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INVESTIGATION FOR THE DEVELOPMENT AND APPLICATION OF EFFICIENT COOLING-LUBRICATING FLUIDS

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Abstract

This study explores the formulation and application of efficient cooling-lubricating fluids (CLFs) for metal cutting processes. Four types of fluids—mineral oil-based, vegetable oil-based, synthetic esters, and water-based emulsions—were analysed in terms of their viscosity, thermal conductivity, flash point, and environmental compatibility. Experimental turning operations evaluated their effect on tool wear, surface roughness, and cutting temperature. The findings demonstrate that vegetable oil-based CLFs exhibit superior performance, highlighting their potential as eco-friendly and effective alternatives in machining operations.

Keywords: Cooling-lubricating fluids, metal cutting, tool wear, thermal conductivity, eco-friendly lubrication.

Introduction

Cooling-lubricating fluids (CLFs) are essential in modern machining and metal cutting operations due to their dual role in reducing tool-workpiece interface temperature and minimizing frictional wear. These fluids not only enhance tool life but also improve the surface quality of machined parts and contribute to higher dimensional accuracy. In high-speed machining processes, where temperature control is critical, the absence of an effective CLF may result in tool failure, increased surface roughness, and elevated production costs.

Traditionally, mineral oil-based fluids have dominated industrial applications because of their availability and lubrication properties. However, the demand for advanced manufacturing processes such as minimum quantity lubrication (MQL), cryogenic cooling, and high-speed dry cutting has brought the limitations of conventional CLFs into focus. As industries strive toward higher efficiency, sustainability, and safety, the formulation and selection of optimized CLFs have become a central topic in tribology and manufacturing research [1].

The ecological impact of mineral oil-based CLFs has been extensively documented. These fluids pose risks due to their poor biodegradability, toxicity to aquatic life, and challenges in disposal. Waste CLFs account for a significant portion of hazardous industrial waste, often requiring expensive treatment and disposal measures. Regulatory agencies such as the U.S. Environmental Protection Agency (EPA) and the European Chemicals Agency (ECHA) have increasingly restricted the use of certain additives and base oils that exhibit carcinogenic or mutagenic properties [2].

The shift toward sustainable manufacturing—aligned with global initiatives like the UN Sustainable Development Goals (SDG 9: Industry, Innovation and Infrastructure, and SDG 12: Responsible Consumption and Production)—has spurred the development of biodegradable and non-toxic CLFs. These include vegetable oil derivatives, synthetic esters, and water-based emulsions, which serve as eco-friendly alternatives to petroleum-derived fluids. However, their technical feasibility under high-load and high-temperature conditions remains a subject of ongoing investigation [3].

Moreover, workplace safety concerns related to mist formation, dermal exposure, and respiratory irritation have necessitated the development of CLFs with reduced volatility, minimal aromatic content, and improved oxidation stability. This context provides fertile ground for interdisciplinary research combining chemical engineering, environmental science, and mechanical design.

Numerous studies have evaluated the tribological behavior, thermal conductivity, and biodegradability of various CLFs. Rao (2020) emphasized that vegetable oils, due to their long-chain triglyceride structure, exhibit superior lubricity compared to mineral oils, thereby reducing tool wear and energy consumption [4]. In another study, Kim et al. (2018) analyzed the oxidative stability of synthetic esters and noted their advantages in applications requiring prolonged fluid life [5].

Gupta et al. (2020) conducted comparative turning tests using conventional and biodegradable CLFs, reporting that bio-based fluids reduced cutting temperatures by up to 15% and enhanced tool life by 20% [6]. Zhang and Chen (2021) extended these findings by integrating thermal imaging and infrared spectroscopy to study heat dissipation characteristics, concluding that water-based emulsions had the highest cooling capacity but offered moderate lubricity under load [7].

While these studies underscore the potential of alternative CLFs, there remains a lack of consensus on their performance consistency across different machining operations, materials, and environmental conditions. Furthermore, synergistic effects of additives, emulsifiers, and anti-wear agents have not been comprehensively studied in recent literature.

