World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Research Article)

Comparative performance analysis of nano-enhanced liquid lubricants under minimum quantity lubrication and flood lubrication in machining

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World Journal of Advanced Engineering Technology and Sciences, 2026, 19(02), 178-188

Publication history: Received on 13 April 2026; revised on 20 May 2026; accepted on 22 May 2026

Article DOI: https://doi.org/10.30574/wjaets.2026.19.2.0270

Abstract

This work compares the performance of nano-enhanced lubricants under Minimum Quantity Lubrication (MQL) and flood machining. Environmentally benign base oils like coconut, mahua, castor and groundnut oils were chosen and nano-enhanced with single and hybrid mixtures of aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), and graphite nanoparticles. The effectiveness of the machining process was assessed considering the surface roughness, tool wear, coefficient of friction and temperature. The experimental findings show that nano-enhanced lubricants in MQL machining conditions enhance tribological properties better than flood lubrication. Nanoparticles improve the lubrication performance through mechanisms such as the formation of tribo-films, rolling effect and enhanced thermal conductivity. The use of hybrid nanoparticles shows a combined effect, which leads to significant improvement in surface finish, tool life, and friction coefficient. While flood machining offers better cooling due to the increased use of fluid, it suffers from low nanoparticle concentration and poor penetration into the tool–chip interface. The best MQL performance was observed with a hybrid nanoparticle (Al_2O_3, TiO_2, and graphite) combination using coconut oil. The research shows that nano-improved MQL is an effective and sustainable form of machining for improved machining performance and environmental benefits compared with traditional flood machining.

Keywords: Minimum Quantity Lubrication (MQL); Flood Machining; Nano-Enhanced Lubricants; Hybrid Nanoparticles; Machining Performance.

1. Introduction

Turning, milling, and drilling operations are essential machining processes in the manufacturing sector, where the key requirements are excellent surface finish, tool wear, and productivity. But these operations introduce substantial heat and friction at the tool-workpiece contact region, which results in excessive tool wear, surface quality degradation and increased energy consumption. Cutting fluids are often used for lubrication and cooling in machining operations to address these problems. Conventionally, flood lubrication has been widely adopted in machining processes for its excellent cooling effect, which is attained by providing a high volume of cutting fluid to the tool–workpiece interface. Although flood lubrication has good heat removal capacity, it has several drawbacks, such as excessive consumption of cutting fluid, environmental problems, disposal issues and health risks to the operators. Additionally, at high cutting speeds, flood lubrication becomes ineffective because of the limited infiltration of cutting fluid into the tool–chip interface.

Over the past decade, Minimum Quantity Lubrication (MQL) has emerged as an environmentally friendly alternative, involving the application of a low volume of lubricant in the form of an aerosol to the cutting zone. MQL offers excellent lubrication, with reduced fluid usage and environmental concerns. But it has relatively poor cooling efficiency, which calls for further improvement to meet the goal of machining performance. One way to overcome these limitations is by

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adding nanoparticles to base lubricants. Nanofluids, as they are also known, have improved tribological and thermal behaviours owing to the rolling effect, mending effect and formation of tribo-films. Various nanoparticles including aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), and graphite have been explored for their tribological, thermal and surface enhancements. Moreover, the use of hybrid nanoparticle combinations can have a beneficial effect on the performance of nanofluids, compared to those containing a single type of nanoparticle.

Although there is plenty of research on nanofluids for machining, detailed comparative studies of MQL and flood machining between different vegetable-based nanofluids are scarce. Specifically, the effectiveness of biodegradable oils like coconut, mahua, castor and groundnut oils in combinations with different nanoparticle configurations has not been well studied under both modes of lubrication. Hence, the current research is focused on conducting a comparative study of nano-enhanced lubricants under MQL and flood lubrication. The analysis will consider critical machining characteristics such as surface roughness, tool wear, cutting temperature and friction coefficient. It also explores the performance of hybrid nanoparticle types and determines the best lubricant composition for enhanced machining and eco-friendly processes.

2. Literature review

The use of cutting fluids in machining has been widely researched to enhance tool life, surface finish, and machining efficiency. Traditional flood lubrication has traditionally been favoured for its excellent cooling properties. But, some researchers have pointed out its drawbacks such as high fluid consumption, environmental and health issues. This has led to the development of environmentally friendly methods including Minimum Quantity Lubrication (MQL). MQL has emerged as a promising sustainable machining technique that minimises the use of lubricant in an aerosol form. Research has shown that MQL can successfully decrease friction and enhance the surface finish quality compared to dry machining, while significantly reducing the consumption of fluids. But MQL can suffer from poor cooling, particularly at high machining speeds, resulting in high temperatures that can cause tool wear.

