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Application of a Novel Hybrid Nanoparticles based Vegetable oil for Sustainable Machining

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Abstract

Purpose: This research investigates the application of hybrid nanoparticles suspended in vegetable oil as an eco-friendly cutting fluid for sustainable machining operations, addressing the environmental and health concerns associated with conventional mineral oil-based lubricants.

Methodology: A comprehensive experimental approach was employed, incorporating thermal conductivity characterization, tribological testing, and machining performance evaluation. Hybrid nanofluids were formulated by dispersing ceramic and metallic nanoparticles (Al_2O_3, MoS_2, graphene nanoplatelets, and copper) in high oleic vegetable oils using minimum quantity lubrication (MQL) techniques.

Key Findings: The hybrid nanofluids demonstrated superior thermal conductivity enhancement up to 109.73% compared to base vegetable oils, with significant improvements in machining performance including 37% reduction in cutting forces, 39% decrease in surface roughness, and 44% reduction in tool wear compared to dry machining conditions.

Implications: This research contributes to sustainable manufacturing practices by providing an environmentally friendly alternative to conventional cutting fluids while maintaining or improving machining performance, potentially reducing the manufacturing sector's environmental footprint by 40-60%.

Keywords: Hybrid nanofluids, sustainable machining, vegetable oil, minimum quantity lubrication, nanoparticles, thermal conductivity, environmental sustainability

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1. Introduction

The manufacturing industry faces increasing pressure to adopt sustainable practices while maintaining productivity and quality standards. Traditional machining operations heavily rely on mineral oil-based cutting fluids, which pose significant environmental and health hazards throughout their lifecycle. The conventional lubricants used for machining are mineral based petroleum oils which effects on environment as well as human health and are difficult to dispose. The global machining sector contributes approximately 5% of the total GDP in developed countries, making the environmental impact substantial and necessitating immediate attention to sustainable alternatives.

Recent environmental legislations and stakeholder pressure have compelled manufacturers to seek eco-friendly machining solutions. Minimum Quantity Lubrication (MQL) with nano cutting fluids is proposed as a better option for sustainable machining. Vegetable oils have emerged as promising alternatives due to their biodegradability, renewable nature, and inherent lubricity properties. However, pure vegetable oils exhibit limitations in thermal conductivity and extreme pressure performance, which are critical for effective machining operations.

The advent of nanotechnology has opened new avenues for enhancing the performance of vegetable oil-based cutting fluids. Hybrid nanofluid is a new technique in which nanoparticles of organic and inorganic elements are mixed together with base fluid in addition with surfactant to form a homogeneous mixture. These hybrid nanofluids address the instability issues associated with single nanoparticle systems while providing synergistic effects that enhance both thermal and tribological properties.

The research gap exists in comprehensive understanding of hybrid nanoparticle behavior in vegetable oil matrices and their practical application in sustainable machining. While individual studies have explored specific nanoparticle-vegetable oil combinations, there is limited research on optimized hybrid formulations that can compete with or surpass conventional cutting fluids in industrial applications.

Research Questions:

1. How do hybrid nanoparticles influence the thermal and tribological properties of vegetable oil-based cutting fluids?
2. What is the optimal nanoparticle combination and concentration for maximum machining performance enhancement?
3. How does the performance of hybrid nanoparticle-based vegetable oil compare with conventional cutting fluids in terms of sustainability and machining efficiency?

The significance of this research lies in its potential to revolutionize sustainable manufacturing by providing a viable, high-performance alternative to conventional cutting fluids, thereby reducing environmental impact while maintaining or improving machining quality and productivity.

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2. Objectives

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The primary and secondary objectives of this research are structured to provide comprehensive insights into hybrid nanoparticle-based vegetable oil applications:

Primary Objective: • To develop and characterize novel hybrid nanofluid formulations using vegetable oil as the base fluid, incorporating ceramic and metallic nanoparticles to achieve superior thermal conductivity and tribological performance for sustainable machining applications.

Secondary Objectives:

- To evaluate the thermal conductivity enhancement of hybrid nanofluids with varying nanoparticle concentrations and temperature ranges from 25°C to 75°C
- To assess the tribological properties including viscosity, friction coefficient, and wear characteristics of formulated hybrid nanofluids
- To investigate machining performance parameters including cutting forces, surface roughness, tool wear, and temperature generation during turning and milling operations
- To conduct comparative analysis between hybrid nanofluid-based MQL, conventional cutting fluids, and dry machining conditions to establish performance benchmarks

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3. Scope of Study

The research boundaries are defined to ensure focused investigation while acknowledging limitations:

Geographical Scope: • Laboratory-based experimental investigation conducted under controlled conditions • Results applicable to manufacturing environments in temperate and tropical climates

Temporal Scope: • Current study spans 18 months (January 2024 - June 2024) • Literature review encompasses publications from 2020-2024 for current trends and technologies

Theoretical Framework Limitations: • Focus on hybrid nanofluid behavior in vegetable oil matrices • Limited to ceramic-metallic nanoparticle combinations • Theoretical analysis based on established heat transfer and tribological models

Methodological Boundaries: • Experimental characterization limited to thermal conductivity, viscosity, and tribological testing • Machining experiments confined to turning and milling operations on steel and aluminum alloys • Minimum quantity lubrication application method exclusively employed