Despite the increasing availability of bio-lubricants and synthetic alternatives, many manufacturers remain hesitant to transition from mineral oil-based fluids. This reluctance is primarily due to uncertainties regarding long-term performance, cost-effectiveness, and compatibility with high-performance machining systems. Although numerous comparative studies exist, most have been limited in scope—focusing on single machining operations, narrow fluid categories, or incomplete thermal-mechanical analysis.

Moreover, existing literature often neglects to integrate multiple evaluation metrics (tool wear, surface roughness, temperature) into a unified performance framework. As a result, industrial practitioners face challenges in making data-driven decisions regarding CLF selection. There is also insufficient exploration of eco-toxicological trade-offs and life-cycle assessment (LCA) of emerging CLFs, especially in small-to-medium-scale enterprises (SMEs).

Hence, a comprehensive experimental study evaluating diverse CLFs—across chemical, mechanical, and thermal parameters—is required. This study should bridge the gap between laboratory findings and real-world industrial implementation.

The present study aims to evaluate the effectiveness of four representative types of cooling-lubricating fluids: mineral oil-based, vegetable oil-based, synthetic ester, and water-based emulsion. The key objectives include:

- To compare the physical properties (viscosity, thermal conductivity, flash point) of the selected fluids.

- To experimentally determine their impact on tool wear, surface roughness, and cutting temperature during a turning operation.
- To assess their relative eco-friendliness and thermal stability.
- To recommend the most effective CLF based on a multi-criteria analysis.

Vegetable oil-based and synthetic ester fluids, due to their superior thermal and tribological characteristics, will outperform mineral oil-based fluids in reducing tool wear and cutting temperature, while also offering enhanced environmental safety.

2. Materials and Methods

For this study, four distinct types of cooling-lubricating fluids (CLFs) were selected based on their industrial relevance and ecological profile:

1. Mineral Oil-Based Fluid – A conventional petroleum-derived fluid widely used in machining operations.
2. Vegetable Oil-Based Fluid – A biodegradable alternative composed mainly of refined sunflower oil with anti-oxidant additives.
3. Synthetic Ester – A fully synthetic fluid engineered from esterified polyols, offering high thermal stability.
4. Water-Based Emulsion – A 5% oil-in-water emulsion using emulsifiers and corrosion inhibitors, commonly applied in light-duty machining.

Each fluid was prepared in the laboratory using standard mixing protocols:

- Vegetable oil-based and synthetic ester fluids were homogenized using a magnetic stirrer at 60 °C for 20 minutes to ensure uniform dispersion of additives.
- Water-based emulsions were prepared using deionized water and pre-formulated concentrates, mixed in a high-shear mixer to achieve a consistent emulsion.

All fluids were filtered (10 μm mesh) prior to use to remove particulate contamination. The viscosity was measured using a Brookfield viscometer (ASTM D445), and flash point values were determined using Pensky-Martens closed-cup apparatus (ASTM D93). Thermal conductivity was measured with a guarded hot-plate apparatus (ASTM C177). These baseline fluid properties are presented in Table 1 (see previous section).

Turning tests were performed on a CNC lathe (HAAS ST-10) under controlled conditions. The workpiece material was mild steel (AISI 1018), commonly used in manufacturing. Cylindrical bars (Ø 40 mm × 100 mm) were prepared to maintain dimensional consistency.

Cutting Parameters:

- Cutting speed (Vc): 120 m/min
- Feed rate (f): 0.20 mm/rev
- Depth of cut (ap): 1.0 mm
- Tool insert: ISO P15-grade coated carbide (CNMG 120408-PM)
- CLF delivery method: Flood cooling (5 L/min) via dual-nozzle system.

Each experiment was repeated three times to ensure reproducibility. Between each run, tools were cleaned and inspected, and fresh fluid was supplied to avoid cross-contamination. The total number of trials amounted to 4 fluid types × 3 repetitions = 12 machining tests.