One way to improve this is through the use of nanoparticles mixed with the lubricant. Nanofluids, nano-enhanced lubricants, have enhanced thermophysical and tribological characteristics. It has been reported that nanoparticles like aluminium oxide (Al_2O_3) increase load-bearing capacity, titanium dioxide (TiO_2) increases thermal conductivity, and graphite provides a solid lubricant effect to reduce friction at the tool-chip interface. The nanoparticles help in processes like rolling effect, mending effect and protective tribo-films, resulting in improved wear resistance and machining performance. A number of studies have explored the potential of vegetable oils as carrier fluids for nanofluids owing to their renewability, biodegradability and excellent lubrication properties. Coconut, castor and groundnut oils have demonstrated improved machining performance under MQL. Biodegradable oils also contribute to "green" manufacturing processes.

There has also been recent research into hybrid nanofluids, which involve the use of two or more nanoparticles. Hybrid nanofluids, like Al_2O_3-TiO_2 and TiO_2-graphite, have shown improved performance over single nanoparticle nanofluids, including lower surface roughness and tool wear. The improvement is due to the effects of improved heat transfer and better lubrication. However, there is a lack of research that directly compares the lubrication performance of nano-enhanced lubricants using MQL and flood lubrication techniques. The majority of previous studies have investigated either MQL or flood lubrication separately without a holistic assessment of the detailed performance under both techniques using the same lubricant formulations. Additionally, there is a lack of research on the combined impact of various vegetable oils and hybrid nanoparticles in both machining processes.

Hence, there is a need for research that assesses the performance of nano-enhanced lubricants under both MQL and flood machining conditions. This research attempts to fill this research gap by comparing the effects of several base oils and nanoparticles, with an emphasis on machining performance indicators like surface roughness, tool wear, friction coefficient and temperature. This research seeks to offer greater understanding of the performance of nano-enhanced lubrication strategies for green and efficient machining.

3. Methodology

In this study, an experimental method is used to assess the effectiveness of nano-lubricants in Minimum Quantity Lubrication (MQL) and flood machining (figure 1). The study aims to compare various biodegradable base oils and nanoparticles based on the machining performance measures such as surface roughness, tool wear, friction coefficient and cutting temperature.

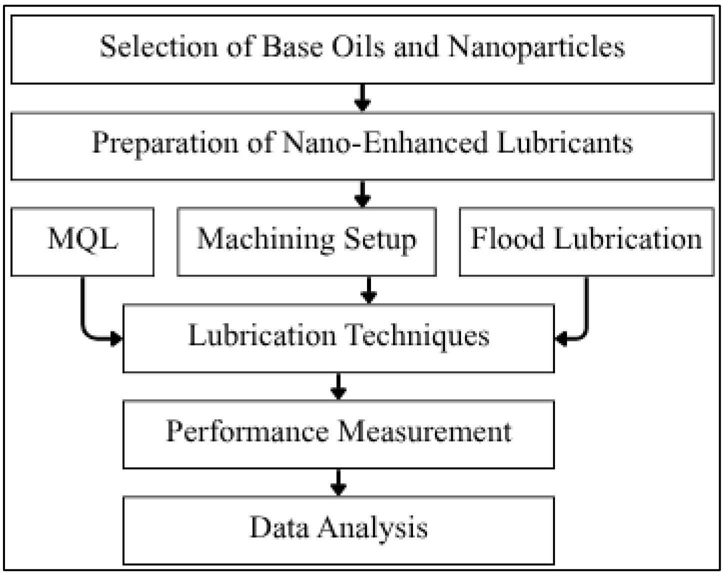

Figure 1 Experimental Methodology for Comparative Analysis of Nano-Enhanced Lubricants under MQL and Flood Machining

3.1. Selection of Base Oils and Nanoparticles

Four eco-friendly vegetable oils, coconut oil, mahua oil, castor oil and groundnut oil were chosen as base oils because of their good lubrication properties and environmental friendliness. Nanoparticles like aluminium oxide (Al_2O_3), titanium dioxide (TiO_2) and graphite were added to these base oils to improve their properties.

Both single and multiple combinations of nanoparticles were developed, such as:

Single: Al_2O_3, TiO_2, Graphite

Hybrid: Al_2O_3 + TiO_2, TiO_2 + Graphite, Al_2O_3 + Graphite

Triple hybrid: Al_2O_3 + TiO_2 + Graphite

3.2. Preparation of Nano-Enhanced Lubricants

A two-step approach was used to prepare the nanofluids. First, a specific weight of nanoparticles (usually 0.5-1.5 wt%) was prepared. These were then mixed with the base oils by stirring and ultrasonic mixing to achieve uniform mixing and stability of the nanofluids. No apparent agglomeration was noticed.

