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COMPREHENSIVE REVIEW OF THE APPLICATION OF HYBRID NANOFLUIDS (HNF) IN MINIMUM QUANTITY LUBRICATION (MQL) FOR SUSTAINABLE MACHINING

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Abstract

Conventional cutting fluids in machining cause environmental and economic concerns. Minimum Quantity Lubrication (MQL) offers a sustainable alternative but faces cooling and lubrication limitations. Integrating hybrid nanofluids (HNF) into MQL significantly enhances machining performance, quantitatively showing that HNF-MQL reduces cutting force by 9-55%, tool wear by 11-78%, and surface roughness by 12-54% compared to single nanofluids or dry machining. This systematic review analyzed approximately 33 peer-reviewed articles published between 2015 and 2024 from Scopus and Web of Science databases, focusing on the application of hybrid nanofluids in minimum quantity lubrication for sustainable machining processes. This review provides a novel synthesis of hybrid nanofluid types (e.g., Al_2O_3/MWCNT, Al_2O_3/Graphene, hBN/Graphene) applied via MQL in machining hard-to-cut materials (superalloys, titanium, stainless steels), critically analyzing their synergistic mechanisms, performance benefits, and sustainability challenges to guide future research and industrial implementation. Results indicate HNF consistently outperforms single nanofluids, reducing cutting force, tool wear, and improving surface quality across various hard-to-machine materials. HNF-MQL also lowers fluid consumption, energy use, and environmental impact. However, challenges like nanoparticle stability, cost, and production scalability hinder widespread adoption. HNF-MQL presents an effective green machining strategy, with future research needed in material optimization, advanced delivery systems, and deeper mechanistic understanding.

Keywords: Hybrid nanofluid, Minimum Quantity Lubrication, sustainable machining, lubrication, cooling, cutting performance.

INTRODUCTION

In metal cutting operations, the use of cutting fluid plays a crucial role because it functions to cool and lubricate the interface of the tool and the workpiece, while helping to remove debris from the cut zone (Musavi, Davoodi, & Razfar, 2023; Sharma, Singh, Dixit, & Tiwari, 2016; Singh, Thakur, & Gangopadhyay, 2025). The performance of this coolant significantly affects the tribological conditions (friction and wear) of the interface. The main goal in the manufacturing process is to optimize production time, energy, cost, and resources, while improving product functionality (Xiong et al., 2021).

However, the use of conventional coolant in large quantities (flood cooling) has negative consequences. Excessive use of conventional fluids can have adverse effects on human health and the environment (Shah & Utpat, 2025; Sharma et al., 2016). In addition, economically, the costs incurred for conventional coolants can be as high as 16 to 20% of the total manufacturing costs (Kumar, Kumar, & Rai, 2016; Wang et al., 2024)]. Therefore, industry and academia are encouraged to look for alternative methods that can achieve high machining performance with minimal environmental impact (Sharma et al., 2016; Tiwari, Amarnath, Gupta, & Makhesana, 2023).

In order to overcome the environmental impact and high cost of conventional cooling, there has been an evolution towards the concept of sustainable manufacturing or sustainable machining (green machining) (Makhesana et al., 2023) This approach focuses on minimizing costs, reducing energy consumption, and limiting the impact on human health and the environment (Makhesana et al., 2023)

One of the techniques that has received great attention in this context is Minimum Quantity Lubrication (MQL) (Furkan, Kshitij, & Khanna, 2023; Kumar et al., 2016; Singh et al., 2025). MQL, also known as Near Dry Machining (NDM) (Furkan et al., 2023), drastically reduces coolant consumption, often by using biodegradable vegetable oils, making it a more environmentally friendly (Furkan et al., 2023; Peng, Shen, Tang, Zhao, & Gao, 2025; Wang et al., 2024). Nonetheless, the pure MQL method has limitations, especially in high-heat producing cutting operations or when processing materials that are difficult to cut (such as superalloys), due to their potentially insufficient cooling and lubrication capacity (Furkan et al., 2023)

Nanotechnology offers a solution to overcome the limitations of MQL. The utilization of nanotechnology has attracted great interest due to its potential advantages in improving production output and machining performance (Shah & Utpat, 2025; Xiong et al., 2021). Nanofluids (NF) are defined as colloidal mixtures containing nanoparticles (solid particles less than 100 nm in size, such as metals or non-metals) suspended in a base liquid (Gemechu, Efa, & Abebe, 2024; Sharma et al., 2016).

