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ABSTRACT

In recent years, sustainability has evolved profoundly and garnered significant global attention, establishing itself as a pivotal topic in contemporary research. In line with this development, the present review thoroughly examines existing studies on machining processes employing minimum quantity lubrication (MQL). The growing imperative for sustainable practices has driven researchers to reassess alternative lubrication techniques within machining operations. Although conventional lubri-cooling agents continue to be widely used for machining engineering alloys, an expanding body of research demonstrates that the incorporation of vegetable oils, nanofluids, and nanoplatelets into MQL systems can yield superior performance compared to traditional methods. The review presents an overview of recent developments and advancements related to MQL technology and provides a rigorous analysis of the performance of vegetable oils and nanofluids as metalworking fluids. This study also demonstrates that eco-friendly MQL approaches can be a sustainable alternative to traditional flood lubrication and serves as a meaningful resource to move toward greener machining solutions.

I. INTRODUCTION

Machining stands as one of the most versatile automated manufacturing methods, which produces accurate dimensions and preferred shapes and produces fine surfaces by converting materials into chips or flakes.[1–3] Significant research during modern decades has examined how to improve machining efficiency by enhancing lubrication methods.[4] Traditional cutting fluids generate major environmental problems together with serious health impacts. Water pollution and land contamination alongside waste production and dangerous air emissions arise from traditional cutting fluid usage, as Weinert *et al.*[5] explain these concerns to be significant areas within the ISO 14000 standards framework. The standards present ecological stability standards through socioeconomic measures to achieve pollution reduction and waste management while protecting natural resources.[6–8] Manufacturing companies aim to decrease their need for cutting fluids because financial considerations combine with environmental restrictions.

MQL represents an emerging sustainable solution that supports the sustainability goals. The implementation of MQL techniques allows decreased cutting fluid usage, which results in substantial cost reductions for lubrication.[9] MQL functions as an efficient method of delivering lubricant directly to tool-workpiece interfaces and goes by the names "Near-Dry Machining"[10] or "Micro Lubrication."[11] Numerous academic works[12,13] demonstrate that the system provides economic advantages through longer tool measurements and decreased energy use, along with its cost efficiency. The main hurdles in adopting fluid jet systems include their high costs along with difficulties in achieving proper lubricant delivery to the machining zone. The development of mist lubrication methods together with Minimum Quantity Cooling Lubrication (MQCL) has emerged as an advanced solution to resolve existing challenges. MQCL delivers combined tool-workpiece interface cooling and lubrication through the use of emulsions to maintain ideal temperature and lubricating effects.[14] Industrial adoption of MQL and MQCL technologies remains slow because they require more development and wider usage in industrial applications.

MQL offers extensive positive influences on the environment, as extensively proven. The technique minimizes cutting fluid usage, which leads to reduced water pollution risks and decreased hazardous waste discharge. Maruda *et al.*[15] documented how MQCL implemented tool wear reduction techniques, while Mia *et al.*[16] discovered that MQCL processes maintain sustainability potential through water-to-oil ratios of 9:1. The enhancements of these systems need to be evaluated together with their operational boundaries. MQL's cooling efficiency surpasses dry machining, but it delivers less efficiency than conventional flood cooling systems.[17] Research shows MQL systems deliver surface roughness and dimensional precision similar to or superior to traditional methods as well as upgrade these performances.[18] The research field requires more investigation into the optimization of MQL parameters such as nozzle distance, airflow, and droplet size.[19,20] Social sustainability evaluations should assess MQL techniques. The MQL system-generated airborne mist represents a health concern that offsets some of the safety improvements provided by cutting fluid reduction. Research published by Rodriguez *et al.*[21] proves that airborne emissions from coolants generate health concerns for individuals who work with MQL techniques. Workplace safety depends on proper mist control systems, which must include enhanced ventilation systems along with non-harmful mist composition for environmental protection. The adoption of MQL technology by the industry requires solving social concerns to establish holistic sustainable manufacturing practices.