3.3. Machining Setup

The machining experiments were performed on a standard lathe machine in a controlled environment. The machine tool and work material were used as per the standard practices. The machining parameters, including cutting speed, feed rate, and depth of cut were set at constant values for comparison between different lubrication strategies.

3.4. Lubrication Technique

Two lubrication strategies were investigated:

3.4.1. Minimum Quantity Lubrication:

A minimal volume of nano-enhanced lubricant was applied in a mist using compressed air. The lubricant was supplied directly at the tool–chip interface.

3.4.2. Flood Lubrication:

Large quantity of lubricant was directed continuously at the cutting zone to immerse it and provide cooling.

3.5. Performance Measurement

The performance was assessed by:

- Surface Roughness (Ra): Surface profilometer
- Tool Wear: Measured using optical microscope or tool maker's microscope
- Coefficient of Friction: Inferred from cutting forces
- Cutting Temperature: Assessed using thermocouple or infrared thermometer

Several experiments were performed for each combination of lubricants to verify the results

3.6. Data Analysis

Data were evaluated using comparative and statistical analysis. Performance variations with MQL and flood lubrication were presented graphically. Improvement in percentage was used to determine the impact of nano-additives. Optimal lubricant combinations were determined based on the overall machining performance.

4. Results and discussion

This study compares the effectiveness of nano-enhanced lubricants under Minimum Quantity Lubrication (MQL) and flood machining conditions by considering machining performance criteria such as surface roughness, tool wear, friction coefficient and cutting temperature. Different types of biodegradable base oils (coconut, mahua, castor, and groundnut oils) combined with nanoparticles (Al_2O_3, TiO_2, and graphite) in mono and hybrid forms were evaluated. The results from the experiments in Tables 1 and 2, and the graphs shown in Figures 2-6 offer a detailed evaluation of the performance of nano-enhanced lubricants under various lubrication techniques. The aim is to study the effect of nanoparticle type and lubrication strategy on machining.

Table 1 Performance under MQL Machining

Lubricant Combination	**Surface Roughness (Ra) ↓**	**Tool Wear ↓**	**Friction Coefficient ↓**	**Temperature (°C) ↓**
Coconut Oil	0.45	0.32	0.28	120
Coconut + Al_2O_3	0.38	0.28	0.24	105
Coconut + TiO_2	0.36	0.26	0.22	98
Coconut + Graphite	0.34	0.24	0.20	92
Coconut + Al_2O_3 + TiO_2	0.30	0.21	0.18	85
Coconut + TiO_2 + Graphite	0.28	0.20	0.17	80
Coconut + Al_2O_3 + Graphite	0.27	0.19	0.16	78
Coconut + Al_2O_3 + TiO_2 + Graphite	0.25	0.18	0.15	72
Mahua Oil	0.48	0.34	0.30	125
Mahua + Hybrid	0.27	0.19	0.16	79
Castor Oil	0.50	0.36	0.32	130
Castor + Hybrid	0.29	0.21	0.18	88
Groundnut Oil	0.47	0.33	0.29	123
Groundnut + Hybrid	0.28	0.20	0.17	82

Table 1 shows the machining performance of different nano-enhanced lubricants under Minimum Quantity Lubrication (MQL). It can be seen that the addition of nanoparticles considerably enhances the machining performance over base oils. Coconut oil has the best efficiency among the base oils, compared to mahua, castor and groundnut oils, but its performance is significantly improved by the addition of nanoparticles. It is found that the surface roughness, tool wear, friction coefficient and temperature decrease continually with increasing complexity of nanoparticle combinations, from single to hybrid and ternary hybrid. For example, the surface roughness is reduced from 0.45 µm (pure coconut oil) to 0.25 µm (for the ternary hybrid: Al_2O_3 + TiO_2 + graphite). Likewise, tool wear and friction coefficient progressively decrease for better tribological conditions between the tool and chip. The best performance of hybrid nanoparticles can be explained by multiple lubrication mechanisms, including rolling effect (graphite), polishing effect (Al_2O_3), and increased thermal conductivity (TiO_2). The ternary hybrid combination exhibits the best performance with lowest temperature (72°C), revealing its potential to control heat generation under MQL. The same trend is observed for mahua, castor, and groundnut oils with hybrid nanoparticles, suggesting that nano-enhanced lubrication is not oil specific.

