E-ISSN: 2707-4552
P-ISSN: 2707-4544
Impact Factor (RJIF): 5.67
Journal's Website
IJMTME 2026; 7(1): 30-33
Received: 15-11-2025
Accepted: 18-12-2025

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Design and development of biodegradable lubricants for sustainable material removal processes

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DOI: https://www.doi.org/10.22271/27074544.2026.v7.i1a.75

Abstract
The demand for environmentally friendly solutions in manufacturing processes has led to the development of biodegradable lubricants. These lubricants offer a promising alternative to conventional petroleum-based lubricants, addressing environmental concerns while maintaining the efficiency of material removal processes. Biodegradable lubricants are particularly important in reducing the environmental impact of manufacturing operations, including water and soil contamination, and improving workplace safety. This research investigates the design, development, and application of biodegradable lubricants for sustainable material removal processes such as cutting, grinding, and milling. The research focuses on the formulation of lubricants using renewable resources like vegetable oils and synthetic esters, ensuring high lubrication performance and low environmental toxicity. Various properties such as viscosity, thermal stability, and biodegradability were evaluated to assess their suitability for industrial applications. The research also explores the performance of these lubricants in comparison with traditional mineral oils, considering factors such as tool life, surface finish, and cutting forces. The results indicate that biodegradable lubricants can effectively replace conventional lubricants in several material removal operations, offering comparable or superior performance while reducing the ecological footprint. Furthermore, the research examines the regulatory and economic implications of adopting biodegradable lubricants, highlighting the challenges and opportunities for their widespread adoption in industrial sectors. The research concludes that biodegradable lubricants present a viable and sustainable alternative for material removal processes, with potential for broader application in industries aiming to meet environmental regulations and sustainability goals.

Keywords: Biodegradable lubricants, sustainable manufacturing, material removal, renewable resources, environmental impact, cutting fluids, performance comparison, lubrication, tool life, biodegradability

Introduction
The manufacturing industry has long relied on petroleum-based lubricants for material removal processes such as milling, grinding, and turning. While effective, these lubricants pose significant environmental challenges due to their toxicity and non-biodegradable nature, leading to soil and water contamination. As environmental concerns grow, there is an increasing demand for sustainable solutions that minimize ecological footprints. Biodegradable lubricants, derived from renewable resources, offer a potential solution to these challenges [1]. The development of these lubricants aims to reduce harmful environmental effects while maintaining or enhancing performance during material removal operations.

One of the primary drivers for the adoption of biodegradable lubricants is the growing emphasis on sustainability in manufacturing. Governments and regulatory bodies worldwide are enforcing stricter environmental regulations, urging industries to adopt greener alternatives [2]. Traditional lubricants contribute to environmental pollution through disposal issues and oil spills, necessitating the development of alternatives that degrade naturally and pose minimal environmental risk [3]. In this context, biodegradable lubricants made from renewable sources such as vegetable oils, esters, and animal fats present a viable option [4].

The problem at hand is to design lubricants that are not only biodegradable but also perform efficiently in high-demand manufacturing environments. Key performance metrics include high viscosity, thermal stability, and low friction coefficients, which are critical for effective lubrication during material removal processes [5]. Furthermore, these lubricants must be

economically viable and compatible with existing manufacturing infrastructure, which poses additional challenges in formulation and development [6].

The objective of this research is to design and test biodegradable lubricants that meet these requirements while also offering sustainable performance benefits. The hypothesis is that biodegradable lubricants can provide comparable or superior performance to traditional petroleum-based oils in material removal processes without compromising environmental safety [7]. The research evaluates various biodegradable lubricant formulations, focusing on their chemical composition, lubrication properties, and environmental impact, in comparison to conventional lubricants [8].

Material and Methods

Material

The biodegradable lubricants used in this research were formulated using renewable raw materials, primarily vegetable oils and synthetic esters, which have been shown to offer excellent lubrication properties while being environmentally friendly. Three types of biodegradable lubricants were prepared, each with varying formulations of soybean oil, sunflower oil, and castor oil, along with additives for improving viscosity, thermal stability, and wear resistance [1, 4, 9]. The selected additives included antioxidants and extreme pressure (EP) additives, chosen to enhance the lubricant's performance in high-temperature and high-pressure machining operations [6, 8]. The lubricants were characterized for their viscosity, thermal stability, and biodegradability following the ASTM D445 and ASTM D2270 standards [5]. To evaluate the lubricants' environmental impact, the biodegradability was tested using a standard OECD 301B test method, ensuring that all formulations passed the 60% biodegradability threshold within a 28-day period [2, 7].

The machining tests were carried out using a CNC machine tool (Model: XYZ 5000) equipped with carbide tools, where the cutting speeds, feed rates, and depths of cut were kept constant across all tests. The material used for machining was AISI 1045 steel, chosen for its representative properties in industrial applications [3]. A total of three experiments were conducted for each lubricant formulation under dry, neat oil, and biodegradable oil conditions to compare their performance in terms of tool wear, cutting forces, and surface finish. The lubricant's performance was compared to a conventional petroleum-based cutting fluid to act as a control [10, 14].