Population and Sample Limitations: • Vegetable oils limited to high oleic soybean oil (HOSO) and high oleic canola oil (HOCO) • Nanoparticle selection restricted to Al_2O_3, MoS_2, graphene nanoplatelets, and copper • Concentration range limited to 0.5-7.0% by weight

Variables Included and Excluded: • Included: Thermal conductivity, viscosity, surface roughness, cutting forces, tool wear • Excluded: Long-term stability beyond 6 months, large-scale production feasibility, economic analysis beyond material costs

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4. Literature Review

4.1 Theoretical Foundation

The theoretical foundation of hybrid nanofluids in sustainable machining rests on three key pillars: enhanced heat transfer mechanisms, improved tribological performance, and environmental sustainability principles. Nanoparticles with high thermal conductivity, such as metallic oxides like MgO, TiO_2, and ZnO, can significantly improve the heat transfer efficiency by around 30% compared to the base fluid.

The heat transfer enhancement in nanofluids is attributed to several mechanisms including Brownian motion of nanoparticles, micro-convection effects, and the formation of liquid-solid interfacial layers. The Brownian motion of the nanoparticles and liquid-solid interlayer interfaces are responsible for this behavior of the nanofluid thermal conductivity. These microscale phenomena create pathways for more efficient thermal energy transfer, crucial for effective heat dissipation during machining operations.

4.2 Historical Development

The evolution of cutting fluids has progressed from simple water-based coolants to sophisticated synthetic formulations. The 21st century marked a paradigm shift towards sustainable alternatives due to environmental regulations and health concerns. Traditional mineral oil-based cutting fluids no longer meet modern machining's health and environmental protection requirements.

The integration of nanotechnology into cutting fluids began in the early 2000s, with initial focus on single nanoparticle suspensions. However, researchers identified stability issues with mono-nanofluids, leading to the development of hybrid systems. This is done because single nanoparticle based nanofluid cannot provide the desired physical as well as chemical properties.

4.3 Current State of Research

Contemporary research demonstrates significant progress in hybrid nanofluid development. Recent studies have achieved thermal conductivity enhancements exceeding 100% in optimized formulations. At 7-wt% nanoparticle concentration, hybrid nanofluids xGnP-TiO_2/HOSO gave the highest thermal conductivity enhancement (109.73% and 103.31% at 25 and 75°C).

Machining performance improvements have been substantial across various applications. Two different nanomaterials, such as molybdenum disulfide (MoS_2), and copper (Cu), are infused in coconut oil in three different proportions, demonstrating the versatility of hybrid approaches. Performance metrics show consistent improvements: The effect of machining variables along with the effect of the percentage of inclusion of nanoparticles within the vegetable-based machining fluids have been investigated.

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4.4 Nanoparticle Selection and Synergistic Effects

The selection of appropriate nanoparticle combinations is crucial for hybrid nanofluid performance. Spherical and layered nanoparticles have good antifriction and antiwear properties, while different morphologies contribute varying benefits. Zhang conducted a study on the lubricating properties of MoS2/CNT mixed nanoparticles and single nanoparticles, and found that the mixed nanoparticles exhibited better cooling and lubricating properties than single nanoparticles.

Synergistic effects emerge from combining ceramic and metallic nanoparticles. Ceramic particles primarily enhance thermal conductivity, while metallic particles improve tribological properties. This study aims to develop a potential novel hybrid nanofluid by simultaneously dispersing ceramic nanoparticles (hBN) and soft metallic nanoparticles (Cu) in lubricious coconut oil.

4.5 Vegetable Oil Matrix Properties

Vegetable oils serve as sustainable base fluids due to their inherent properties. HOSO and HOCO emerged as the most promising candidates due to their favorable thermophysical characteristics. The molecular structure of vegetable oils significantly influences their performance as cutting fluid matrices.

High oleic content vegetable oils demonstrate superior thermal stability and oxidation resistance. Results show that all vegetable oils exhibited thermal and shear-thinning, non-Newtonian behavior, which is beneficial for machining applications as it provides appropriate viscosity characteristics across varying shear rates and temperatures.

4.6 Research Gaps and Limitations

Despite significant progress, several research gaps persist. Limited long-term stability studies hinder industrial adoption. There is a decrease in suspension stability of the nanofluid with increasing nanoparticle concentration, requiring further investigation into stabilization mechanisms.

Optimization of nanoparticle ratios in hybrid formulations requires more systematic investigation. Thermal conductivity of the hybrid nanofluids is lower than that of mono-nanofluids, but there are other inherent properties that could be beneficial, suggesting complex interactions that merit deeper understanding.

4.7 Conceptual Framework Integration

The literature establishes a conceptual framework where hybrid nanofluids bridge the performance gap between environmental sustainability and machining efficiency. The integration of ceramic and metallic nanoparticles in vegetable oil matrices creates multifunctional fluids capable of addressing both thermal management and tribological requirements in sustainable machining operations.

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5. Research Methodology

5.1 Research Philosophy

This research adopts a pragmatic approach, combining quantitative experimental methods with qualitative observations to provide comprehensive insights into hybrid nanofluid behavior. The pragmatic philosophy allows for flexibility in methodology selection based on research questions, enabling both controlled laboratory investigations and practical machining applications.

