

Sustainability-Oriented Evaluation of Carbon Nanofluid-Based Minimum Quantity Lubrication: Machining Performance and Resource-Efficiency Implications

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ABSTRACT

Sustainable machining requires lubrication strategies that improve machining performance while considering efficient use of manufacturing resources. This study examines the sustainability-related implications of carbon nanofluid-based minimum quantity lubrication (MQL) using multiple measured machining performance indicators. Carbon nanopowder (CNP) and carbon nanofiber (CNF) were incorporated into distilled water and vegetable oil at selected concentrations, with the base fluids used as control conditions. The formulations were evaluated based on flow rate, cooling rate, viscosity, frictional force, tool wear rate and surface roughness to characterise lubricant delivery, thermal performance, fluid rheological behaviour, tribological response, tool utilisation and measured surface quality. The results showed that carbon-based formulations generally improved the measured machining responses, although their effects varied according to additive type and base fluid. The 0.6 g CNP–vegetable oil formulation achieved the highest cooling rate of 1.30 °C/min, the lowest frictional force among the vegetable-oil formulations at 0.71 N, the lowest tool wear rate of 0.0097 mm/min, and the lowest surface roughness of 0.15 µm. These results indicate favourable thermal, tribological, tool-wear and surface-quality responses compared with the corresponding vegetable-oil control. The combined findings suggest potential resource-efficiency benefits associated with reduced tool wear and improved surface quality, although downstream reductions in tool consumption and finishing requirements were not directly measured. Overall, 0.6 g CNP in vegetable oil exhibited the most favourable combination of measured machining responses among the formulations investigated. The study provides a sustainability-oriented evaluation of carbon nanofluid-based MQL by relating measured machining performance to potential resource-efficiency implications, while recognising that comprehensive environmental, economic and occupational sustainability assessment requires additional direct measurements.

Keywords: Sustainable manufacturing; Minimum quantity lubrication (MQL); Carbon nanofluids; Machining performance; Resource efficiency.

INTRODUCTION

Sustainable manufacturing has become increasingly important as manufacturing industries seek to improve production efficiency while reducing resource consumption and environmental impacts. Machining processes are particularly relevant because cooling and lubrication conditions directly influence heat generation, friction,

tool degradation and machined surface quality. Conventional flood cooling can provide effective cooling and lubrication; however, its relatively high fluid consumption creates additional requirements for fluid handling, maintenance and disposal. These concerns have encouraged the development of alternative cooling and lubrication strategies that aim to maintain machining performance while reducing lubricant consumption [1].

Minimum Quantity Lubrication (MQL) has emerged as an alternative to conventional flood cooling by supplying a small amount of lubricant directly to the machining zone. The lower lubricant consumption associated with MQL has contributed to its consideration as an alternative to conventional flood lubrication, while direct delivery of lubricant to the machining zone may improve lubrication at the tool–workpiece and tool–chip interfaces. Previous studies have reported that MQL can reduce friction, cutting temperature and tool wear while maintaining satisfactory surface quality [2]. However, the cooling capability of conventional MQL fluids may be limited under machining conditions where substantial heat is generated. The incorporation of nanoparticles into MQL fluids has therefore been investigated as a means of improving their thermal and tribological performance.

Carbon-based nanofluids containing carbon nanopowder (CNP) and carbon nanofiber (CNF) are of particular interest because carbon-based additives can influence heat transfer and interfacial lubrication. Nanoparticle-enhanced cutting fluids have been reported to improve cooling and lubrication behaviour, although their performance depends on factors such as nanoparticle type, concentration, base-fluid properties and dispersion stability [3,4]. Experimental studies have also reported that carbon nanotube-based nanofluids can improve surface finish and cutting temperature under selected MQL conditions [5]. However, improvements in individual machining responses do not necessarily indicate better overall manufacturing sustainability.