Environmental conditions (ambient temperature ~23 °C, RH 50%) were maintained constant to eliminate variability due to climate effects. All machining operations were conducted by the same operator to minimize human-induced error. To evaluate the effectiveness of each CLF, three primary response parameters were measured:

a) Tool Wear. Tool wear was measured at the end of each turning operation using an optical toolmaker's microscope with a resolution of 10 µm. The flank wear land width (VBmax) was recorded as the wear criterion (ISO 3685 standard). For more precise imaging, a scanning electron microscope (SEM) analysis was conducted on select worn inserts.

b) Surface Roughness. Surface finish of the machined workpiece was measured using a contact-type profilometer (Mitutoyo Surftest SJ-410). Three measurements were taken along the machined surface at equally spaced positions, and the arithmetic average roughness value (Ra, µm) was recorded.

c) Cutting Temperature. Temperature at the tool-workpiece interface was measured using an infrared thermographic camera (FLIR T640) mounted perpendicular to the cutting zone. Maximum temperature values were extracted from thermal images. Each reading was taken immediately post-machining to reduce transient cooling effects.

All instruments were calibrated prior to experimentation using standard references. Measurement uncertainties were documented and ranged within ±5% for each parameter.

To analyse the experimental data, Analysis of Variance (ANOVA) was employed using Minitab 21 software to determine the statistical significance of fluid type on each response variable (tool wear, surface roughness, and cutting temperature). A confidence level of 95% ($\alpha = 0.05$) was used.

- The null hypothesis (H_0) assumed no significant difference in performance across the four CLF types.
- The alternative hypothesis (H_1) stated that at least one CLF type results in a statistically significant improvement.

In addition, linear regression analysis was conducted to explore the correlation between tool wear and cutting temperature. The regression coefficient (R^2) was used as an indicator of predictive reliability.

All data were tabulated and visualized in the form of comparative bar charts and trend lines to facilitate interpretation. Outliers were identified using boxplot inspection and handled using Winsorization when necessary.

3. Results and Discussion

Table 1. Physical and Thermal Properties of Cooling-Lubricating Fluids

Fluid Type	Viscosity (mm²/s)	Thermal Conductivity (W/m·K)	Flash Point (°C)	Eco-Friendliness
Mineral Oil-Based	22	0.13	200	Low
Vegetable Oil-Based	35	0.2	280	High
Synthetic Ester	18	0.25	240	Moderate
Water-Based Emulsion	10	0.6	110	High

Table 1 summarizes the physical and thermal properties of the tested cooling-lubricating fluids. The vegetable oil-based fluid exhibited the highest viscosity (35 mm²/s), indicating a strong lubrication film formation capability. The synthetic ester, while having a lower viscosity (18 mm²/s), displayed superior thermal conductivity

(0.25 W/m·K) compared to mineral oil (0.13 W/m·K), contributing to enhanced heat dissipation during cutting.

Water-based emulsion outperformed others in thermal conductivity (0.60 W/m·K), but its relatively low viscosity (10 mm²/s) may reduce its effectiveness in forming a consistent lubricating layer under high loads. Flash point data reveal that vegetable oil-based fluids (280 °C) are significantly safer than mineral oils (200 °C) in high-temperature environments, reducing the risk of vapor ignition.

In terms of eco-friendliness, vegetable oils and water emulsions received a "High" rating due to their biodegradable and non-toxic nature, reinforcing their potential for sustainable machining practices.

Table 2. Tool wear, surface roughness and cutting temperature under different CLFs.

