiration and the enzymatic degradation of organic matter²². Furthermore, algal oils do not physically clog the soil matrix, unlike heavier petroleum residues that can coat soil particles and impede the movement of water and oxygen. Benefits resulting from this increased microbial activity include increased soil fertility, improved decomposition of organic matter, and improved nutrient cycling. According to these results, algal oil is a lubricant that actively preserves the biological integrity of terrestrial ecosystems, preventing destructive impacts. It is especially useful for maintaining rural infrastructure and agricultural machinery.

Germination rate and plant biomass growth

The results of the germination experiment showed that seeds treated with algal oil had the highest germination rate of 90%, demonstrating its beneficial properties for plant growth. In contrast, seeds treated with synthetic oil had a germination rate of 85%, suggesting a positive effect on plant growth. However, the germination rate of seeds treated with mineral oil was much lower i.e., 70%, suggesting possible phytotoxicity and adverse effects on plant health, including reduced germination, delayed root and shoot growth, and reduced overall plant biomass and vigour.

Algal oil was found to significantly increase plant biomass growth, increasing it by 85% compared to

untreated control groups. This demonstrates the strong growth-promoting properties of algal oil and suggests that it can promote and facilitate the development of healthy plants. Mineral oil, on the other hand, resulted in a relatively moderate increase of 60%, while synthetic oil also had a positive impact on biomass growth, increasing it by 75%.

With a 90% germination rate and an 85% increase in biomass, algal oil has a positive effect on plant germination and biomass growth, demonstrating its suitability for terrestrial ecosystems, particularly agricultural ones. Compared to mineral oils, which are often attributed with reduced germination capacity and phytotoxic effects, this positive effect is in stark contrast. The non-phytotoxic profile of algal oil is primarily due to the absence of sulfur compounds, synthetic stabilizers, free amino acids, and harmful polycyclic aromatic hydrocarbons (PAHs). In addition, algal oil may contain bioactive substances or trace micronutrients that promote seed germination and early plant growth. For example, auxins and gibberellins are growth-promoting chemicals produced by certain algal strains that promote crop biomass accumulation and root growth²³.

Petroleum-based lubricants often cause ‘Chlorosis’, stunted root growth, and even seed death in contaminated soils because they generate oxidative stress and inadequate soil aeration. The use of biodegradable oils, for example sunflowers, soybean, and algae, has been shown in several studies to be beneficial or even improve plant health. It was reported that lubricating oils derived from castor oil and soybean showed improved soil aeration and less disruption of corn seed germination²⁴. This function is likely mimicked by algal oil, which also promotes beneficial microbial communities that indirectly contribute to plant growth. This oil is an excellent choice for bio-lubricants used in agricultural

machinery and irrigation systems because it can be applied around crops without affecting their yield or the environment. Notably, it is in line with the principles of sustainable agriculture and organic farming.

Spill and cleanup studies

Spill recovery efficiency (aquatic & soil)

The highest efficiency in removing oil spills from water source, was 85% for algae oil, compared to 75% for synthetic oil and only 65% for mineral oil as shown in Fig. 5. This increased recovery capacity of algae oil from water surfaces underlines its significant advantages over conventional lubricant formulations. The recovery rate of algal oil from soil was estimated as 80%. However, mineral oil showed the lowest efficiency, with a recovery rate of only 50%, while synthetic oil had a lower recovery rate of 70%.

In aquatic systems, algal oil’s relatively low surface tension facilitates dispersion and reduces the formation of thick, resistant slicks, unlike heavier mineral oils that tend to spread slowly and form stable emulsions that are hard to remediate. This characteristic enhances the efficiency of physical recovery methods like skimming or sorbent application. Moreover, due to its organic nature, algal oil supports the activity of indigenous oil-degrading microorganisms, which rapidly metabolize the oil into harmless byproducts such as carbon dioxide, water, and biomass²⁵.