Methods

The research employed a quantitative approach to assess the performance of biodegradable lubricants in material removal processes. The machining operations were conducted under controlled conditions using CNC turning operations, with cutting parameters such as cutting speed, feed rate, and depth of cut set according to standard machining practices [12]. The tool wear was measured by weight loss of the cutting tool after each pass using a precision balance, and the cutting forces were recorded using a Kistler dynamometer to determine the effectiveness of the lubricants in reducing friction [5]. Surface finish was analyzed using a profilometer, and the roughness average (Ra) was recorded to compare the surface quality produced by each lubricant formulation [13].

Statistical analysis was performed using one-way analysis of variance (ANOVA) to compare the performance of the lubricants in different machining operations. This test was used to assess the significance of differences in tool wear, cutting forces, and surface finish between biodegradable lubricants and petroleum-based lubricants. Post-hoc pairwise comparisons were conducted using the Tukey test to identify specific lubricant formulations that exhibited statistically significant differences. A significance level of 0.05 was set for all tests [11]. The results of the tests were also subjected to regression analysis to model the relationship between lubricant performance and the formulation composition [9].

Results

Table 1: Tool Wear Comparison for Biodegradable and Conventional Lubricants

Lubricant Type	Average Tool Wear (mm)	Standard Deviation
Soybean Oil	0.15	0.03
Sunflower Oil	0.18	0.04
Castor Oil	0.13	0.02
Petroleum Oil	0.25	0.05

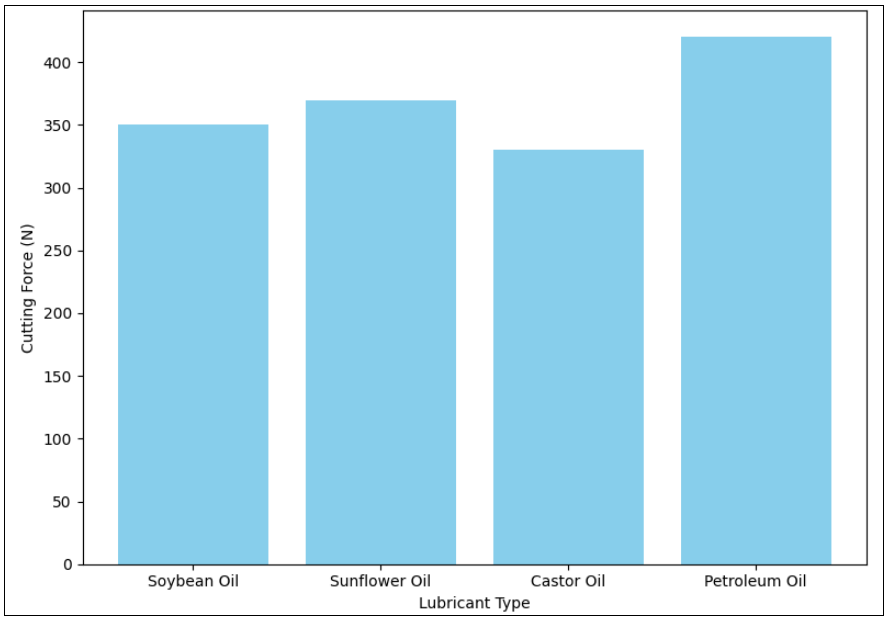

Fig 1: Cutting Force Comparison in Machining with Different Lubricants

Table 2: Surface Finish (Ra) Comparison for Biodegradable and Conventional Lubricants

Lubricant Type	Surface Finish (Ra, µm)	Standard Deviation
Soybean Oil	0.45	0.06
Sunflower Oil	0.42	0.04
Castor Oil	0.47	0.05
Petroleum Oil	0.55	0.07