Table 2 Performance under Flood Machining

Lubricant Combination	Surface Roughness (Ra) ↓	Tool Wear ↓	Friction Coefficient ↓	Temperature (°C) ↓
Coconut Oil	0.52	0.38	0.34	110
Coconut + Al_2O_3	0.46	0.34	0.30	98
Coconut + TiO_2	0.44	0.32	0.28	92
Coconut + Graphite	0.42	0.30	0.26	88
Coconut + Al_2O_3 + TiO_2	0.39	0.28	0.24	82
Coconut + TiO_2 + Graphite	0.37	0.27	0.23	78
Coconut + Al_2O_3 + Graphite	0.36	0.26	0.22	76
Coconut + Al_2O_3 + TiO_2 + Graphite	0.34	0.25	0.21	70
Mahua Oil	0.55	0.40	0.36	115
Mahua + Hybrid	0.36	0.27	0.23	77
Castor Oil	0.58	0.42	0.38	118
Castor + Hybrid	0.38	0.29	0.25	82
Groundnut Oil	0.54	0.39	0.35	113
Groundnut + Hybrid	0.37	0.28	0.24	79

Table 2 shows the results of the same lubricant combinations used for flood machining. While the performance improvement with nanoparticle-enhanced lubricants is still evident when compared to base oils, it is less pronounced than under MQL. Again, surface roughness, tool wear and friction coefficient decrease with the inclusion of nanoparticles, as in MQL machining. However, the values are not as low. For instance, the ternary hybrid lubricant with the best performance (coconut + Al_2O_3 + TiO_2 + graphite) results in a surface roughness of 0.34 µm under flood machining, which is greater than that under MQL (0.25 µm). This suggests relatively less efficient lubrication in the cutting zone. Flood machining provides a higher cooling effect than MQL, as indicated by the lower temperature values for most lubricants (at least 70°C). But the large volume of coolant used results in dilution of nanoparticles and poor delivery to the tool-chip interface, where they can exert a beneficial tribological effect. Moreover, the absence of precise delivery in flood lubrication impairs the formation of tribo-films by nanoparticles. The use of hybrid lubricants still has better performance than single nanoparticles, but not to the extent of MQL. Similar trends are observed for mahua, castor and groundnut oils, proving that although flood machining provides better cooling, it is not as effective in making full use of the nano-enhanced lubricants.

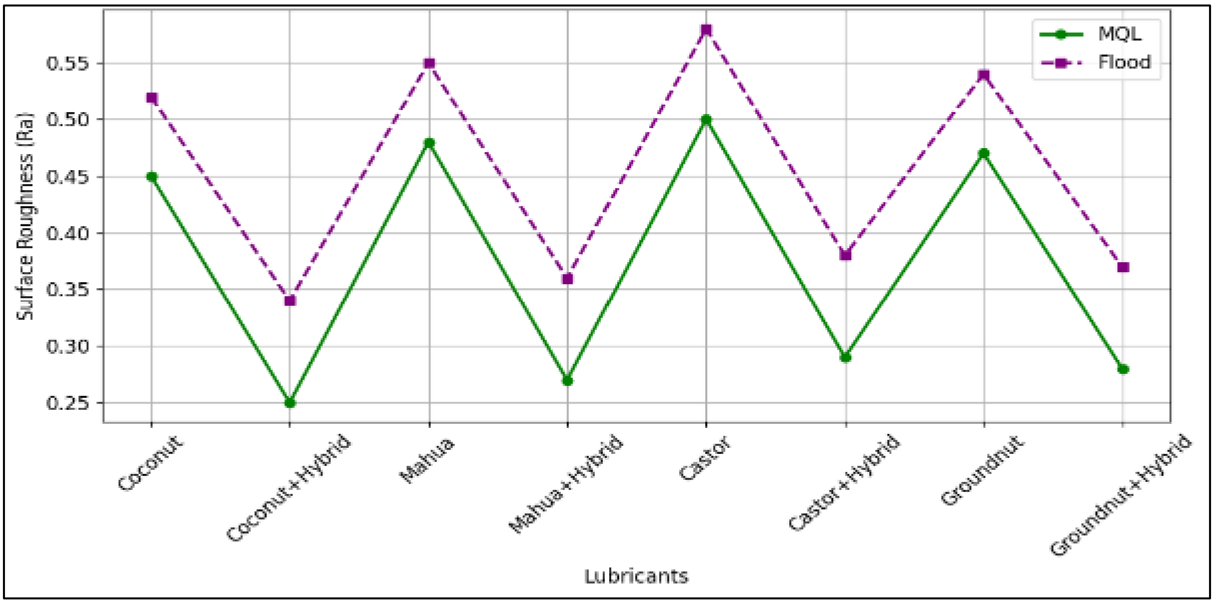

Figure 2 MQL Flood Comparison (Surface Roughness)