A multi-indicator assessment is therefore useful for evaluating the broader implications of alternative lubrication strategies. Flow rate can indicate lubricant delivery characteristics, cooling rate can indicate thermal management, viscosity and frictional force can describe lubrication behaviour, while tool wear rate and surface roughness provide information related to tool utilisation and product quality, respectively. Previous sustainability-oriented machining studies have demonstrated the value of integrating several machining responses when evaluating alternative lubrication conditions [6,7]. Nevertheless, there remains a need for empirical assessments that relate multiple measurable machining responses to sustainability-relevant considerations when comparing CNP and CNF based MQL formulations. In particular, comparative evidence on CNP and CNF across different base-fluid conditions remains limited, especially when thermal, fluid, tribological, tool-wear and surface-quality responses are considered together.

Therefore, this study examines the sustainability-related implications of CNP and CNF based MQL through selected experimentally measured machining performance indicators. The study assesses flow rate, cooling rate, viscosity, frictional force, tool wear rate and surface roughness under distilled-water- and vegetable-oil-based formulations. The measured responses are subsequently interpreted in terms of thermal performance, tribological behaviour, tool utilisation, potential resource-efficiency implications and possible downstream effects on finishing requirements. The objective is to identify the formulation exhibiting the most favourable combination of measured machining responses and to discuss its potential contribution to resource-efficient machining within the broader context of sustainable manufacturing.

METHODOLOGY

Nanofluid Preparation

Two carbon-based additives, namely carbon nanopowder (CNP) and carbon nanofiber (CNF), were used with distilled water and vegetable oil as the base fluids. The formulation composition and measured MQL flow rate for all investigated conditions are summarised in Table 1. Gum Arabic (GA) was used as a dispersing and stabilising agent for the carbon-based formulations. Distilled water and vegetable oil without GA or carbon-based additives were used as the respective control fluids. For the water-based formulations, 0.1 g GA was dispersed in 1000 mL of distilled water using an ultrasonic homogeniser for 15 min, with the amplitude and cycle settings set to 50 and 0.5, respectively. Subsequently, 0.1 g or 0.5 g of CNP or CNF was separately added

Table 1. Formulation composition and measured MQL flow rate of the investigated conditions

Sample	Base fluid	GA	CNP	CNF	Flow rate (mL/h)
DW	1000 mL distilled water	–	–	–	25.2
CNP-DW-0.1	1000 mL distilled water	0.1 g	0.1 g	–	50.4
CNP-DW-0.5	1000 mL distilled water	0.1 g	0.5 g	–	56.4
CNF-DW-0.1	1000 mL distilled water	0.1 g	–	0.1 g	45.6
CNF-DW-0.5	1000 mL distilled water	0.1 g	–	0.5 g	52.8
VO	Vegetable oil	–	–	–	1.26
CNP-VO-0.6	Vegetable oil	0.25 g	0.6 g	–	1.51
CNF-VO-0.6	Vegetable oil	0.25 g	–	0.6 g	1.57

and ultrasonicated for a further 45 min. For the vegetable-oil-based formulations, 0.25 g GA was initially dispersed in the vegetable oil under the same ultrasonic conditions for 15 min, followed by the separate addition of 0.6 g CNP or CNF and a further 30 min of ultrasonication. The prepared formulations were subsequently used for fluid characterisation and MQL machining experiments. The MQL flow rate was measured as the volume of lubricant delivered per hour using the same nozzle opening size for all formulations and was considered as an indicator of lubricant delivery characteristics under the tested MQL conditions.

Experimental Procedure

The machining experiments were conducted under controlled MQL conditions using the prepared formulations as the lubrication media. Distilled water and vegetable oil were used as control conditions, while the CNP- and CNF-based formulations were evaluated at the specified additive quantities. The machining tests were performed using AISI D2 steel and a PVD-coated carbide insert under fixed machining conditions. The spindle speed, feed rate and depth of cut were maintained constant at 2790 rpm, 558 mm/min and 1.5 mm, respectively. Each test was conducted for 10 passes over a machining length of 101 mm, corresponding to a tool travel time of 5.05 min under the specified feed condition. The same machining procedure and fixed cutting parameters were applied consistently across all lubrication conditions to facilitate comparative evaluation. The experimental responses comprised flow rate, cooling rate, viscosity, frictional force, tool wear rate and surface roughness. The overall relationship between the formulations, measured machining indicators and their sustainability-related implications is illustrated in Figure 1.