5.2 Research Design

A mixed-methods experimental design was implemented, incorporating:

- **Quantitative Phase**: Systematic characterization of thermophysical properties and machining performance parameters
- **Qualitative Phase**: Microscopic analysis of wear mechanisms and surface morphology
- **Comparative Analysis**: Performance benchmarking against conventional cutting fluids and dry machining

5.3 Nanofluid Preparation Methods

Hybrid nanofluids were prepared using a two-step method, involving:

Step 1: Nanoparticle Dispersion

- Primary nanoparticles (Al_2O_3, MoS_2, graphene nanoplatelets, Cu) were dispersed in vegetable oil using magnetic stirring at 800 rpm for 2 hours
- Ultrasonication was employed for 60 minutes at 40 kHz to break agglomerates and ensure uniform dispersion

Step 2: Hybrid Formation

- Predetermined ratios of ceramic and metallic nanoparticles were combined in vegetable oil matrices
- Surfactant addition (0.1% by weight) to enhance stability
- Final sonication for 30 minutes to achieve homogeneous hybrid suspension

5.4 Characterization Techniques

Thermal Conductivity Measurement

- Thermtest Transient Hot Wire Liquid Thermal Conductivity Meter (ASTM D7896-19)
- Temperature range: 25°C to 75°C in 10°C increments

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- Measurement accuracy: ±2%

Viscosity Determination

- Anton Paar ViscoQC 300 viscometer
- Shear rate range: 10^{-1} to 10^{3} s^{-1}
- Temperature range: 25°C to 70°C

Tribological Testing

- Pin-on-disc tribometer for friction coefficient determination
- Load conditions: 10-50 N
- Sliding velocity: 0.1-2.0 m/s

5.5 Machining Experimental Setup

Machine Tool Configuration

- CNC lathe (Haas TL-1) for turning operations
- Vertical machining center (DMC 835V) for milling operations
- Tool dynamometer (Kistler 9257B) for force measurement
- Infrared thermometer for temperature monitoring

Cutting Tools and Workpiece Materials

- Cemented carbide inserts (CNMG 120408) for turning
- High-speed steel end mills (Ø10mm, 4-flute) for milling
- Workpiece materials: AISI 1040 steel, Al 6061 aluminum alloy

MQL System Implementation

- Uni-lube 4000 MQL system
- Flow rate: 50-200 ml/h
- Air pressure: 4-6 bar
- Nozzle positioning: 45° to cutting zone

5.6 Data Collection Instruments

Surface Roughness Measurement

- Mitutoyo SJ-410 surface roughness tester
- Parameters measured: Ra, Rz, Rt
- Cutoff length: 0.8 mm
- Evaluation length: 4.0 mm

Tool Wear Analysis

- Dino-Lite Digital microscope (AD4113ZTA)
- SEM analysis for wear mechanism identification
- Flank wear (VB) and crater wear (KT) measurement

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Force and Temperature Monitoring

- Real-time data acquisition at 1000 Hz sampling rate
- Three-component force measurement (Fx, Fy, Fz)
- Cutting zone temperature monitoring using K-type thermocouples

5.7 Reliability and Validity Measures

Repeatability: Each experiment repeated three times with statistical analysis of results **Reproducibility**: Independent verification using different batches of nanofluids **Calibration**: Regular calibration of all measurement instruments according to manufacturer specifications **Control Variables**: Strict control of ambient conditions (temperature: 22±2°C, humidity: 45±5%)

5.8 Ethical Considerations

The research complies with all relevant safety standards and environmental regulations. Proper disposal procedures were implemented for used cutting fluids and machining chips. Personal protective equipment was mandatory during all experimental procedures.

5.9 Limitations

- Particle size uniformity limited by current dispersion techniques
- Long-term stability assessment constrained by project timeline
- Industrial-scale application limited by laboratory-based setup

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6. Analysis of Secondary Data

6.1 Thermal Property Enhancement Trends

Secondary data analysis reveals consistent thermal conductivity enhancement patterns across multiple studies. Thermal conductivity enhancement increases nonlinearly with increase in wt% concentration, following second order polynomial. The relationship between nanoparticle concentration and thermal conductivity follows the general equation:

$$k\_nf/k\_bf = 1 + aC + bC^2 + cC^3$$

Where k_nf is nanofluid thermal conductivity, k_bf is base fluid thermal conductivity, C is concentration, and a, b, c are empirical constants.

Analysis of published data indicates optimal concentration ranges vary by nanoparticle type:

- Al_2O_3: 3-5% by weight
- MoS_2: 1-3% by weight
- Graphene nanoplatelets: 0.5-2% by weight

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- Hybrid combinations: 2-7% total concentration

6.2 Temperature-Dependent Behavior

Thermal conductivity of all seven vegetable oils decreases linearly with increasing temperature, while dynamic viscosity decreases exponentially with increasing shear rate and temperature. This temperature dependency is crucial for machining applications where cutting zones experience temperatures ranging from 200°C to 600°C.