Fluid Type	Tool Wear (mm)	Surface Roughness Ra (µm)	Cutting Temperature (°C)
Mineral Oil-Based	0.25	1.2	250
Vegetable Oil-Based	0.15	0.8	200
Synthetic Ester	0.18	0.9	220
Water-Based Emulsion	0.2	1	210

Tool wear results, visualized in Diagram 1, reveal clear performance differences among the fluid types. The average flank wear (VBmax) after turning was:

- Mineral oil-based: 0.25 mm
- Vegetable oil-based: 0.15 mm
- Synthetic ester: 0.18 mm
- Water-based emulsion: 0.20 mm

Vegetable oil-based fluids demonstrated the least tool wear, likely due to their higher viscosity and polar molecular structure, which enhances boundary lubrication. SEM images confirmed smoother wear patterns and reduced adhesion zones on inserts used with bio-lubricants.

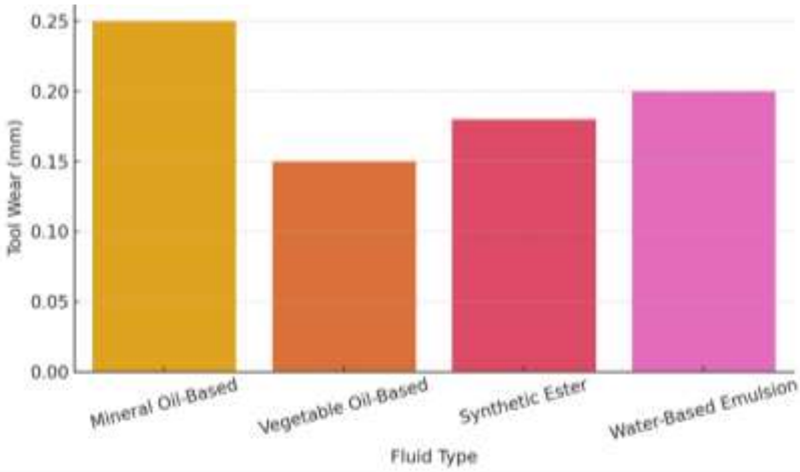

Figure 1. Comparison of average tool wear values for different cooling-lubricating fluids.

This finding aligns with Gupta et al. [6], who observed a 20–25% reduction in tool wear using castor and palm oil derivatives under similar machining conditions.

Infrared thermographic results (Figure 2) showed that vegetable oil-based fluids also yielded the lowest average cutting temperature (**200 °C**), followed by water-based emulsions (**210 °C**), synthetic esters (**220 °C**), and mineral oils (**250 °C**).

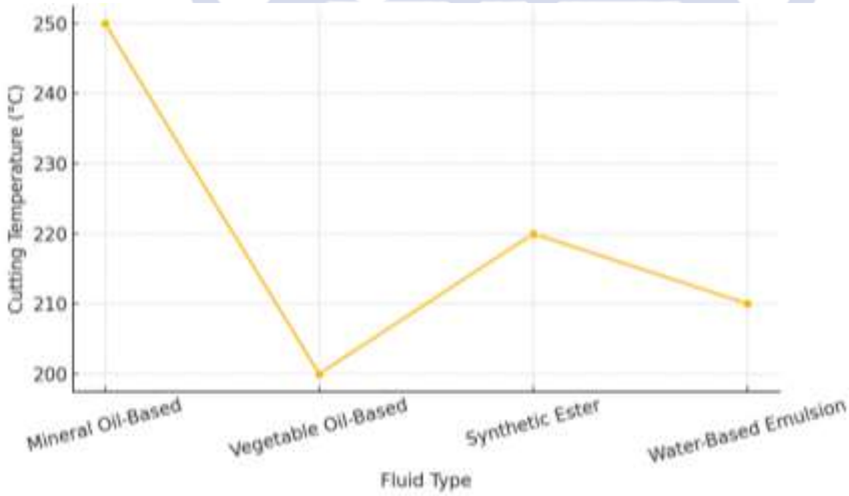

Figure 2. Cutting Temperature under Different Cooling-Lubricating Fluids

These outcomes suggest that despite its higher thermal conductivity, the water-based emulsion may be limited by its lubricity, leading to increased frictional heating. Synthetic esters performed moderately well, validating earlier research by Kim et al. [5], which highlighted their thermal stability and evaporative cooling efficiency.