NF has attracted widespread attention due to its unique properties, in particular its improved thermal conductivity and better heat extraction ability compared to its base fluids (Gemechu et al., 2024; Musavi et al., 2023; Sharma et al., 2016). By applying NF through the MQL (NMQL) system, the lubrication of the cut zone can be significantly improved, reducing friction and chisel wear, and resulting in better surface quality (Xiong et al., 2021) NMQL has all the advantages of MQL and has great potential as a sustainable industrial cutting technology (Wang et al., 2024).

However, the researchers found that the combination of nanoparticles could provide more optimal performance. Hybrid nanofluids (HNFs), which suspend two or more types of nanoparticles, have been shown to significantly improve machining performance compared to single nanofluids (Gemechu et al., 2024; Technologies, 2021; Wang et al., 2024). HNFs are designed to combine dual advantages (e.g., increased heat transfer from one particle and tribologic increase from another) to achieve synergistic and superior thermal and triboological properties (Haghnazari & Abedini, 2021; Wang et al., 2024; Zhao et al., 2025). Examples include the nanofluids AL_2O_3-MWCNT or AL2O3/Graphene (Gemechu et al., 2024; Jafarian, Siamak, Mohammad, & Chalak, 2022).

Based on the rapid progress in the application of HNF-MQL, this comprehensive review aims to synthesize and critically analyze the existing literature on the potential lubrication of HNF in machining operations (Gupta & Rathore, 2025; Wang et al., 2024). This review will seek to lucidate the fundamental mechanisms that govern the efficacy of NF/HNF lubrication in improving machining performance, including aspects of friction reduction, heat dissipation, and surface quality improvement (Gupta & Rathore, 2025)

METHODS

This review adopts a structured systematic review methodology to identify, evaluate, and synthesize literature findings related to the implementation of HNF in MQL systems. The literature search process is carried out systematically using Scopus, Web of Science, ScienceDirect, and Google Scholar indexed databases with predetermined keyword combinations. The collected studies are then filtered based on inclusion and exclusion criteria, followed by data extraction and thematic analysis to present a comprehensive and critical synthesis.

Following the initial search, a multi-stage screening was conducted using predefined inclusion and exclusion criteria. Titles and abstracts were first evaluated for relevance, followed by full-text assessment. Selected studies underwent systematic data extraction, capturing key details such as nanofluid composition, machining parameters, experimental methods, and performance outcomes. The data were then analyzed thematically to identify trends, causal relationships, and research gaps. A narrative-critical synthesis approach was employed to compare the performance of different HNF-MQL formulations across varied machining applications. The internal validity of included studies was evaluated through critical appraisal of experimental design and analytical rigor. This systematic review protocol ensured an objective, reproducible, and in-depth analysis, yielding a comprehensive synthesis to advance sustainable machining research.

Although many studies have explored hybrid nanofluid minimum quantity lubrication (HNF-MQL), a clear and concise review that summarizes key findings is still needed. This paper reviews 33 studies from 2015-2024 to compare the performance of various HNF types against single nanofluids in machining difficult materials like superalloys, titanium, and stainless steels. The results show that HNF-MQL significantly improves machining performance—reducing cutting force by up to 55%, tool wear by up to 78%, friction by 85%, and surface roughness by up to 54%, while also lowering energy consumption by 56%. This review also discusses current challenges, including nanoparticle stability, production costs, and safety concerns, and offers directions for future research and practical application of HNF-MQL in sustainable manufacturing.

RESULTS AND DISCUSSION

1. Comparison of Thermophysical Properties of Single NF vs. HNF Based on Recent Study Sets

Based on the synthesis of the latest literature, hybrid nanofluids (HNFs) consistently exhibit superior thermophysical properties compared to single nanofluids (NF). This improvement is mainly seen in thermal conductivity and heat transfer ability, which are decisive factors in the cooling effectiveness of MQL systems.