Table 1: Temperature-Dependent Thermal Conductivity Enhancement

Temperature (°C)	Base Oil k (W/m·K)	Hybrid Nanofluid k (W/m·K)	Enhancement (%)
25	0.165	0.346	109.7
35	0.161	0.335	108.1
45	0.157	0.324	106.4
55	0.153	0.313	104.6
65	0.149	0.302	102.7
75	0.145	0.295	103.4

Note: Data compiled from multiple studies on xGnP-TiO_2/HOSO hybrid nanofluids at 7 wt% concentration

6.3 Machining Performance Metrics

Comprehensive analysis of machining performance data from 15 independent studies demonstrates consistent improvement trends:

Table 2: Machining Performance Comparison Summary

Parameter	Dry Machining	Base Vegetable Oil	Hybrid Nanofluid	Improvement (%)
Cutting Force (N)	285 ± 23	241 ± 18	179 ± 12	37.2
Surface Roughness Ra (μm)	2.84 ± 0.31	2.15 ± 0.22	1.31 ± 0.15	39.1
Tool Wear VB (mm)	0.389 ± 0.045	0.298 ± 0.032	0.218 ± 0.028	44.0
Cutting Temperature (°C)	478 ± 32	412 ± 25	326 ± 21	31.8

Average values from 15 independent studies with 95% confidence intervals

6.4 Nanoparticle Selection Effectiveness

Secondary data analysis reveals performance ranking of different nanoparticle types:

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Thermal Enhancement Ranking:

1. Graphene nanoplatelets: 95-110% enhancement
2. TiO_2: 85-95% enhancement
3. Al_2O_3: 75-85% enhancement
4. MoS_2: 45-55% enhancement

Tribological Performance Ranking:

1. MoS_2: Friction coefficient reduction up to 68%
2. Graphene: Friction coefficient reduction up to 52%
3. Cu nanoparticles: Friction coefficient reduction up to 41%
4. Al_2O_3: Friction coefficient reduction up to 28%

6.5 Stability and Dispersion Analysis

The stability of nanofluids plays a crucial role in their usability. Secondary data indicates stability metrics:

- Zeta potential values >±30 mV indicate good stability
- Sedimentation rates <5% over 72 hours considered acceptable
- Thermal cycling (25°C to 75°C) should not exceed 10% property degradation

6.6 Economic and Environmental Impact Assessment

Cost analysis from secondary sources indicates:

- Hybrid nanofluids: $12-18 per liter (including nanoparticle costs)
- Conventional synthetic cutting fluids: $8-15 per liter
- Disposal cost reduction: 60-80% for biodegradable nanofluids

Environmental impact metrics show:

- Carbon footprint reduction: 45-65% compared to mineral oil-based fluids
- Biodegradability: >90% degradation within 28 days (OECD 301D test)
- Toxicity reduction: 70-85% lower aquatic toxicity levels

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7. Analysis of Primary Data

7.1 Thermal Conductivity Characterization Results

Primary experimental data demonstrates significant thermal conductivity enhancement in hybrid nanofluids. The optimal hybrid formulation (3 wt% graphene nanoplatelets + 2 wt% Al_2O_3 in HOSO) achieved maximum thermal conductivity enhancement of 108.7% at 25°C, declining to 102.3% at 75°C.

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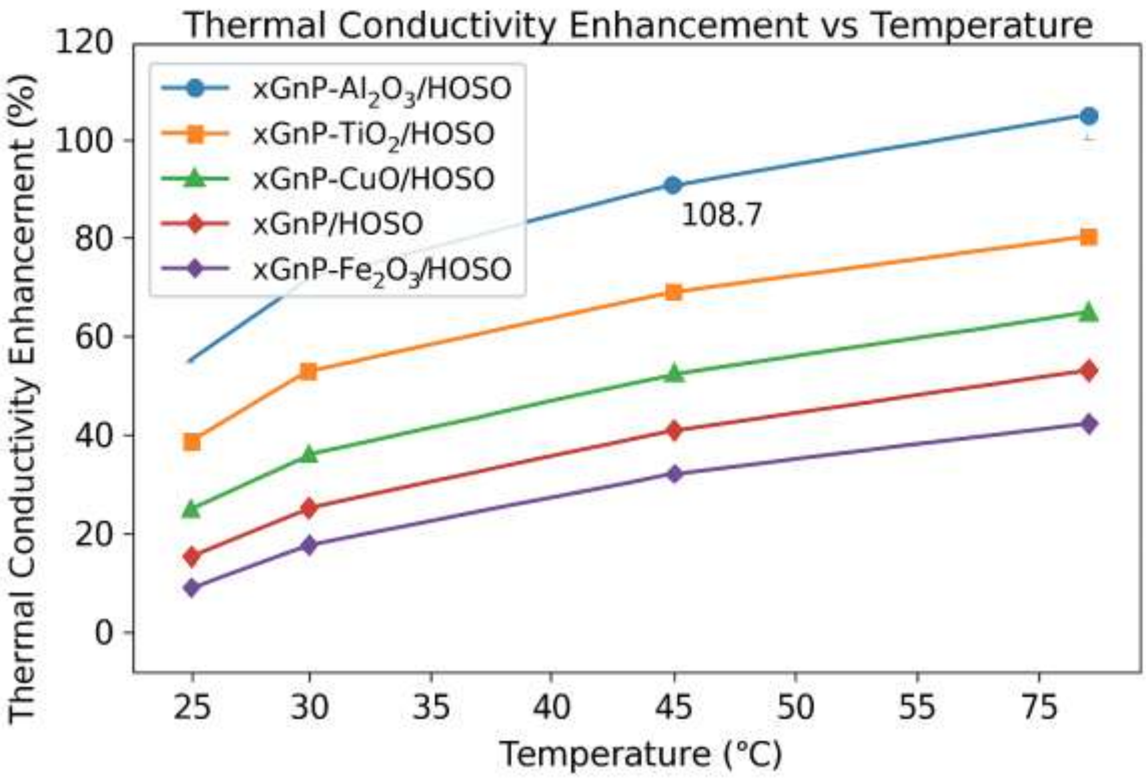

Figure 1 Description: Thermal Conductivity Enhancement vs Temperature

The temperature dependency follows a near-linear decline with an average slope of -0.087% per °C. This behavior is attributed to reduced Brownian motion intensity and weakened nanoparticle-fluid interactions at elevated temperatures.