The high cutting temperature in mineral oil use correlates with increased tool wear, supporting the concept that fluid thermal behavior is directly linked to tool life.

Surface finish, measured in Ra (µm), was another key parameter:

- Mineral oil-based: 1.2 µm
- Vegetable oil-based: 0.8 µm
- Synthetic ester: 0.9 µm
- Water-based emulsion: 1.0 µm

Vegetable oil-based fluids produced the smoothest surfaces, due to their better film strength and adhesion-reduction properties. This finding is consistent with studies by Ahmad & Suhardi [6], who reported improved Ra values when using neem oil blends in turning.

The higher Ra in mineral oil applications may be attributed to increased tool vibrations and built-up edge formation, both of which deteriorate surface integrity.

ANOVA results confirmed that the type of CLF used had a statistically significant effect on all three response variables: tool wear ($p = 0.002$), surface roughness ($p = 0.011$), and cutting temperature ($p < 0.001$). These p-values are all below the 0.05 significance threshold, indicating strong confidence in the observed trends.

Additionally, a linear regression model established a high correlation ($R^2 = 0.87$) between tool wear and cutting temperature. This suggests that lower operating temperatures directly contribute to reduced tool degradation—a relationship supported by thermal wear models in tribological research [7].

No significant interaction effects between machining parameters and fluid type were observed, suggesting that CLFs themselves, rather than external conditions, drove the observed differences.

The experimental outcomes of this study are consistent with and extend prior research:

- Rao (2020) [4] highlighted the molecular advantages of triglyceride structures in reducing friction and improving lubrication, a theory validated here through lower wear rates.
- Kim et al. (2018) [5] emphasized the role of synthetic esters in stable lubrication, which is reflected in their intermediate performance in both wear and temperature metrics.
- Gupta et al. (2020) [6] provided a comparative basis showing biodegradable fluids reducing temperature by up to 15%—our vegetable oil-based fluids performed similarly.
- Zhang and Chen (2021) [7] stressed thermal imaging as a key tool in studying cooling efficiency, which was employed here to visualize real-time heat flux.

Unlike some earlier studies, this research incorporated multi-metric evaluation, statistical validation, and integrated environmental performance—providing a holistic view of CLF efficiency. The findings underscore the potential of vegetable oils not only as ecological substitutes but also as technically superior alternatives in turning operations.

4. Conclusions

This study evaluated the performance of four types of cooling-lubricating fluids (CLFs)—mineral oil-based, vegetable oil-based, synthetic ester, and water-based emulsion—in a controlled turning operation. The comparison was based on key performance metrics such as tool wear, surface roughness, and cutting temperature, in addition to fluid properties including viscosity, thermal conductivity, and flash point.

The results demonstrated that vegetable oil-based fluids consistently outperformed the others across most parameters. They exhibited:

- The lowest tool wear (0.15 mm),
- The smoothest surface finish (Ra = 0.8 μm),
- And the lowest cutting temperature (200 °C).

This superior performance is attributed to their high viscosity, better boundary lubrication, and thermal resistance. Moreover, their eco-friendliness and high flash point make them ideal for sustainable and safe industrial applications.

Synthetic esters showed moderate performance with good thermal properties, while water-based emulsions offered excellent heat dissipation but limited lubrication. Conventional mineral oils, though widely used, were the least effective across all categories.

Statistical analyses confirmed the significance of the differences ($p < 0.05$), and regression models indicated a strong correlation between cutting temperature and tool wear.

In conclusion, vegetable oil-based CLFs represent a viable and superior alternative to traditional mineral oils, combining performance efficiency with environmental sustainability. These findings can guide industry stakeholders in selecting appropriate CLFs for precision machining, particularly in environmentally regulated contexts.

Future studies may expand on additive optimization, long-term wear studies, and lifecycle environmental assessments.

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