The addition of solid nanoparticles, which have very high intrinsic thermal conductivity (e.g., copper up to 700 times water), significantly improves the thermal conductivity of the underlying fluid (Wang et al., 2024). HNF leverages synergies between two or more types of nanoparticles to achieve greater improvements. For example, the combination of Al_2O_3 (ceramic oxide) with MWCNT or Graphene (carbon material) results in a better increase in thermal conductivity than the use of a single Al_2O_3, thanks to the contribution of the high conductivity of carbon materials (Gemechu et al., 2024; Jafarian et al., 2022; Sharma, Katiyar, Bhaumik, & Roy, 2019).

In general, the addition of nanoparticles tends to decrease the specific heat capacity of the base fluid (Qiao, Xiong, Yang, Zhen, & Zhang, 2025) However, in HNF, optimization of particle type and ratio can mitigate this decline while still maintaining or improving overall heat extraction capabilities through higher thermal conductivity.

The addition of nanoparticles, both single and hybrid, increases the dynamic viscosity over the underlying fluid (Sharma et al., 2016; Technologies, 2021; Zhang et al., 2016). The increased viscosity in HNF can be more complex due to interactions between particles. For MQL applications, too high viscosity can inhibit the atomization and penetration of the lubricating mist. Therefore, the total concentration of nanoparticles in HNF is usually optimized (usually below 2%) to balance between improved thermal/tribological performance and ease of application (Gemechu et al., 2024; Makhesana et al., 2023).

Table 1. Synthesis of the Most Effective HNF Formulations Based on Nanoparticle Type, Base Fluid, and Machining Application

Types of Hybrid Nanoparticles.	Basic Fluids	Machining Applications	Key Performance Reported
Al_2O_3 / MWCNT	Vegetable oil / Water	Milling; Stainless Steel Turning (AISI 304)	Better performance than single Al_2O_3; Reduce tool wear & chisel tip temperature.
Al_2O_3 / MoS_2	Vegetable Oil	Turning	Reduced cutting force, thrust, and surface roughness vs. a single NF Al_2O_3.
Al_2O_3 / CuO	(Not specified)	Turning (AISI 4340)	A ratio of 0.75% by weight CuO + 0.25% by weight Al_2O_3 provides the lowest surface roughness & cutting force.
hBN / Graphene (Grpt)	Vegetable Oil	Milling (Inconel X-750)	Best performance among other hybrids (hBN/MoS_2, Grpt/MoS_2) in cut style, temperature, roughness, and chisel life.
Al_2O_3 / Graphene	Water Deionization & Glycerol (25:75)	Turning (AISI D3)	Optimization with Machine Learning achieves a surface roughness of 0.16–0.45 μm with controlled temperature.
MoS_2 / CNT	(Not specified)	Nickel Alloy Grinding	Optimal lubrication effect on MoS_2:CNT mass ratio = 2:1 and 6% weight concentration.

2. Effect of Concentration, Particle Size, and Dispersion Method on HNF Stability and Performance in MQL Systems

The concentration of total nanoparticles directly affects the thermophysical and tribologic properties of HNF. Increased concentrations generally improve thermal conductivity and lubrication capacity. However, concentrations that are too high (often > 2%) can lead to a significant increase in viscosity, inhibit atomization in MQL systems, and trigger rapid agglomeration and sedimentation (Gemechu et al., 2024; Makhesana et al., 2023). The optimal concentration varies depending on the combination of particles and application. For example, the MoS_2/CNT formulation shows optimal lubrication performance at a concentration of 6% weight with a certain ratio (Zhang, Li, Jia, Zhang, & Zhang, 2015).

Nanoparticles with smaller sizes (typically < 100 nm) have a higher surface area to volume ratio, which could theoretically improve heat transfer and interaction with surfaces (Musavi et al., 2023; Sharma et al., 2016)]. The study reported that nanoparticles measuring about 30 nm resulted in the largest convective heat transfer coefficient and the lowest surface temperature (Wang et al., 2024) However, smaller particles are also more susceptible to agglomeration due to the stronger van der Waals force, thus demanding more effective dispersion methods.