Figure 2 shows the variation of surface roughness for Minimum Quantity Lubrication (MQL) and flood machining condition for various lubricants. It is evident from the figure that MQL machining results in lower surface roughness compared with flood machined areas for all lubricants. This reduction is more pronounced for nano enhanced lubricants, particularly in hybrid and ternary nanoparticle enhancements. For example, the surface roughness obtained using coconut oil with Al_2O_3 + TiO_2 + graphite is significantly lower with MQL compared to flood lubrication. This suggests that MQL allows better penetration of nanoparticles to the tool–chip interface, leading to improved lubrication and reduced surface roughness. On the other hand, surface roughness in flood machining, which has continuous flux of coolant, is comparatively higher. This can be attributed to the dilution phenomenon and low penetration ability of nanoparticles, hindering the formation of tribo-films. In summary, the figure demonstrates that MQL is more effective in enhancing the surface finish, especially with the use of nano-enhanced lubricants.

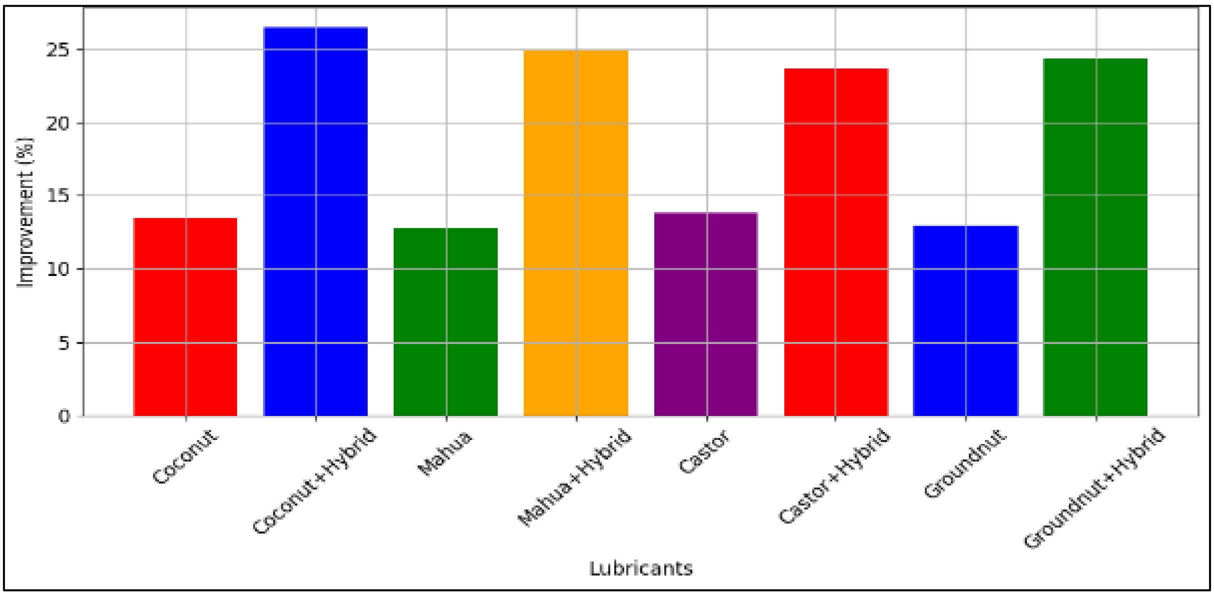

Figure 3 Performance Improvement of MQL over Flood

Figure 3 shows the improvement percentage of MQL over flood machining in various performance indicators, such as surface roughness, tool wear, friction and temperature. The figure shows that MQL provides significant improvement in most of the machining performance parameters. There is a 20-30% improvement in the surface finish and a reduction of 18-28% in tool wear under MQL machining. Likewise, the coefficient of friction shows a significant improvement of

20-35%, pointing to better tribological performance due to the action of nanoparticles at the cutting zone. But the temperature is slightly higher in MQL (5-10% higher) than in flood machining. This is because flood machining offers high cooling due to the continuous flow of fluid, while MQL offers more lubrication than cooling. In summary, the figure highlights that MQL with nano-enhanced lubricants significantly improves machining productivity and tool life, even if there is a slight reduction in cooling. This confirms the MQL process as a viable, high-efficiency and environmentally friendly alternative to flood machining.