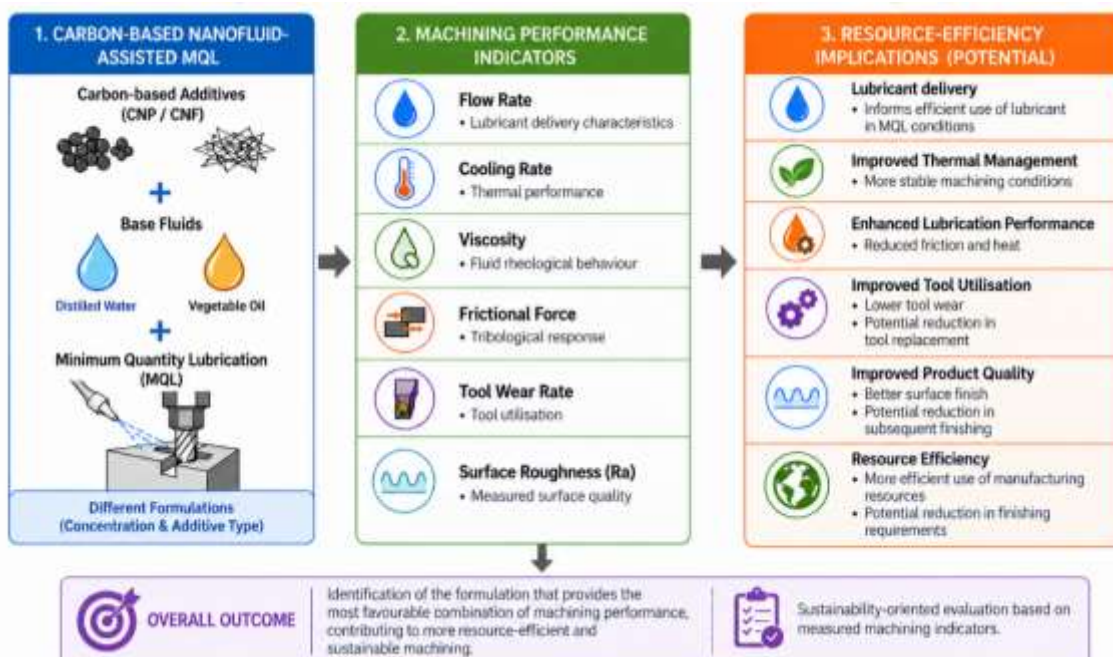


Figure 1: Conceptual framework linking carbon-based nanofluid-assisted MQL, measured machining performance indicators and potential resource-efficiency implications.

Performance Measurements

Cooling Rate

Thermal performance was evaluated based on the measured cooling rate of each lubrication condition. The cooling rate was determined from the temperature reduction over the specified measurement period and expressed in °C/min. For the cooling-rate measurement, 100 mL of each formulation was heated to an initial temperature of 50 °C using a hot plate. The temperature reduction was then recorded over a 5-min period using a digital thermometer, and the cooling rate was calculated from the temperature change per unit time. The same procedure was applied to all formulations.

Viscosity

The viscosity of each formulation was determined using the marble falling method. A 15 mm diameter marble was placed into 50 mL of each sample contained in a measuring cylinder, and the time required for the marble to travel through the sample was recorded. The terminal velocity was calculated from the known travel distance and measured time. The viscosity was subsequently calculated based on the density difference between the marble and liquid, terminal velocity, gravitational acceleration and marble radius.

Frictional Force

Frictional force was evaluated using a Micro-pod Tribology Tester (CM-9109) based on a ball-on-disc configuration. Each lubricant was supplied to the disc for 10 min, with a normal load of 10 N and a rotational speed of 200 rpm. The frictional response was recorded using the associated data acquisition software.

Tool Wear Rate

Tool wear rate was calculated from the measured tool wear and tool travel time according to:

$$\text{Tool wear rate} = \frac{\text{Tool wear}}{\text{Tool travel}} \quad (1)$$

For each machining condition, tool wear was evaluated after 10 machining passes over the 101 mm workpiece length. The resulting tool travel time was 5.05 min, and tool wear rate was calculated from the measured flank wear divided by the corresponding tool travel time.