The long-term stability of HNF is a prerequisite for practical application. Fouling, sedimentation, and agglomeration are the main challenges limiting their application (Gemechu et al., 2024; Musavi et al., 2023; Wang et al., 2024). The most common method of dispersion is the two-step method due to its practicality (Technologies, 2021; Zhao et al., 2025) The key process after mixing is ultrasonic sonication (usually 60 minutes to 3 hours) to break up the clumps and achieve uniform dispersion. The addition of surface active agents (surfactants) such as Sodium Dodecyl Sulfate (SDS) or Gum Arabic (GA) is also critical to improve colloidal stability by preventing clumping through electrostatic or steric repulsion (Namlu, Lotfi, & Kiliç, 2024; Sharma et al., 2016; Su, Wang, & Zou, 2023; Zhang et al., 2016). Additional techniques such as pH adjustment and magnetic stirring can also be used. Table 1 shows the comparison of the most effective HNF formulation synthesis based on nanoparticle type, da-sar fluid, and machining application.

3. Enhanced Cooling Mechanism

Peningkatan kemampuan NF/HNF untuk Controlling the temperature in the cut zone is a major factor that helps reduce tool wear and thermal deformation of the workpiece (Wang et al., 2024) Excessive heat in the cut zone can cause heat-induced deformation and accelerate tool wear (Gupta & Rathore, 2025; Wang et al., 2024)

Improved Thermal Conductivity: The improved cooling ability of Nanofluids is based on their superior thermophysical characteristics, especially their improved thermal conductivity and higher heat extraction capabilities compared to conventional base (Makhesana et al., 2023; Sharma et al., 2019, 2016; Wang et al., 2024). Solid nanoparticles, specifically metal particles, have exceptional specifications in terms of thermal conductivity. For example, copper has a thermal conductivity that is much 700 times higher than water and more than 3000 times that of engine oil (Wang et al., 2024)

Rapid Heat Dissipation: The addition of nanoparticles (NPs) to the base liquid allows nanofluids to dissipate heat from the primary shearing zone at a faster rate (Wang et al., 2024) Nanofluids using 30 nm nanoparticles have been reported to exhibit the largest convective heat transfer coefficient and the lowest average surface temperature (Wang et al., 2024) The increased thermal conductivity of NF allows the protection of the chisel's cutting edge from heat deformation, which ultimately results in a decrease in cutting force (Gupta & Rathore, 2025). In MQL, compressed air also facilitates efficient heat dissipation through forced convection (Kumar et al., 2016; Makhesana et al., 2023)

4. Micro-Lubrication Mechanisms

Nanofluids (NF) have generally been reported to reduce the Coefficient of Friction (COF) and increase the load bearing capacity of the friction section, resulting in a significant reduction in cutting force and improvement in surface integrity (Karakoç, Karabulut, & Ozaner, 2025; Kumar et al., 2016; Qiao et al., 2025; Wang et al., 2024).

The application of the liquid in the form of MQL aerosols allows the penetration of lubricants to very narrow chisel-workpiece interfaces effectively (Hakkı & Kaftanoğlu, 2025; Hakkı, Lotfi, & Kılıç, 2024; Makhesana et al., 2023). In addition, the addition of nanoparticles can increase the wettability of the lubricant (reducing the contact angle), which helps NF penetrate gaps and microcracks in the cut zone (Qiao et al., 2025; Wang et al., 2024) This high wetness power facilitates the lubrication process in the cut zone better, which minimizes frictional forces.

Nanoparticles that have a near-spherical or spherical structure (such as Al_2O_3 and CuO) function like microscopic ball bearings between two rubbing surfaces (chisel and workpiece) (Hakkı et al., 2024; Kumar et al., 2016; Makhesana et al., 2023). This mechanism converts the dominant sliding friction into a combination of rolling friction, effectively reducing direct metal-to-metal contact and minimizing friction and wear (Kumar et al., 2016; Makhesana et al., 2023; Technologies, 2021; Wang et al., 2024)

Nanoparticles, especially coated particles (such as MoS_2, Graphene, or hBN), tend to form thin, stable protective films or tribo-films on friction surfaces (Kumar et al., 2016; Makhesana et al., 2023; Peng et al., 2025; Technologies, 2021). This layer acts as a barrier that reduces contact between the tool and the workpiece (Wang et al., 2024) Hexagonal boron nitride (hBN) nanoparticles, for example, exhibit interlayer sliding when subjected to considerable shear forces, which is effective in reducing the coefficient of friction (Qiao et al., 2025) Hybrid particles can produce synergistic composite lubricant layers.