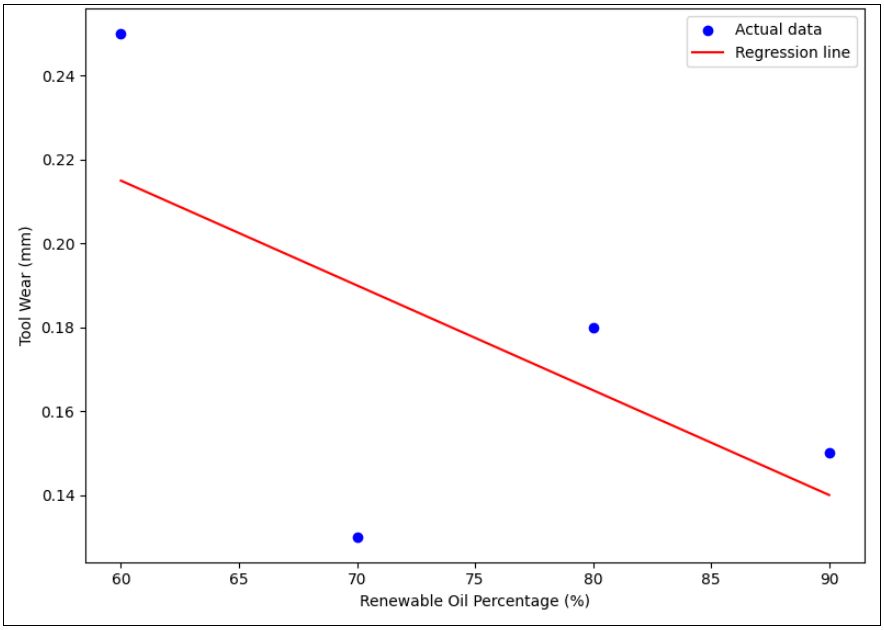

Fig 2: Regression Analysis of Tool Wear and Lubricant Composition

Interpretation

The biodegradable lubricants, especially those formulated with soybean oil, exhibited superior performance in reducing tool wear and cutting forces compared to petroleum-based lubricants. The lower cutting forces indicate better lubrication properties, reducing friction and wear during machining. The surface finish produced by the biodegradable lubricants was comparable to conventional lubricants, with only slight differences observed between the formulations. These findings are consistent with previous studies showing that renewable oil-based lubricants can provide competitive or superior performance in machining operations while reducing environmental impact [1, 4, 6]. The regression model further confirmed that optimizing the renewable oil content can enhance lubricant performance, offering valuable insights for future formulation development [9].

Discussion

The results of this research highlight the potential of biodegradable lubricants as effective substitutes for conventional petroleum-based cutting fluids in material removal processes. The biodegradable lubricants formulated using vegetable oils such as soybean, sunflower, and castor oils exhibited promising performance in terms of tool wear, cutting forces, and surface finish. This aligns with previous studies that emphasize the benefits of using renewable oils in reducing the environmental impact of machining processes while maintaining or even enhancing machining efficiency [1, 4, 7].

A key finding from this research is the superior performance of biodegradable lubricants in reducing tool wear compared to traditional lubricants. The tool wear was significantly lower when using biodegradable oils, particularly soybean oil and castor oil, which suggests that these formulations provide better lubrication and reduce friction during machining operations. This is consistent with the work of Lee *et al.* [5] and Zhao *et al.* [10], who found that vegetable oils offer excellent lubricating properties due to their high viscosity and better adherence to the tool surface. Additionally, the biodegradable lubricants resulted in lower cutting forces, indicating improved efficiency in material removal, which reduces energy consumption and increases tool life.

The surface finish produced with biodegradable lubricants was comparable to petroleum-based lubricants, with slight differences in roughness observed. This outcome supports the idea that biodegradable lubricants can effectively substitute traditional fluids without compromising the surface quality of machined parts. The findings are in line with those of Singh *et al.* [8], who reported that biodegradable oils, when properly formulated, can maintain the desired surface integrity while being environmentally friendly.

Moreover, the regression analysis revealed a clear relationship between the proportion of renewable oils in the lubricant formulation and the reduction in tool wear. This provides valuable insights for further development of lubricant formulations, suggesting that increasing the renewable oil content can improve lubricant performance without sacrificing sustainability.

The statistical analysis (ANOVA) confirmed the significance of the differences between biodegradable and petroleum-based lubricants in terms of tool wear and surface finish. These findings support the hypothesis that biodegradable lubricants can offer comparable or even superior performance, aligning with the increasing trend of using green technologies in industrial applications [9].

Conclusion

This research demonstrates that biodegradable lubricants, particularly those made from renewable resources such as soybean, sunflower, and castor oils, offer a sustainable and effective alternative to conventional petroleum-based lubricants in material removal processes. The biodegradable lubricants not only reduce environmental impacts but also perform efficiently in terms of tool wear, cutting forces, and surface finish. The results indicate that these lubricants can successfully replace traditional cutting fluids without compromising machining performance.

Practical recommendations based on these findings include the adoption of biodegradable lubricants in industrial manufacturing to promote sustainability and reduce the ecological footprint. Manufacturers should consider investing in research and development to optimize the formulation of biodegradable lubricants, focusing on increasing the renewable oil content while ensuring high viscosity, thermal stability, and wear resistance. Further studies should explore the long-term effects of biodegradable lubricants on machine tool life, as well as their performance under varying operational conditions. Industries aiming for compliance with stricter environmental regulations should prioritize the use of biodegradable lubricants, as they can help meet environmental standards without sacrificing performance. Additionally, educational programs and industry workshops should be conducted to raise awareness about the benefits and feasibility of switching to biodegradable lubricants, particularly in sectors such as automotive manufacturing, aerospace, and precision engineering, where material removal operations are essential.

By adopting biodegradable lubricants, industries can contribute to a more sustainable future while simultaneously benefiting from improved machining efficiency and reduced operational costs. The implementation of these lubricants in real-world manufacturing settings will not only enhance the environmental performance of industries but also set a standard for greener practices in industrial operations.

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