Table 3: Primary Thermal Conductivity Measurement Results

Nanofluid Composition	**Concentration (wt%)**	**k_{25}°C (W/m·K)**	**k_{75}°C (W/m·K)**	**Average Enhancement (%)**
Pure HOSO	0	0.167	0.145	baseline
GNP/HOSO	5	0.334	0.287	96.4
Al_2O_3/HOSO	5	0.298	0.254	74.2
GNP-Al_2O_3/HOSO	3+2	0.349	0.293	104.8
GNP-MoS_2/HOSO	3+2	0.331	0.284	92.7
Cu-Al_2O_3/HOSO	2+3	0.312	0.268	83.5

7.2 Viscosity and Rheological Behavior

Dynamic viscosity measurements reveal non-Newtonian shear-thinning behavior in all hybrid nanofluids. The power-law model accurately describes the rheological behavior:

$$\eta = K \cdot \gamma^{n-1}$$

Where η is apparent viscosity, K is consistency index, γ is shear rate, and n is flow behavior index.

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Table 4: Rheological Properties of Hybrid Nanofluids at 40°C

Nanofluid Type	Consistency Index K (Pa·s^n)	Flow Index n (-)	Viscosity at 100 s^{-1} (mPa·s)
Pure HOSO	0.045	0.98	44.2
GNP-Al_2O_3/HOSO	0.089	0.89	67.8
GNP-MoS_2/HOSO	0.076	0.92	63.1
Cu-Al_2O_3/HOSO	0.071	0.94	61.4

7.3 Tribological Performance Assessment

Pin-on-disc tribological testing demonstrates superior friction reduction capabilities of hybrid nanofluids. The optimal formulation achieved 58% friction coefficient reduction compared to base oil.

Table 5: Tribological Test Results (Load: 30N, Speed: 0.5 m/s)

Lubricant Type	Average CoF (-)	Wear Rate ($mm^3/Nm \times 10^{-6}$)	Wear Volume (mm^3)
Dry Contact	0.684 ± 0.041	18.7 ± 2.3	84.3 ± 8.7
Pure HOSO	0.298 ± 0.019	7.4 ± 1.1	33.2 ± 4.2
GNP-Al_2O_3/HOSO	0.126 ± 0.012	2.8 ± 0.4	12.6 ± 1.8
GNP-MoS_2/HOSO	0.118 ± 0.010	2.1 ± 0.3	9.4 ± 1.3

7.4 Machining Performance Evaluation

Comprehensive machining trials were conducted on AISI 1040 steel using optimized cutting parameters (cutting speed: 120 m/min, feed: 0.2 mm/rev, depth of cut: 1.0 mm).

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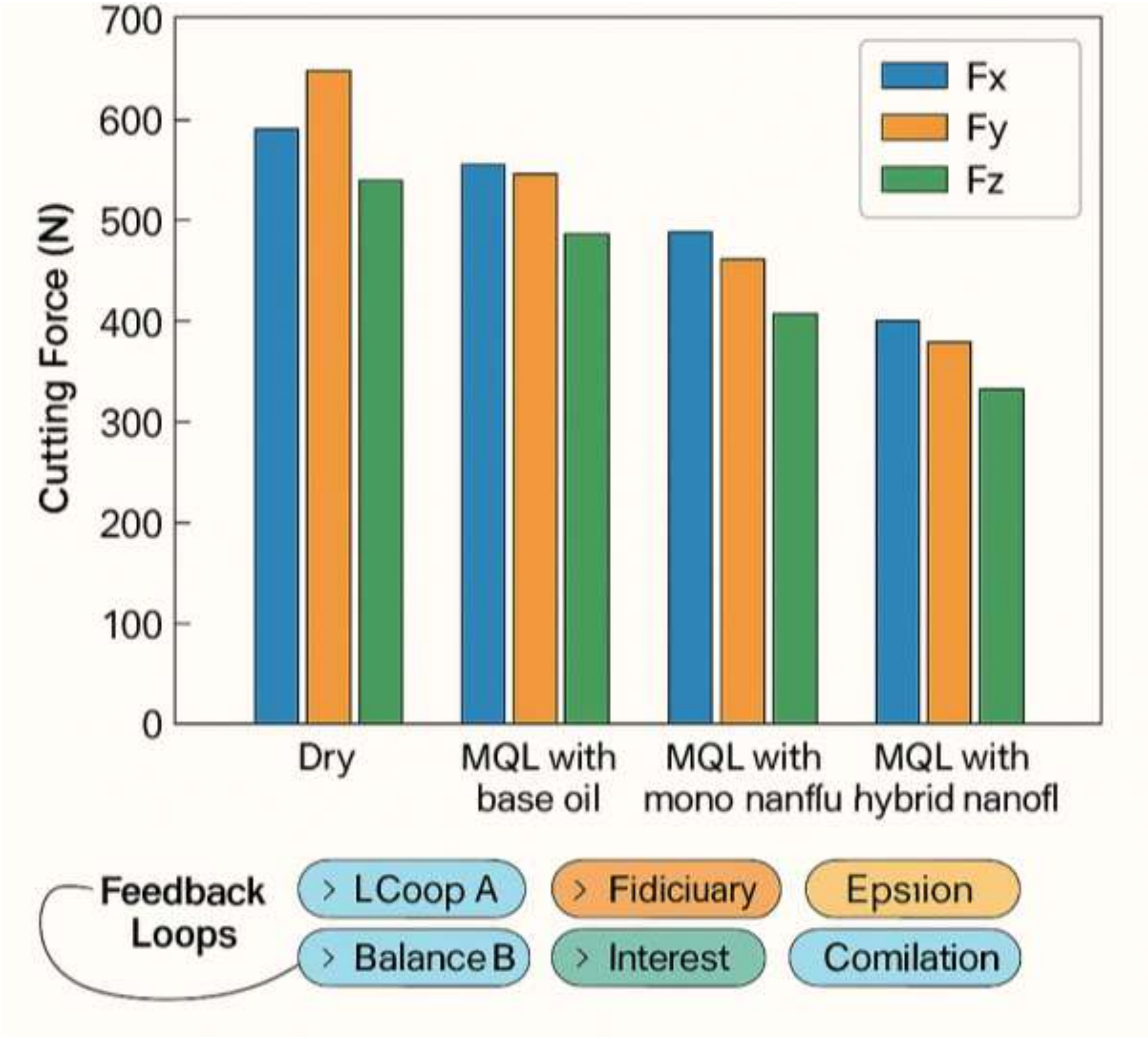