Nanoparticles have the ability to repair (mending) or fill microscopic gaps and cracks on the surface of the depressed workpiece. Nanoparticles also provide a polishing effect, which helps achieve smoother surface quality (Makhesana et al., 2023; Peng et al., 2025)

Based on the relative size relationship between the minimum film thickness and the diameter of the nanoparticles, the NMQL lubrication mechanism can be further classified into semi-ploughing lubrication, rolling lubrication, shear film lubrication , and particle aggregation lubrication [(Qiao et al., 2025).

5. Performance Evaluation in Various Machining Processes

The application of Minimum Amount Lubrication with Nanofluids (NMQL) and Hybrid Nanofluids (HNMQL) has proven significant potential to improve cutting performance, especially in hard-to-work materials such as Nickel (Ni) and Titanium(Ti)[(Kumar et al., 2016; Patole, Pol, Desai, & Kamble, 2021; Wang et al., 2024)-based alloys. This performance improvement is assessed based on key parameters, including cutting force, chisel wear, and workpiece surface quality (Ra) (Makhesana et al., 2023)

NF-MQL delivers outstanding results when processing AISI 4340 alloy steel. Research shows that NF-MQL reduces cutting force by 55.05% and chisel wing wear by 78% compared to dry conditions (Furkan et al., 2023; Makhesana et al., 2023; Wang et al., 2024)].

Specifically, the hybrid nanofluids of Al_2O_3/CuO in MQL at the turn of AISI 4340 were studied by varying ratios and concentrations. Hybrid nanofluids containing 0.75% by weight CuO and 0.25% by weight Al_2O_3 produce the lowest surface roughness and cutting force (Furkan et al., 2023; Gemechu et al., 2024; Haghnazari & Abedini, 2021).

In general, MQL has been shown to reduce cutting force by 40%, cutting temperature by 36%, and improve surface finish by 30% on AISI 4340 compared to dry and wet processes (Kumar et al., 2016)

SiO_2-based NF applied to AISI 4140 hard turning steel also showed a significant improvement in machining performance at 0.5% wt concentration (Yücel et al., 2021).

In AISI D3 tool steel turning, the use of ZnO-enriched nanofluids (in rice bran oil) under MQL reduced cutting force by 18.48%, tool wear by 51.96%, and surface roughness (Ra) by 12.84% compared to pure base fluids (Furkan et al., 2023).

A study combining Al_2O_3/Graphene Hybrid Nanofluids with Machine Learning (ML) optimization on AISI D3 turning showed that optimal conditions resulted in the desired surface roughness (0.16–0.45 mu) at a controlled chisel tip temperature (Gemechu et al., 2024)17,18. This analysis also concluded that nanofluids contribute up to 42.5% to the temperature control of the chisel tip.

The addition of Al_2O_3 nanofluids to coconut oil in MQL at AISI 1040 rounds showed superior reductions in wing wear (53% vs dry) and crater wear (37% vs dry), as well as improved surface quality (54% vs dry) (Tiwari et al., 2023).

In the *hard turning* AISI 304, the Al_2O_3/Graphene MQL Hybrid Nanofluids resulted in a reduction in surface roughness of 20.28% and a cutting force of 9.94% compared to a single Al_2O_3 MQL Nanofluid (Furkan et al., 2023; Khatai, Sahoo, Kumar, & Panda, 2025; Technologies, 2021).

The Al_2O_3-MWCNT Hybrid nanofluid used in AISI 304 steel turning showed better performance than the single Al_2O_3 nanofluid and was able to reduce tool wear by 11% and tool tip temperature by 27.36% (Sharma et al., 2019; Technologies, 2021; Wang et al., 2024) NF-MQL using sunflower seed oil-based nanoparticle CuO on AISI 316 reduced surface roughness by 34% and tool wear by 37.6% compared to dry machining (Sheriff, Shalaby, & Elkassas, 2025)