The performance of machining functions greatly benefits from the implementation of MQL technology. The experimental findings from different studies establish MQL as a technique that minimizes cutting forces and enhances tool-chip dynamics while supporting tool edge retention. Upadhyay *et al.*[22] explored the complex interplay between key machining parameters and minimum quantity lubrication (MQL) conditions. Based on this analysis, a fishbone diagram has been created, as illustrated in Fig. 1. The reduction of cutting forces occurs with higher MQL flow rates yet reaches a saturation point.[23] The application of MQL leads to surface roughness results comparable to flood cooling methods, which makes it a superior alternative to dry machining approaches.[24] The advantages of MQL machining come with the requirement for additional research because material properties and machining parameters influence result stability.

MQL represents a pivotal advancement in sustainable machining, addressing environmental, economic, and machining performance challenges. However, its social implications, particularly regarding worker health and safety, demand greater attention. The machinability of high-strength engineering alloys remains a pivotal area of research due to the inherent challenges in their processing. Consequently, numerous investigations have focused on the effectiveness of MQL in machining applications. This study contributes by providing a comprehensive analysis of MQL-assisted machining strategies, highlighting its contextual relevance and potential within the machining landscape. A holistic approach, integrating advancements in mist control, parameter optimization, and collaborative policy development, is essential for realizing the full potential of MQL as a sustainable machining solution.

II. RESEARCH AIMS AND STRATEGIES

The primary objectives of this research are to consolidate relevant studies within the specified domain, pinpoint key areas where the MQL technique has been successfully implemented, and underscore the advantages of incorporating vegetable oils, nanofluids, and nanoplatelets in diverse MQL applications. The research evaluates sustainability aspects of MQL-assisted machining and examines

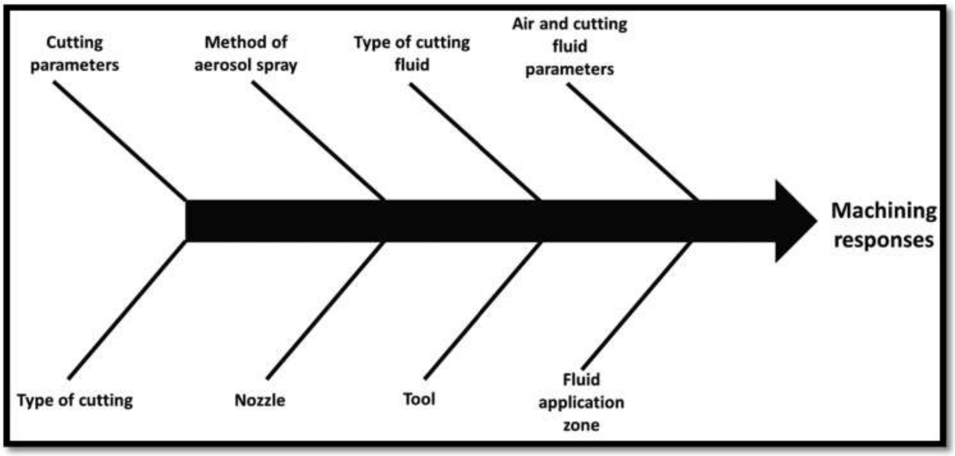

FIG. 1. Fishbone diagram illustrating the MQL machining conditions.

barriers this method faces along with prospective developments of the MQL approach. A systematic review, according to Denyer and Tranfield,[25] needs to exhibit four essential traits: reproducibility, exclusivity, data aggregation, and algorithmic rigor. To achieve a thorough evaluation of the MQL literature, researchers followed the defined framework. This systematic analysis required researchers to establish unique research queries that determined the review's boundaries and then studied a large number of relevant resources as they traced MQL's evolutionary history. The developed research meticulously analyzed collected studies to determine both strengths and weaknesses of MQL method implementation. Researchers used insights gained from this extensive review process for developing well-supported conclusions.