Surface Roughness

Surface roughness was measured after machining using a Portable Surface Roughness Tester (Mitutoyo SJ-410 Surftest). Measurements were taken at seven locations along the machined surface using a 0.8 mm cut-off, and the average surface roughness, Ra, was used as an indicator of measured surface quality and reported in µm.

Sustainability-Oriented Evaluation Approach

The sustainability-oriented evaluation was based on the combined interpretation of measured machining indicators, including flow rate, cooling rate, viscosity, frictional force, tool wear rate and surface roughness. Flow rate provides an indication of lubricant delivery characteristics, while cooling rate, viscosity and frictional force describe thermal, rheological and tribological behaviour, respectively. Tool wear rate and surface roughness provide information on tool utilisation and measured surface quality. These indicators were considered together to interpret potential resource-efficiency implications, particularly in relation to lubricant delivery, tool utilisation and product surface quality. The evaluation is not intended to represent a comprehensive life-cycle, environmental, economic or occupational sustainability assessment, but rather a sustainability-oriented

interpretation of experimentally measured machining performance. This multi-indicator approach is consistent with previous sustainable machining studies that relate machining performance indicators to broader sustainability considerations [6,7].

RESULTS AND DISCUSSION

Lubricant Delivery Characteristics

The measured flow rate varied according to the base fluid and carbon-based additive. For distilled-water-based formulations, the flow rate ranged from 25.2 to 56.4 mL/h, while the vegetable-oil-based formulations showed lower flow rates ranging from 1.26 to 1.57 mL/h. The results indicate that lubricant delivery characteristics varied with formulation, providing an additional resource-related parameter for the sustainability-oriented evaluation of MQL formulations.

Thermal Performance

The thermal performance of the tested lubrication conditions was evaluated based on cooling rate, as presented in Figure 2. The distilled-water and vegetable-oil controls recorded cooling rates of 0.82 and 0.90 °C/min, respectively. The addition of carbon-based additives increased the cooling rate under both base-fluid conditions. For distilled water, the cooling rate increased to 0.92 and 1.10 °C/min with 0.1 and 0.5 g CNP, respectively, while CNF produced 1.00 and 1.06 °C/min. For vegetable oil, 0.6 g CNP and CNF increased the cooling rate to 1.30 and 1.14 °C/min, respectively. The highest cooling rate was therefore obtained with 0.6 g CNP in vegetable oil. The improved cooling response is consistent with previous findings showing that nanoparticle-enhanced fluids can improve heat transfer and cooling behaviour during machining [4,8]. From a sustainability-oriented perspective, the improved cooling response suggests potential for improved thermal management under the tested conditions. However, cooling performance should be considered together with lubrication, tool wear and surface quality before determining the overall sustainability implications.