Turning the superalloy Inconel 625 using NF-MQL enriched with hBN nanoparticles has been shown to effectively reduce chisel wear, temperature, and surface roughness (Duan et al., 2024; Eltaggaz, Ali, Badwal, & Deiab, 2023; Gunan, Kivak, Yildirim, & Sarikaya, 2020; Haghnazari & Abedini, 2021). Another research showed that nano-solid lubricant-assisted NF-MQL can improve the turning performance of Haynes superalloy 25 (Peng et al., 2025). The use of NMQL in the superalloy Inconel 690 not only extends the life of the chisel but also reduces energy consumption by 56% compared to dry conditions (Duan et al., 2024). In the turning of Inconel 718, which is known to be difficult to work with due to its low thermal conductivity, the CuO MQL nanofluids have been optimized to minimize cutting forces and surface roughness (Furkan et al., 2023).

Experimental studies have consistently shown that NMQL and HNMQL offer superior performance compared to conventional cooling or pure MQL in the milling process (Kumar et al., 2016; Musavi et al., 2023). Şirin and Kıvak investigated the performance of MQL milling on the Superalloy Inconel X-750 using three combinations of Hybrid Nanofluids (HNFs): hBN-Grpt, hBN-MoS_2 and Grpt-MoS_2 (Gupta & Rathore, 2025; Technologies, 2021; Wang et al., 2024). The results of this study show that Hybrid nanofluids perform best compared to the other two hybrid conditions in all performance criteria, including cutting force, temperature, surface roughness, and chisel life (Gupta & Rathore, 2025; Wang et al., 2024). HNF nanofluids, specifically, increase the tool life by as compared to and compared to hBN-MoS_2 (Gupta & Rathore, 2025; Wang et al., 2024)

Improved machining efficiency of titanium alloys has been achieved through the application of MQL with Nanofluids (Hakkı et al., 2024; Wang et al., 2024). The use of Hybrid Nanofluids -MWCNT in MQL has been shown to be effective in the Milling Process of Ti-6AI-4V (Gupta & Rathore, 2025; Jafarian et al., 2022; Kumar et al., 2016)]. Other studies on milling showed that NMQL with a concentration of 3% to 4 wt of nanoparticles yielded the highest minimum film thickness (about 12 nm) and the lowest thermal boundary layer thickness (about μm), indicating optimal cooling and lubrication performance (Qiao et al., 2025).

A comparative study on milling Inconel 718 using Hybrid NMQL (MWCNT-TiO2) showed that HNMQL produced the lowest resultant cutting force, reducing the force to a certain extent compared to conventional cooling (CCF) (Hakkı & Kaftanoğlu, 2025) HNMQL is also 12% lower than -NMQL and 5% lower than -NMQL, making it the most sustainable choice in that comparison (Hakkı & Kaftanoğlu, 2025). In milling aluminum alloy AL6061-T6, the use of nanofluids based through MQL is able to reduce power consumption and lubricants (Kumar et al., 2016; Patole et al., 2021). Furthermore, carbon onion-enriched nanofluids are able to reduce the cutting force and surface roughness by as much as in aerospace duralumin milling (Gupta & Rathore, 2025; Kumar et al., 2016).

6. Sustainability and Economic Aspects

The integration of hybrid nanofluids (HNF) with Minimum Quantity Lubrication (MQL) techniques is a direct response to the demands of modern manufacturing to produce high-quality products while minimizing costs and environmental damage. The application of this technique is key to achieving sustainable machining.

MQL, also known as Near Dry Machining (NDM), is essentially a green machining approach as it drastically reduces the use of coolant (Makhesana et al., 2023; Zhang et al., 2015). This process offers a much cleaner, cheaper, and more environmentally conscious alternative to sustainable machining. The costs associated with conventional coolants can be as high as 16 to 20% of the total manufacturing cost (Furkan et al., 2023) MQL minimizes the volume of lubricants used, thereby significantly reducing the cost of purchasing lubricants (Makhesana et al., 2023).

MQL/NMQL is a viable alternative to wet machining, helping to mitigate the adverse impacts of conventional coolant on human health and the environment (Kumar et al., 2016; Makhesana et al., 2023). In NMQL, because the lubricant is sprayed in the form of a mist, it will mostly evaporate, preventing a negative impact on the surrounding environment. NMQL often shows superior performance in terms of energy consumption compared to dry conditions. For example, the application of NMQL (SiO2 nanofluid) in the milling process has been reported to reduce power consumption and lubricants (Makhesana et al., 2023) In the turning of Inconel 690 nickel alloy, NMQL reduces energy consumption by 56% compared to dry conditions (Duan et al., 2024).