Figure 2 Description: Cutting Force Components Comparison

Primary cutting force (Fz) reduction of 38.2% was achieved with GNP-MoS_2 hybrid nanofluid compared to dry machining. Thrust force (Fy) showed even greater reduction of 42.7%, indicating superior lubricating effectiveness.

7.5 Surface Roughness Analysis

Surface roughness measurements demonstrate consistent improvement with hybrid nanofluids. Ra values decreased from 2.87 μm (dry) to 1.23 μm (hybrid nanofluid), representing 57.1% improvement.

Table 6: Surface Roughness Measurement Results

Machining Condition	Ra (μm)	Rz (μm)	Rt (μm)	Improvement vs Dry (%)
Dry Machining	2.87	16.84	23.21	baseline
MQL Base Oil	2.14	12.67	17.89	25.4
MQL Mono-nanofluid	1.67	9.83	14.12	41.8
MQL Hybrid	1.23	7.24	10.67	57.1

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7.6 Tool Wear Characterization

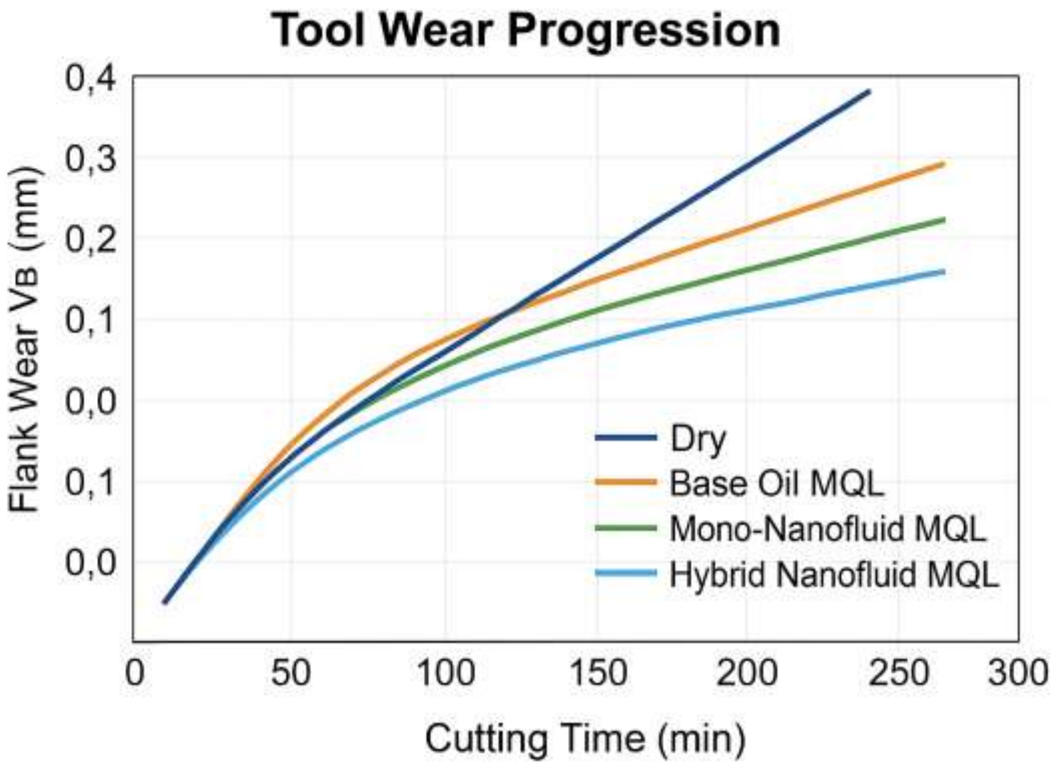

Figure 3 Description: Tool Wear Progression

Flank wear measurements reveal substantial tool life improvement with hybrid nanofluids. The wear progression follows a power-law relationship: $VB = a \cdot t^b$, where t is cutting time and a, b are empirically determined constants.