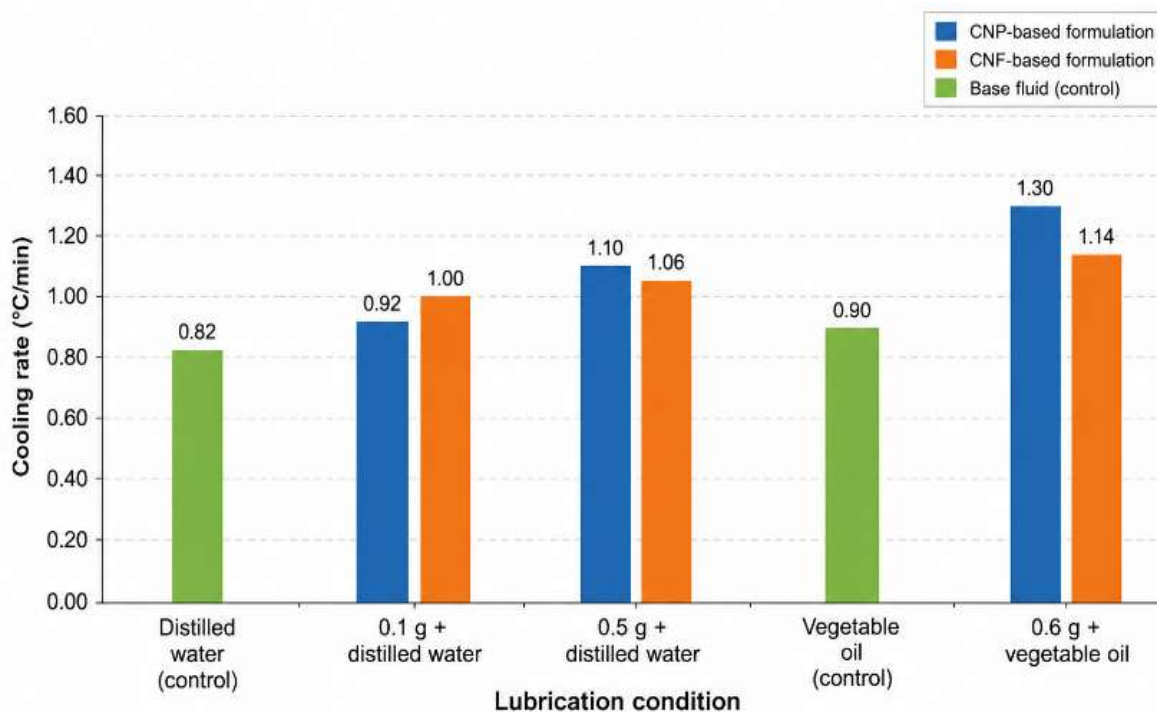


Figure 2: Cooling rate of CNP and CNF based formulations under distilled water and vegetable oil conditions.

Lubrication Performance

The fluid and tribological performance was evaluated using viscosity and frictional force, as shown in Figure 3. The addition of CNP and CNF increased viscosity from 0.14 Pa·s for distilled water to 0.34–0.38 Pa·s for the CNP formulations and 0.32–0.37 Pa·s for the CNF formulations. For vegetable oil, viscosity increased from 0.44 Pa·s to 0.49 Pa·s with CNP and 0.55 Pa·s with CNF. The observed increase in viscosity indicates that the addition of carbon-based additives altered the measured flow properties of the base fluids, consistent with previous observations that nanoparticle concentration and type can influence nanofluid viscosity [9]. The frictional-force results showed that all carbon-based formulations under distilled water reduced friction relative to the distilled-water control of 3.55 N. The lowest value was obtained with 0.1 g CNF (0.85 N). For vegetable oil, 0.6 g CNP reduced friction from 1.33 to 0.71 N, whereas 0.6 g CNF resulted in 1.47 N. The dry condition recorded the highest frictional force at 7.62 N. The results indicate that the tribological response depended on additive type and base fluid rather than viscosity alone. The lower measured frictional force for most formulations is consistent with reported tribological benefits of nanoparticle-enhanced MQL [3,8]. Notably, CNF in vegetable oil did not reduce friction relative to vegetable oil alone, suggesting that increased viscosity alone does not necessarily result in lower frictional force.