A specific method ensured a comprehensive literature review using selection criteria that guided the research process. Researchers executed their search in the academic databases of Scopus along with Web of Science and Science Direct. The research keywords focused on both "performance of vegetable oils in MQL-assisted machining" and "performance of nanofluids in MQL-assisted machining." The strategy for searching publications included restrictive criteria of English documentation while keeping the outcome to journal articles and conference papers to ensure quality and relevance. The search parameters included every available relevant publication extending from the current year until October 2024. The evaluation started with title and abstract tests to eliminate irrelevant papers before researchers conducted complete text analyses of remaining studies. The initial screening yielded 1500 publications, out of which the research examined only studies related to eco-friendly MQL fluids utilized in machining operations (Fig. 2). The authors implemented thorough screening procedures that secured the inclusion of suitable and high-quality research articles for their review work.

Research activities regarding vegetable oils and nanofluids in MQL systems have experienced notable growth due to their prominent advantages. Researchers have conducted a thorough systematic effort to compile necessary studies about eco-friendly MQL

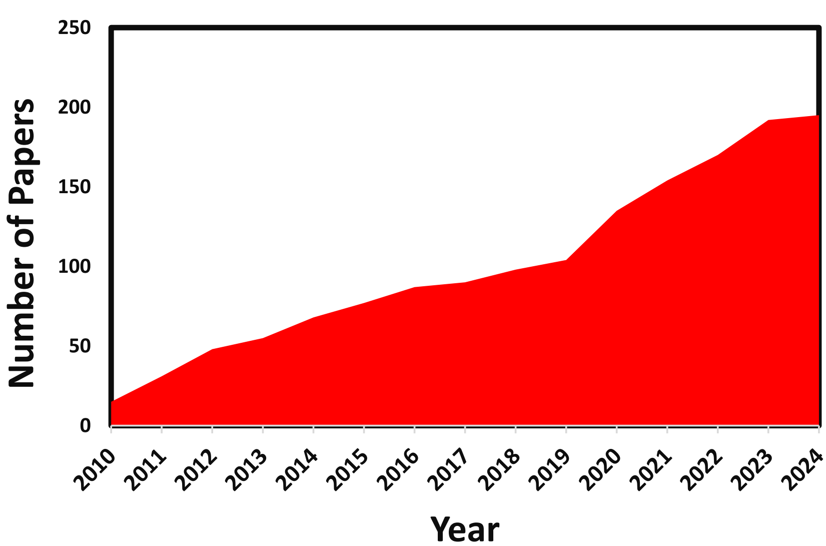

FIG. 2. Number of articles published annually (data sourced from Scopus, Web of Science, and Science Direct).

fluids. The implementation of environmentally friendly lubricants in machining operations has become primary because of escalating environmental worries along with an urgent need for sustainable practices. A comprehensive review of current literature reveals that, despite the widespread use of vegetable oils and nanofluids in various machining applications, their utilization in the machining of heat-resistant alloys and superalloys remains relatively unexplored. This highlights a critical research gap, underscoring the urgent need to expand investigations into the efficacy of environmentally benign lubricants in enhancing the machining performance of superalloys.

III. CONVENTIONAL MQL PRACTICES

A. Effectiveness of vegetable oils

The utilization of conventional cutting fluids has raised significant environmental and health concerns, prompting many researchers to strive for a reduction in dependence on traditional lubricants. In this context, dry machining has gained popularity as a viable alternative to minimize cutting fluid usage. However, this method introduces increased friction and adhesion at the tool-workpiece interface, resulting in higher thermal loads on both components, which accelerates wear, diffusion, and oxidation. Furthermore, the lack of cutting fluids complicates chip removal from the machining zone, potentially exacerbating wear and tear.[26] Recently, some studies have explored the application of solid lubricants to provide cooling and lubrication solutions.[27–30] Despite this, the majority of researchers are increasingly focusing on the environmentally sustainable MQL technique, which significantly reduces coolant usage while promoting ecological responsibility. Belluco and De Chiffre[31] conducted a detailed analysis of five vegetable oils as lubricants in the drilling of AISI 316L, using chip formation, tool life, and cutting forces as key performance indicators. The investigation by the research team established that vegetable oils led to tool life extensions by as much as 177%. Ojolo *et al.*[32] studied forces in the machining of copper along with mild steel and aluminum while using groundnut, palm kernel, shea butter, and coconut oils as vegetable oil materials. Research findings showed that vegetable oils improve turning operations, but palm kernel and groundnut oils specifically provide maximum reductions in cutting forces depending on the processed material. The research by Khan *et al.*[33] examined how vegetable oil operated as an MQL base fluid when turning AISI 9310 steel with carbide tools without coatings. The researchers studied chip formation as well as surface roughness tool wear and cutting temperature under three machining conditions consisting of dry operation, wet operation, and MQL-assisted operation. The researchers documented that elevated cutting speed and feed rate elevated cutting temperatures, yet these rising temperatures did not affect chip morphology. The authors concluded that MQL-assisted machining delivered superior operational results compared to both dry and wet machining techniques.