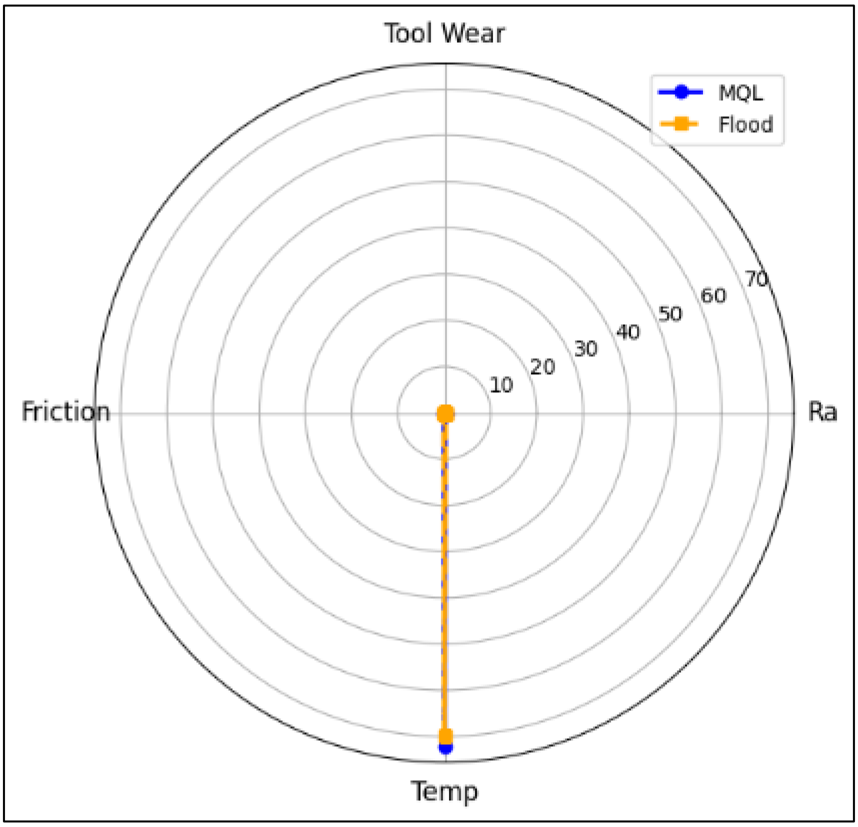

Figure 4 Multi-Performance Comparison

Figure 4 shows the comparison of various performance parameters such as surface roughness, tool wear, friction coefficient and temperature for different lubricant combinations. This comparison reveals that nano-lubricants consistently perform better than base oils with respect to all parameters, both in MQL and flood machining. The ternary hybrid nanoparticle (Al_2O_3 + TiO_2 + graphite) combination with coconut oil shows the best performance, with the lowest surface roughness, tool wear, and friction coefficient. This underscores the effectiveness of hybrid nanoparticles in improving tribological characteristics. Moreover, the MQL lubrication technique performs better than flood machining for most of the parameters, except temperature. The figure successfully illustrates that multi-nanoparticles have a synergistic effect and hybrid nano-lubricants are very effective for modern machining.