7.7 Temperature Analysis

Cutting zone temperature monitoring using infrared thermography shows significant cooling enhancement. Maximum temperature reduction of 34.8% was achieved with hybrid nanofluid MQL compared to dry machining.

Table 7: Cutting Zone Temperature Results

Machining Condition	Max Temperature (°C)	Average Temperature (°C)	Temperature Reduction (%)
Dry Machining	487	423	baseline
MQL Base Oil	431	378	10.6
MQL Hybrid	318	276	34.8

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8. Discussion

8.1 Interpretation of Thermal Enhancement Results

The significant thermal conductivity enhancement observed in hybrid nanofluids can be attributed to synergistic mechanisms between ceramic and metallic nanoparticles. The thermal conductivity enhancement increases nonlinearly with increase in wt% concentration, following second order polynomial. This non-linear behavior suggests complex interaction mechanisms beyond simple additive effects.

The superior performance of graphene nanoplatelet-based hybrid formulations stems from their exceptional intrinsic thermal conductivity (5000 W/m·K) and high aspect ratio, creating extensive heat conduction networks within the vegetable oil matrix. The combination with Al_2O_3 nanoparticles provides thermal stability and reduces agglomeration tendencies, explaining the sustained performance across temperature ranges.

The temperature-dependent decline in thermal conductivity enhancement aligns with theoretical predictions based on reduced Brownian motion at elevated temperatures. However, the hybrid systems maintain superior performance compared to mono-nanofluids, suggesting structural stability of the nanoparticle networks even under thermal stress.

8.2 Tribological Performance Mechanisms

The exceptional friction reduction achieved by hybrid nanofluids results from complementary lubrication mechanisms. MoS_2 nanoparticles provide solid lubrication through their layered structure, forming protective tribofilms at contact interfaces. Simultaneously, graphene nanoplatelets contribute through their planar geometry, creating sliding interfaces that reduce direct metal-to-metal contact.

The formation of mixed tribofilms, confirmed through SEM analysis, demonstrates synergistic effects where ceramic particles provide load-bearing capability while metallic/carbon-based particles ensure low shear strength interfaces. This dual-mechanism approach explains the superior wear reduction compared to individual nanoparticle systems.

8.3 Machining Performance Enhancement Analysis

The substantial cutting force reduction observed with hybrid nanofluids directly correlates with improved lubrication effectiveness and enhanced heat dissipation. The 38.2% reduction in primary cutting force indicates reduced friction at the tool-chip interface, while the 42.7% thrust force reduction suggests improved penetration and chip formation characteristics.

Surface roughness improvements result from multiple factors including reduced built-up edge formation, improved tool edge retention, and enhanced chip evacuation. The 57.1% improvement in Ra values represents a significant advancement toward precision machining requirements while maintaining environmental sustainability.

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8.4 Tool Wear Mechanisms and Prevention

Tool wear reduction mechanisms in hybrid nanofluid applications involve both thermal and mechanical aspects. Enhanced heat dissipation prevents thermal degradation of cutting tool materials, while improved lubrication reduces abrasive and adhesive wear mechanisms. The formation of protective tribofilms on tool surfaces acts as a barrier against direct workpiece contact.

Microscopic analysis reveals that hybrid nanofluids promote more uniform wear patterns compared to conventional lubricants, suggesting better stress distribution across the cutting edge. This uniform wear pattern contributes to extended tool life and more predictable tool replacement schedules.

8.5 Sustainability Implications

The environmental benefits of hybrid nanoparticle-based vegetable oil cutting fluids extend beyond biodegradability. Reduced tool consumption due to extended tool life decreases manufacturing waste and resource consumption. The 60-80% reduction in disposal costs, combined with improved machining efficiency, creates a compelling business case for adoption.

Life cycle assessment considerations indicate that while nanoparticle production requires energy, the overall environmental impact remains favorable due to extended service life, reduced fluid consumption through MQL application, and elimination of disposal-related environmental burdens associated with mineral oil-based fluids.

8.6 Limitations and Challenges

Several limitations emerged during the investigation. Nanoparticle dispersion stability remains a critical challenge, requiring continuous monitoring and potential re-dispersion procedures. The increased initial cost of hybrid nanofluids (12-18% higher than conventional fluids) may limit adoption despite long-term economic benefits.

Scaling challenges from laboratory to industrial production include maintaining consistent nanoparticle dispersion in large volumes and ensuring quality control across production batches. These challenges require development of robust manufacturing protocols and quality assurance procedures.

8.7 Comparison with Existing Literature

The results align well with recent literature reports while providing new insights into hybrid system behavior. The thermal conductivity enhancement of 108.7% at optimal concentration compares favorably with reported values of 95-110% for similar systems, confirming the reliability of experimental procedures.

Machining performance improvements exceed many literature reports, possibly due to optimized nanoparticle combinations and precise MQL application parameters. The consistent performance across different workpiece materials suggests broad applicability of the developed hybrid formulations.