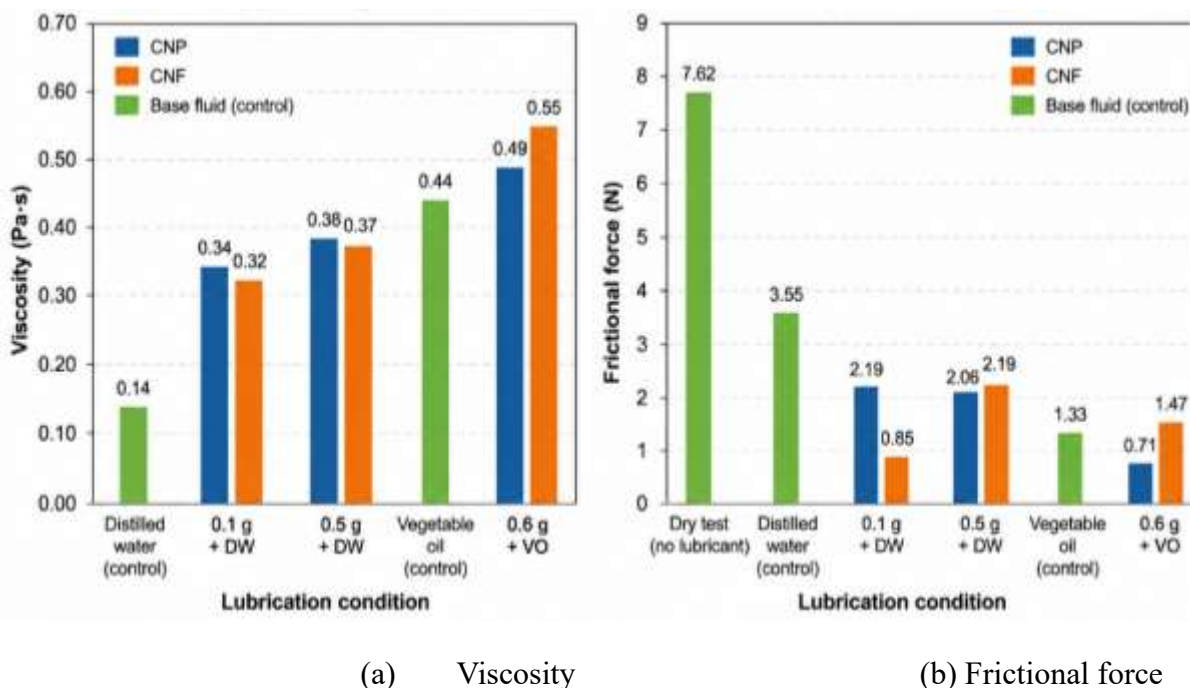


Figure 3: Viscosity and frictional force responses of the investigated lubrication conditions.

Tool Wear Rate and Resource Efficiency

The tool wear rate was used as an indicator of tool utilisation, with its potential implications for resource efficiency subsequently considered, as presented in Figure 4. All carbon-based formulations produced lower tool wear rates than their respective base-fluid controls. For distilled water, the tool wear rate decreased from 0.0305 mm/min to 0.0186 and 0.0160 mm/min with CNP, while CNF resulted in 0.0178 and 0.0158 mm/min. For vegetable oil, the rate decreased from 0.0200 mm/min to 0.0097 mm/min with CNP and 0.0103 mm/min with CNF. The lowest tool wear rate was obtained with 0.6 g CNP in vegetable oil (0.0097 mm/min), corresponding to a 51.5% reduction compared with vegetable oil alone. The lower measured tool wear rate indicates favourable tool-utilisation performance and may contribute to lower tool replacement frequency. However, actual tool consumption and replacement requirements were not directly measured in this study. This interpretation is consistent with previous sustainable machining studies that relate tool wear and machining performance to resource utilisation and sustainability considerations [6,7].