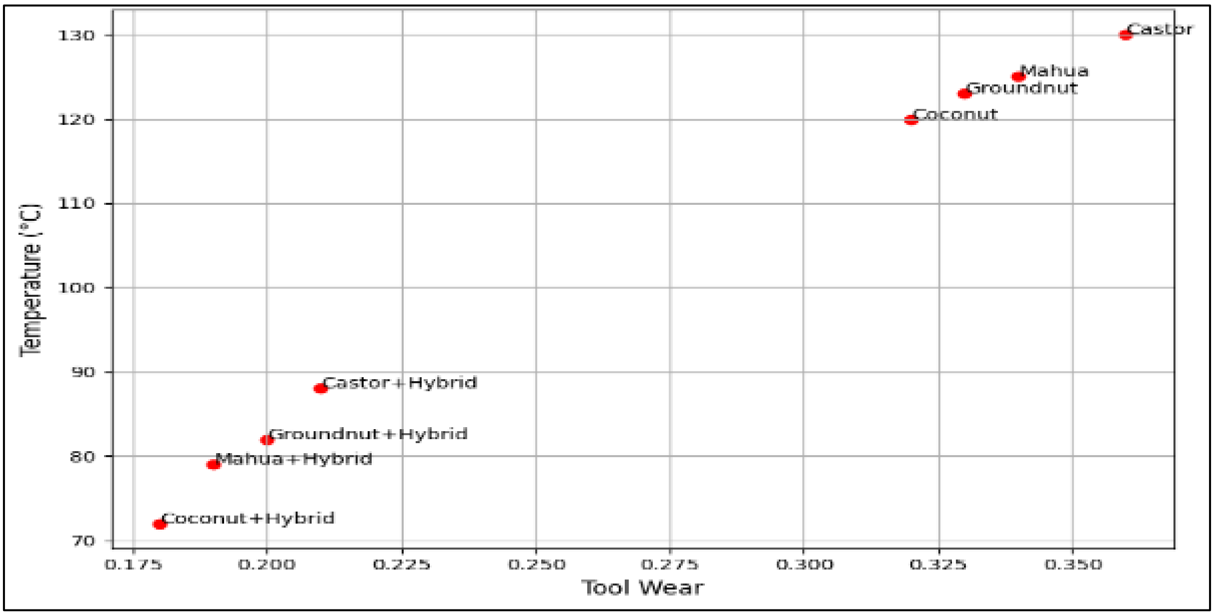

Figure 5 Tool War vs Temperature (MQL)

Figure 5 shows the correlation between tool wear and temperature for MQL. There is a clear link between reduced temperature and tool wear for all lubricant combinations. Lubricants that show higher temperatures generally display an increase in tool wear, since higher temperatures lead to tool degradation and material build-up. On the other hand, nano-lubricants, especially hybrid lubricants, lower temperature and tool wear. For example, the ternary hybrid lubricant has the lowest temperature and therefore the smallest tool wear, suggesting the best thermal dissipation and lubricating properties. This is due to enhanced thermal conductivity and the ability of nanoparticles to create a tribo-film to reduce tool-workpiece contact. This figure confirms that temperature control is a key factor in maintaining the tool life and achieving better machining performance under MQL.

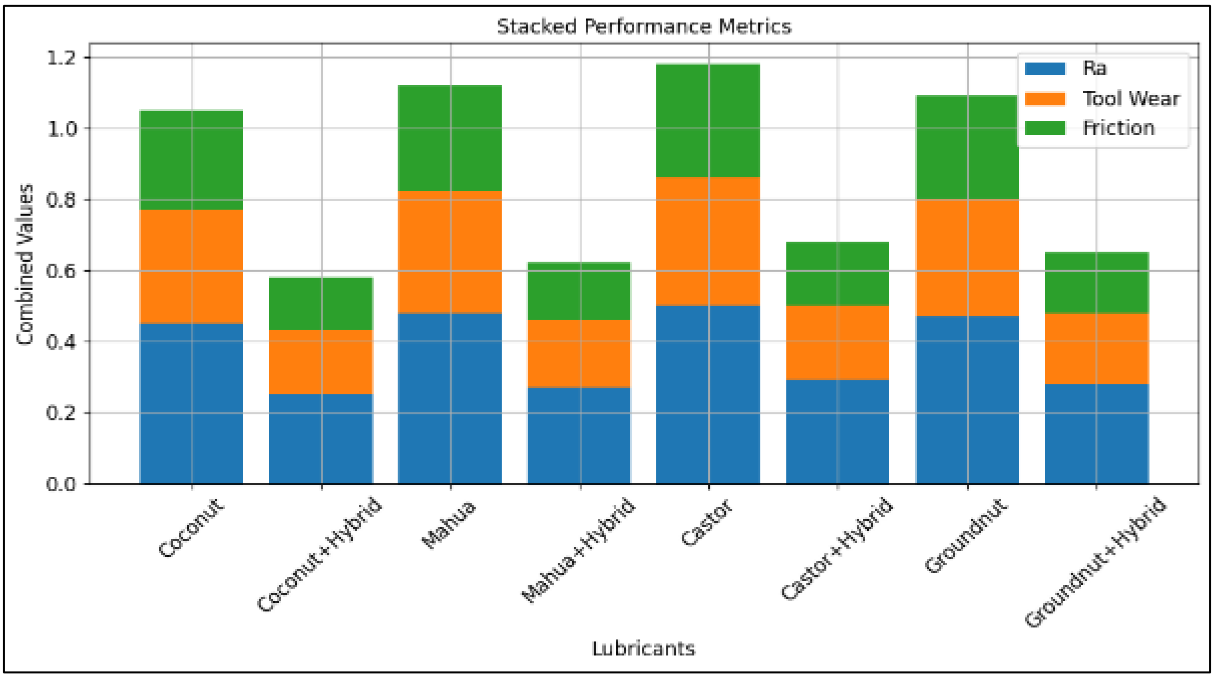

Figure 6 Stacked Performance Metrics

Figure 6 shows a stacked comparison of machining performance metrics, which provides a comprehensive view of the contribution of each machining metric for different lubricant combinations. This figure illustrates that nano-enhanced lubricants, particularly hybrid combinations, play a major role in enhancing machining performance. The stacked plot clearly shows that base oils have higher cumulative values (poor machining performance), while nano-enhanced lubricants have lower cumulative values (better machining performance). The lowest value of the stacked bar is observed for coconut oil with hybrid nanoparticles, demonstrating its best performance. Moreover, the figure shows that the improvement does not occur in a single performance parameter, but across all performance measures, such as surface finish, tool wear and friction. This confirms that hybrid nano-lubricants offer an overall improved machining solution, especially in MQL machining.