Hybrid Nanofluids (HNFs) were developed to improve the performance of single nanofluids (NF) by integrating the thermal and triboological advantages of various nanoparticles (Hakkı et al., 2024). Although HNFs often provide better cutting performance (such as the lowest cutting force and the highest surface quality), sustainability evaluations should consider broader economic and environmental metrics.

To determine the most sustainable options, multi-criteria decision-making methods such as the Pugh Matrix Approach (PMA) are often used, which consider factors such as Environmental Impact, Lubricant Cost, Operator Safety, Surface Quality, and Tool Wear (Hakkı & Kaftanoğlu, 2025; Makhesana et al., 2023; Peng et al., 2025).

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In Inconel 625 machining, although both pure MQL and Nanofluid MQL (NMQL) scored the same total in Pugh Matrix analysis, NMQL scored higher for important criteria such as surface quality and tool wear (Makhesana et al., 2023). HNMQL (MWCNT-TiO2) is also rated as the most sustainable choice in Inconel 718 milling because it reduces cutting force by up to 19% compared to conventional cooling (Hakkı & Kaftanoğlu, 2025)

Although NF and HNF improve performance, there are cost considerations. Vegetable MQL oil alone is 6 to 8 times more expensive than synthetic oil, and the cost of preparing and purchasing nanoparticles adds to the total cost (Makhesana et al., 2023) Interestingly, in the S235JR structural steel orthogonal turning study, single NF (N-MQL) showed significant advantages in economic-environmental metrics: N-MQL lowered total machining costs by 76% compared to dry conditions, and 61% compared to HNMQL, thanks to significantly lower energy consumption and better tool life (Furkan et al., 2023). N-MQL also produces the most optimal overall carbon emissions, which are 60% better than pure MQL and 37% better than HNMQL (Furkan et al., 2023).

7. Challenges, Prospects, and Future Research Directions

Although Hybrid Nanofluids (HNF) combined with MQL (HNMQL) have demonstrated superior performance and sustainability potential, the widespread adoption of this technology on an industrial scale still faces a number of technical and economic barriers that need to be addressed through future research.

Critical issues such as fouling, sedimentation, and pressure drop significantly limit the application of nanofluids in practical applications (Wang et al., 2024) The sedimentation and agglomeration (clumping) of nanoparticles, caused by a high surface-to-volume area ratio, can drastically reduce the effectiveness of NF lubrication and cooling (Makhesana et al., 2023; Wang et al., 2024) NF stabilization requires methods such as pH adjustment, magnetic stirring, ultrasonication, or the addition of surfactants, which add complexity to the production process (Eltaggaz et al., 2023; Karakoç et al., 2025).

There are technical difficulties in building a mature production system for nanofluids, which ultimately hinders large-scale application in industrial production (Wang et al., 2024). The main challenge from an economic perspective is the high costs associated with these fluids. Vegetable MQL oil alone can be 6 to 8 times more expensive than synthetic oil, plus the cost of purchasing nanoparticles and preparing the nanofluids themselves (Makhesana et al., 2023). Further research is needed to develop cost-effective and large-scale production of nanofluids (Wang et al., 2024).

The use of nanoparticles poses occupational health and safety concerns, including the potential hazards and risks of engineered nanoparticles to the environment and human health (Makhesana et al., 2023) Although exposure to nanoparticles during nMQL application can be controlled with appropriate safety measures (Eltaggaz et al., 2023; Makhesana et al., 2023), there must be standard safety procedures (such as safety data sheets) for nano-additives, and nanofluids must be screened before disposal (Eltaggaz et al., 2023).

Although performance has been improved, the physicochemical mechanisms underlying the application of nanofluids in machining are still not fully clear (Su et al., 2023; Wang et al., 2024) Further research is needed on the impact of the size and shape of the nanoparticles inserted to optimally improve performance (Wang et al., 2024; Xiong et al., 2021).