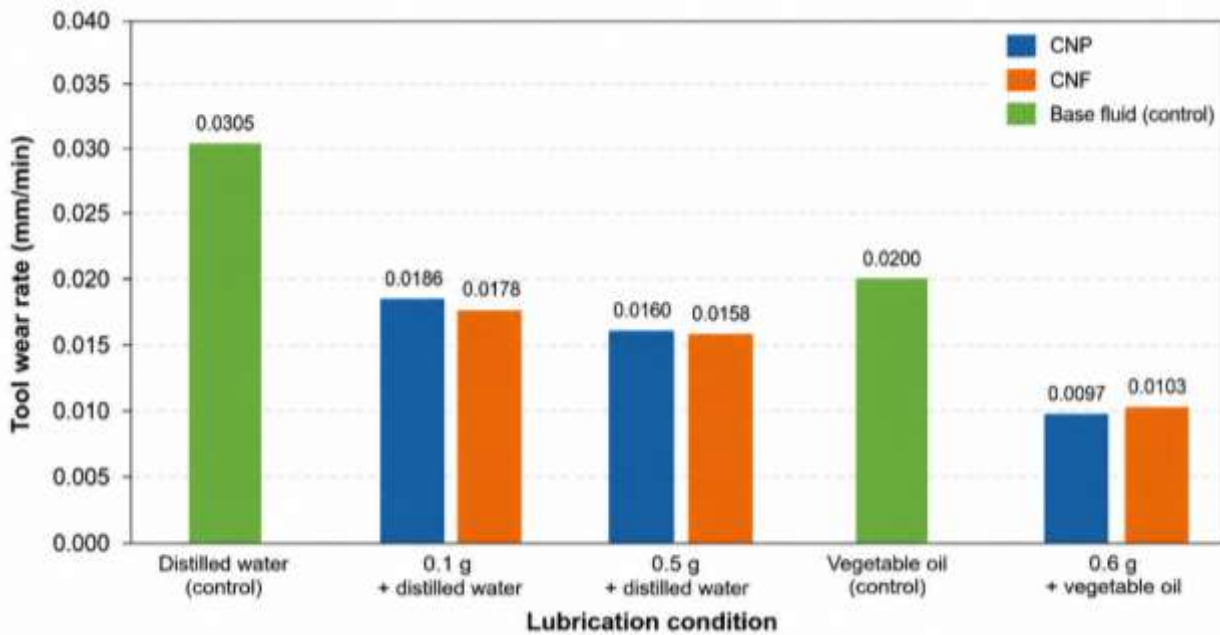


Figure 4: Tool wear rate of CNP and CNF based formulations under distilled water and vegetable oil conditions.

Product Quality

Surface roughness was evaluated as an indicator of measured surface quality, as presented in Figure 5. The carbon-based formulations generally reduced surface roughness compared with their respective base fluids. For distilled water, CNP reduced surface roughness from 0.34 μm to 0.22 and 0.16 μm , while CNF reduced it to 0.29 and 0.16 μm . For vegetable oil, the addition of 0.6 g CNP and CNF reduced surface roughness from 0.33 μm to 0.15 and 0.22 μm , respectively. The lowest surface roughness was obtained with 0.6 g CNP in vegetable oil (0.15 μm), representing a 54.5% reduction compared with vegetable oil alone. The 0.5 g CNP and CNF formulations in distilled water also achieved 0.16 μm , corresponding to a 52.9% reduction from the distilled-water control. Similar improvements in surface finish and tool wear have been reported for nanofluid-based MQL machining [5,9,10]. The lower measured surface roughness indicates improved surface quality and may reduce the need for subsequent finishing operations. However, finishing time and material consumption were not directly measured.