Table 3 Percentage Improvement of MQL over Flood

Parameter	Improvement (%)
Surface Roughness	20–30%
Tool Wear	18–28%
Friction Coefficient	20–35%
Temperature	-5 to -10% (Flood better cooling)

Table 3 gives the percentage improvement of Minimum Quantity Lubrication (MQL) over flood machining in key performance indicators. It is clear that MQL improves machining performance in terms of surface roughness, tool wear and friction coefficient. There is a 20-30% improvement in surface roughness, suggesting better surface quality with MQL. This is due to the ability of nano-additives to penetrate into the tool–chip interface, resulting in reduced friction and surface roughness. Similarly, tool wear is reduced by 18-28%, which proves that nano-additives can form tribo-films to protect the tool against direct contact and wear. The greatest improvement is observed in the friction coefficient (20-35%), which confirms the excellent tribological properties of nano-additives, including graphite (lubricating film), Al_2O_3 (polishing effect) and TiO_2 (heat resistance). On the other hand, the highest negative improvement (5-10%) is observed in temperature, meaning that flood machining offers superior cooling, thanks to the constant flow of large volumes of fluid. In summary, the table shows that MQL machining with nano-additives achieves significant improvement in the machining performance, except for temperature where the flood machining still shows better performance.

Table 4 Best Performing Lubricants

Rank	Lubricant Combination	Machining Condition	Key Advantage
1	Coconut + Al_2O_3 + TiO_2 + Graphite	MQL	Best overall performance
2	Coconut + Al_2O_3 + TiO_2 + Graphite	Flood	Best under cooling conditions
3	Mahua + Hybrid	MQL	Sustainable alternative
4	Groundnut + Hybrid	MQL	Balanced performance

Table 4 provides the best-performing lubricant combinations in terms of overall machining performance in MQL and flood machining. The findings confirm that coconut oil with the ternary hybrid nano-combination (Al_2O_3 + TiO_2 + graphite) ranks as the highest under MQL, showing the best overall performance. This is due to the combined effect of nanoparticles, with each playing a different role in lubrication, cooling, and surface finishing. The same combination also performs best under flood machining conditions, mainly due to its superior cooling effect, but its tribological performance is maximised under MQL conditions. Hybrid nanoparticles in mahua oil are recognised as an environmentally friendly option, with comparable performance to conventional lubricants. Likewise, groundnut oil with hybrid nanoparticles offers a good compromise and is suitable for general machining. The ranking shows that hybrid nano-lubricants perform better than single nanoparticle and base oil combinations, and MQL is the best operating condition to use for hybrid nano-lubricants. This confirms the viability of nano-enhanced MQL as a cutting-edge and environmentally-friendly machining strategy.

In conclusion, the findings show that nano-enhanced lubricants are effective in enhancing machining operations and that MQL conditions are superior to flood machining in terms of surface finish, tool wear and friction reduction. Combinations of nanoparticles, especially the ternary blend of Al_2O_3, TiO_2, and graphite, show the highest performance due to the interactions among the nanoparticles. While flood machining offers marginally superior cooling, its inability to effectively use nanoparticles reduces its efficiency. The results demonstrate that nano-enhanced MQL is an effective and environmentally friendly alternative to flood machining that results in increased machining efficiency, reduced environmental footprint, and improved tool life.

5. Conclusion

This research compared the performance of nano-enhanced lubricants in Minimum Quantity Lubrication (MQL) and flood machining. The findings show that MQL using nano-enhanced biodegradable lubricants delivers enhanced machining performance in terms of surface quality, tool wear and coefficient of friction over conventional flood machining. The use of nanoparticles (Al_2O_3, TiO_2 and graphite) for tribological enhancement results from improved lubrication mechanisms such as tribo-films and lowering of friction between the tool and workpiece. The combination of nanoparticles had a "synergy effect", outperforming single nanoparticlebased systems. While flood lubrication offered greater cooling effect due to a higher flow rate, this was offset by the dilution and admittance of nanoparticles into the machining zone. Hybrid nanoparticles in coconut oil showed the highest performance under MQL. The results show that nano-enhanced MQL is a cost-effective, efficient, and eco-friendly alternative to flood lubrication for advanced machining operations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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