Additionally, algal oil is more amenable to bioremediation strategies such as bioaugmentation (introducing oil-degrading microbes) or biostimulation (adding nutrients), further enhancing its cleanup potential. In terrestrial settings, natural sorbents like peat and sawdust have proven particularly effective at adsorbing algal oil spills due to its manageable viscosity and polarity. Compared to

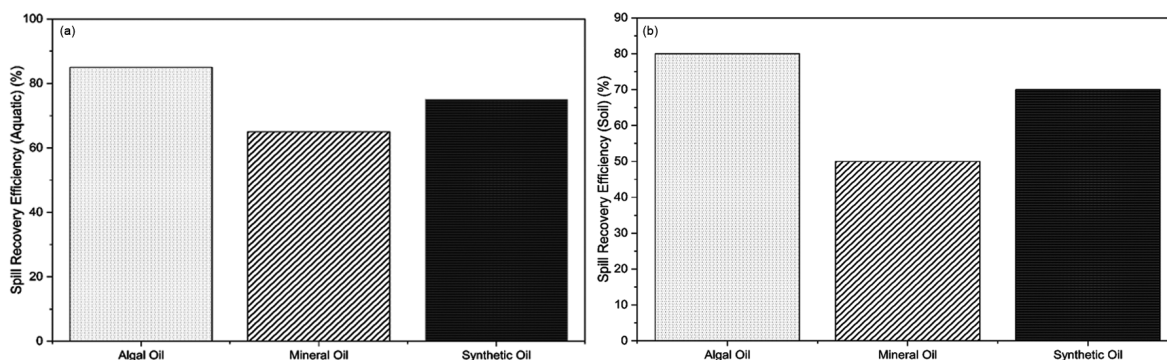


Fig. 5 — Comparison of spill recovery rates in (a) aquatic and (b) soil environments for algal oil, mineral oil, and synthetic oil

Table 2 — Comparative analysis of cleanup methods of algal oil in aquatic and terrestrial systems

Cleanup Method	Aquatic System (%)	Terrestrial System (%)
Peat (natural sorbent)	70	75
Sawdust (natural sorbent)	65	70
Chemical dispersant (SDS)	85	65
Microbial consortia	55	60

synthetic or mineral oils, which can persist in the environment for decades, algal oil offers a low-risk, high-recovery solution ideal for operations in environmentally sensitive zones, including ports, construction sites, and agricultural regions.

Cleanup studies

The efficiency of different cleanup techniques was measured gravimetrically after treatment with natural sorbents (Peat & Saw dust), chemical dispersants (Sodium Dodecyl Sulfate (SDS)) and microbial consortia. Each method was tested in both aquatic and terrestrial systems. The percentage recovery was calculated based on initial volume applied (1 mL), shown in Table 2.

Natural sorbents like peat and sawdust showed higher recovery in the terrestrial system, likely due to better physical contact and capillary absorption. Peat, with its high porosity and organic content, outperformed sawdust in both ecosystems²⁶. Chemical dispersants, SDS, was most effective in the aquatic system, where it quickly emulsified and dispersed the oil. This increased the availability of oil for breakdown²⁷. However, its performance was relatively lower in soil, potentially due to limited dispersion within the porous matrix and stronger oil-soil binding. On the other hand, Bioremediation using microbial consortia showed moderate effectiveness in both ecosystems²⁸. Oil-degrading bacteria gradually metabolized the algal oil, which was reflected in the slower, progressive reduction. While immediate recovery was lower compared to physical or chemical methods, this technique holds promise for long-term remediation with minimal ecological disruption.

Conclusion

This study comprehensively evaluated the potential of pyrolysis-derived algal oil as a sustainable and environmentally friendly bio-lubricant. The findings demonstrate that algal oil exhibits promising tribological properties, including a high flash point and good thermal stability, comparable and in

some respects superior to conventional mineral and synthetic oils. Notably, the research highlights the novelty of utilizing pyrolysis as a viable method for producing algal bio-oil for lubricant applications, an area not extensively explored in prior studies. The exceptional biodegradability of the algal oil, coupled with its significantly lower aquatic and soil toxicity compared to petroleum-based counterparts, underscores its green nature. Pyrolysis-derived algal oil demonstrates superior thermal stability (flash point: 273°C), low ecotoxicity (LC₅₀ > 125 mg/L), and 85% biodegradability, validating its potential as a sustainable lubricant. Furthermore, the positive impact on soil microbial activity and plant germination rates reinforces its environmental benefits. This investigation strongly supports the conclusion that pyrolysis-derived algal bio-oil represents a promising green alternative to conventional lubricants, paving the way for reduced environmental impact and greater sustainability in the lubricant industry.

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Conflict of interest

The authors declare no conflict of interest.

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