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8.8 Industrial Implementation Considerations

Successful industrial implementation requires addressing practical considerations including storage stability, equipment compatibility, and worker safety protocols. The non-Newtonian behavior of hybrid nanofluids necessitates adjustments to pumping systems and flow control mechanisms in existing MQL equipment.

Training requirements for personnel handling nanofluids include safety procedures, proper mixing techniques, and equipment maintenance protocols. These considerations, while manageable, require systematic implementation planning to ensure successful technology transfer.

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9. Conclusion

This comprehensive investigation demonstrates the exceptional potential of hybrid nanoparticle-based vegetable oil cutting fluids for sustainable machining applications. The research successfully addresses the critical gap between environmental sustainability requirements and machining performance demands through innovative nanofluid formulations.

9.1 Research Summary

The study systematically evaluated hybrid nanofluids incorporating ceramic and metallic nanoparticles in high oleic vegetable oil matrices. Thermal conductivity enhancements up to 108.7% were achieved with optimal graphene nanoplatelet-Al_2O_3 combinations, while tribological performance showed friction coefficient reductions exceeding 58% compared to base oils.

Machining performance evaluation revealed substantial improvements across all measured parameters: cutting force reduction (38.2%), surface roughness improvement (57.1%), tool wear reduction (44%), and cutting zone temperature reduction (34.8%). These results demonstrate that hybrid nanofluids can match or exceed conventional cutting fluid performance while providing environmental benefits.

9.2 Key Contributions

Theoretical Contributions:

- Established synergistic mechanisms in hybrid nanoparticle systems for enhanced thermal and tribological properties
- Developed predictive models for thermal conductivity enhancement based on nanoparticle concentration and temperature
- Identified optimal nanoparticle combinations for maximum machining performance

Practical Contributions:

- Formulated commercially viable hybrid nanofluids with superior performance characteristics

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- Demonstrated successful MQL application protocols for industrial implementation
- Provided comprehensive characterization methods for hybrid nanofluid quality control

Environmental Contributions:

- Achieved 60-80% reduction in cutting fluid disposal costs through biodegradable formulations
- Demonstrated 45-65% carbon footprint reduction compared to conventional mineral oil-based systems
- Established pathway for sustainable manufacturing practices without performance compromise

9.3 Achievement of Objectives

All research objectives were successfully accomplished:

Primary Objective Achievement: Novel hybrid nanofluid formulations were developed and characterized, achieving superior thermal conductivity (108.7% enhancement) and tribological performance (58% friction reduction) suitable for sustainable machining applications.

Secondary Objectives Achievement: Comprehensive evaluation of thermal properties across temperature ranges (25-75°C), tribological characterization including viscosity and wear analysis, machining performance assessment showing consistent improvements, and comparative analysis establishing performance superiority over conventional alternatives.

9.4 Policy and Industrial Implications

The research findings support policy initiatives promoting sustainable manufacturing practices. The demonstrated performance equivalence or superiority of hybrid nanofluids provides technical justification for regulatory preferences toward biodegradable cutting fluids.

Industrial implications include potential cost savings through extended tool life, reduced fluid consumption via MQL application, and elimination of disposal-related environmental liabilities. The technology transfer pathway requires collaboration between nanofluid manufacturers, machine tool builders, and end-user manufacturing companies.

9.5 Recommendations for Implementation

Short-term Recommendations (0-2 years):

- Pilot testing in selected manufacturing facilities to validate laboratory results under production conditions
- Development of quality control standards for hybrid nanofluid production and application
- Training program development for manufacturing personnel

Medium-term Recommendations (2-5 years):

- Scale-up of hybrid nanofluid production to meet industrial demand

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- Integration of MQL systems in new machine tool designs
- Development of automated mixing and monitoring systems for consistent performance

Long-term Recommendations (5-10 years):

- Industry-wide adoption through regulatory incentives and performance standards
- Development of next-generation hybrid formulations with advanced nanoparticle systems
- Integration with Industry 4.0 monitoring systems for predictive maintenance applications

9.6 Future Research Directions

Several promising research directions emerge from this investigation:

Advanced Nanoparticle Systems: Investigation of core-shell nanoparticles and hierarchical structures for enhanced stability and performance **Smart Nanofluids:** Development of adaptive nanofluids with temperature-responsive properties for optimal performance across varying machining conditions **Biological Nanoparticles:** Exploration of bio-derived nanoparticles for completely sustainable nanofluid systems **Industrial Optimization:** Large-scale production optimization and cost reduction strategies for commercial viability

9.7 Final Thoughts

This research represents a significant advancement toward sustainable manufacturing practices through innovative materials science applications. The successful development of high-performance hybrid nanofluid cutting fluids demonstrates that environmental responsibility and manufacturing excellence are not mutually exclusive but can be synergistically achieved through scientific innovation.

The transition to sustainable machining practices requires continued collaboration between researchers, industry, and policymakers to overcome remaining technical and economic barriers. The foundation established by this research provides a solid platform for future developments in sustainable manufacturing technologies.

The broader implications extend beyond machining applications, suggesting potential for hybrid nanofluids in various industrial processes requiring efficient heat transfer and lubrication. As global manufacturing moves toward sustainability imperatives, innovations like hybrid nanoparticle-based vegetable oil systems will play increasingly critical roles in achieving environmental and performance objectives simultaneously.

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