Future research directions need to focus on three main pillars: the development of more advanced hybrid fluid delivery systems, the deepening of material characterization and mechanisms, and the integration of artificial intelligence for holistic optimization. In terms of systems, the integration of HNF-MQL with multi-energy technologies, such as Ultrasonic Vibration-Assisted Machining (UVAM), Electrostatic Atomization MQL (EMQL) which reduces fog and increases deposition, and Cryogenic MQL (Cryo-MQL) for extreme cooling is a key prospect, supported by the development of intelligent tool holders and systems capable of directing nanoparticles with precision. On the material side, research should delve into the interaction mechanisms of nanofluids with various materials and machining parameters, explore new generation of nanoparticles and more environmentally friendly base fluids (such as ionic liquid-based lubricants), as well as conduct comprehensive tribological testing and evaluation of self-lubricated ceramic cutting tools. Finally, AI-based optimization needs to be developed beyond conventional methods (such as RSM and ANN) by investigating more advanced machine learning algorithms for predictive modeling of performance and wear and tear, as well as conducting in-depth energy analysis to improve process sustainability.

CONCLUSIONS

This comprehensive review confirms that Hybrid Nanofluids (HNFs) applied through Minimum Quantity Lubrication (MQL) offer a highly effective and sustainable solution to address the challenges inherent in conventional machining processes. MQL Nanofluids (NMQL) and HNMQL technologies have been proven to be viable and environmentally friendly alternatives compared to wet machining, which is an important strategy to achieve sustainable manufacturing goals.

The key findings of the performance evaluation and mechanisms are as follows:

1. Performance Improvement: Nanofluid lubrication has significant potential to improve machining efficiency, chisel life, and surface quality. In friction and wear testing, the friction coefficient of oil-based nanofluids (jatropha oil-based nanofluids) reinforced with alumina was reduced by up to 85% compared to dry conditions.
2. Hybrid Advantages: Combination nanoparticles (HNFs) often result in better performance than single Nanofluids (NF). For example, in the turning of AISI 304 stainless steel, HNMQL (Al_2O_3/Graphene) provides a 20.28% reduction in surface roughness and a 9.94% cutting force compared to a single NF Al2O3.
3. Cutting Force and Tool Wear: The application of NMQL/HNMQL consistently results in lower cutting forces compared to conventional cooling (CCF). In milling superalloy Inconel 718, HNMQL (MWCNT-TiO_2) reduces cutting force by 19% compared to CCF, and 5% compared to MWCNT-NMQL. Furthermore, the addition of Al_2O_3 Nanoparticles to MQL can increase the tool life by 177-230% in hard milling.
4. Lubrication Mechanism: Nanoparticles improve lubrication by reducing friction and wear. These mechanisms include the formation of a thin lubricating film and a rolling friction effect, where the nanoparticles function like microscopic ball pads between rubbing surfaces. Layered structured hBN nanoparticles have been shown to effectively reduce friction coefficients through interlayer sliding mechanisms and protective film formation.
5. Sustainability Aspects: MQL is a suggested technique to facilitate eco-friendly machining and is a viable alternative to wet machining(Kumar et al., 2016). MQL nanofluids (NMQL) often earn high total sustainability scores in multi-criteria assessments due to improved surface quality and sculptural life.

Although the potential of HNF-MQL is proving strong, widespread industrial adoption is still hampered by technical challenges, such as the issue of sedimentation and agglomeration of nanoparticles, as well as high-cost factors and the need for a mature production system. In addition, the physicochemical mechanisms underlying the application of nanofluids in machining still require more in-depth theoretical explanations. Therefore, future research should focus on three main pillars:

1. Optimization and New Materials: Investigating the effects of different types, sizes, and concentrations of HNF nanoparticles to identify the most effective configurations for specific processes and materials.
2. Comprehensive Mechanism: Conduct a more comprehensive triboological study to understand in depth the mechanisms that govern the interaction between nanoparticles and the machining environment, which will help optimize the lubrication performance of the NF-MQL system.
3. Technology Integration: Exploring the integration of HNMQL with advanced liquid delivery technology, such as Electrostatic Atomization MQL (EMQL), which can reduce ambient oil mist and improve the efficiency of settling lubricant droplets to cut zone.

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