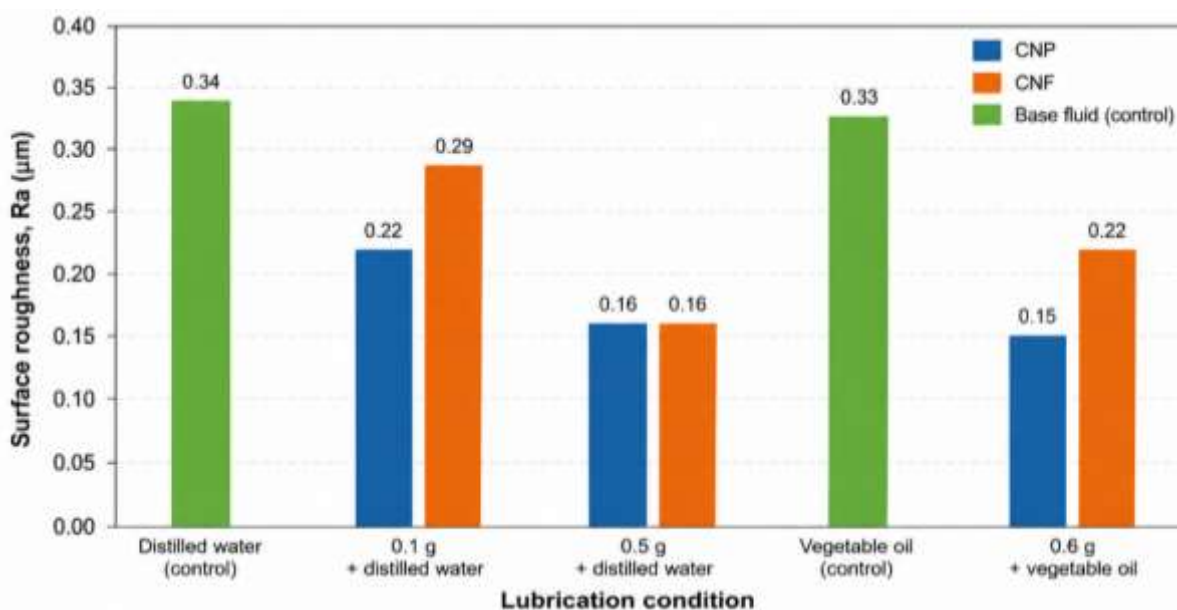


Figure 5: Surface roughness of CNP and CNF based formulations under distilled water and vegetable oil conditions.

Sustainability-Oriented Evaluation and Resource-Efficiency Implications

The sustainability-oriented evaluation was based on the combined interpretation of measured machining indicators rather than a formal life-cycle assessment, carbon-footprint analysis or comprehensive sustainability assessment. The measured indicators comprised flow rate, cooling rate, viscosity, frictional force, tool wear rate and surface roughness. Flow rate was considered an indicator of lubricant delivery characteristics, cooling rate was considered a thermal-performance indicator, viscosity was used to characterise fluid rheological behaviour, and frictional force was used as a tribological indicator. Tool wear rate was interpreted in relation to tool utilisation, while surface roughness was used as an indicator of measured surface quality. The interpretation of these indicators and their potential resource-efficiency implications are summarised in Table 2. The combined

Table 2: Interpretation of Machining Performance Indicators and Potential Resource-Efficiency Implications

Performance indicator	Key finding	Potential Resource-Efficiency Implication
Flow rate	1.51 mL/h with 0.6 g CNP + vegetable oil	Measured lubricant delivery characteristic
Cooling rate	1.30 °C/min with 0.6 g CNP + vegetable oil	Potentially improved thermal management
Frictional force	0.71 N with 0.6 g CNP + vegetable oil	Improved measured tribological response
Tool wear rate	0.0097 mm/min with 0.6 g CNP + vegetable oil	Potentially improved tool utilisation
Surface roughness	0.15 µm with 0.6 g CNP + vegetable oil	Improved measured surface quality and potential for reduced downstream finishing

findings were interpreted particularly in relation to lubricant delivery, tool utilisation and possible downstream effects on tool replacement and finishing requirements. The present evaluation focuses on experimentally measured machining responses and their potential resource-efficiency implications. Direct quantification of lubricant consumption, energy use, environmental impacts, economic costs, nanoparticle-related environmental considerations and social or occupational impacts was beyond the scope of the present study. This multi-indicator approach is consistent with previous sustainable machining studies that relate machining responses to broader sustainability considerations [6,7].

CONCLUSION

This study evaluated the sustainability-related implications of CNP- and CNF-based minimum quantity lubrication using measured flow rate, cooling rate, viscosity, frictional force, tool wear rate and surface roughness. The results demonstrated that the effects of carbon-based additives varied with additive type and base fluid. Among the investigated formulations, 0.6 g CNP in vegetable oil exhibited the most favourable combination of measured machining responses, including a cooling rate of 1.30 °C/min, frictional force of 0.71 N, tool wear rate of 0.0097 mm/min and surface roughness of 0.15 µm.

The observed reduction in tool wear and surface roughness indicates favourable machining performance and potential resource-efficiency implications through improved tool utilisation and surface quality. The measured flow-rate results further demonstrate that lubricant delivery characteristics vary according to the formulation and should be considered when evaluating MQL-based resource efficiency. Overall, 0.6 g CNP in vegetable oil showed the most favourable measured machining performance among the investigated conditions under the tested laboratory parameters.

The findings provide a sustainability-oriented perspective based on experimentally measured machining indicators rather than a comprehensive sustainability assessment. Future studies should extend this evaluation by directly considering lubricant consumption, energy use, environmental impacts, economic performance, nanoparticle-related considerations and occupational factors, together with systematic experimental replication and statistical analysis.

Declaration

AI-assisted tools were used for language editing and manuscript writing refinement. All experimental data and research findings are original and were produced by the authors. The authors remain responsible for the accuracy and integrity of the manuscript.

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