Xavior and Adithan published their experimental study about vegetable oil-based lubricant effects on tool wear alongside surface morphology during AISI 304 steel machining approximately ten years ago.[34] Their research used carbide tools to test the efficiency between coconut oil, emulsion, and non-water-miscible cutting oil. The investigators discovered that coconut oil created superior machining outcomes, but the emulsion produced restricted alterations to tool wear and surface roughness measurements. Researchers at Kuram *et al.*[35] studied how different cutting fluids influenced the drilling process of AISI 304 steel through utilization of an HSS-E tool. Commercial oil proved optimal for machining operations under spindle speed 720 rpm because it produced minimum surface roughness and thrust force results. The application of olive oil in MQL systems for turning hardened steel received evaluation from Mia *et al.*,[36] who examined its biodegradable characteristics. The performance evaluation, including surface quality and cutting temperature zone analysis, determined that MQL cooling with olive oil outperformed other coolant methods, which made it the optimal sustainable solution. Ross *et al.* conducted research on the machining processes of AlSi10Mg specimens through coolant testing to optimize surface quality.[37] The authors protested against mineral-based traditional cutting fluids because of their negative environmental impact and health risks while advocating for vegetable oils that would provide sustainable alternatives. Surface roughness, together with heat generation and cutting temperatures, decreased significantly when using soybean oil and other vegetable oils as a lubricant under MQL compared to standard flood coolant. Tensile strength, along with hardness and wear resistance, proved to improve as one of the study's noted achievements. Microstructures obtained from using MQL with vegetable oil produced refined grain arrangements that enhanced cutting efficiency while supporting environmental sustainability. In their work, Wang *et al.*[38] examined the lubri-cooling effect of multiple green oils when used in the machining process of GH4169. The researchers arranged mineral and vegetable oils according to their effectiveness, which resulted in the ranking of castor oil followed by palm oil and then peanut oil and sunflower oil and soybean oil and rapeseed oil and ending with maize oil. The research developers used a thorough examination of crucial grinding parameters to create this ranking system. Moreover, Fig. 3 illustrates the machined surface behavior of GH4169 obtained under different lubri-cooling conditions.

A multitude of studies has demonstrated that the integration of vegetable oil with MQL produces enhanced performance relative to conventional lubrication systems, attributed to several critical factors. First, vegetable oils are abundant in fatty acids and triglycerides, which contain polar functional groups such as –COOH and –COOR. These polar groups act similarly to microscopic magnets, forming a lubricating film on the work surface (see Fig. 4).[39] This film significantly diminishes friction and wear throughout the machining process. Furthermore, research conducted by Sarkar *et al.*[40] indicates that at higher temperatures, these polar molecules engage with the metal surface to form a metallic soap film, thereby improving lubrication properties. In addition, the fatty acid chains within vegetable oils are composed of non-polar methyl groups, which generate London dispersion forces. These intermolecular forces facilitate attractive interactions among the molecules, and as the number of carbon atoms in the fatty acid chain increases, so does the dispersion force, further enhancing lubrication. Finally, the droplets of vegetable oil display elevated viscosity at increased cutting temperatures, enabling them to persist longer in the cutting zone and thereby augmenting the lubrication effect during machining operations.[40]

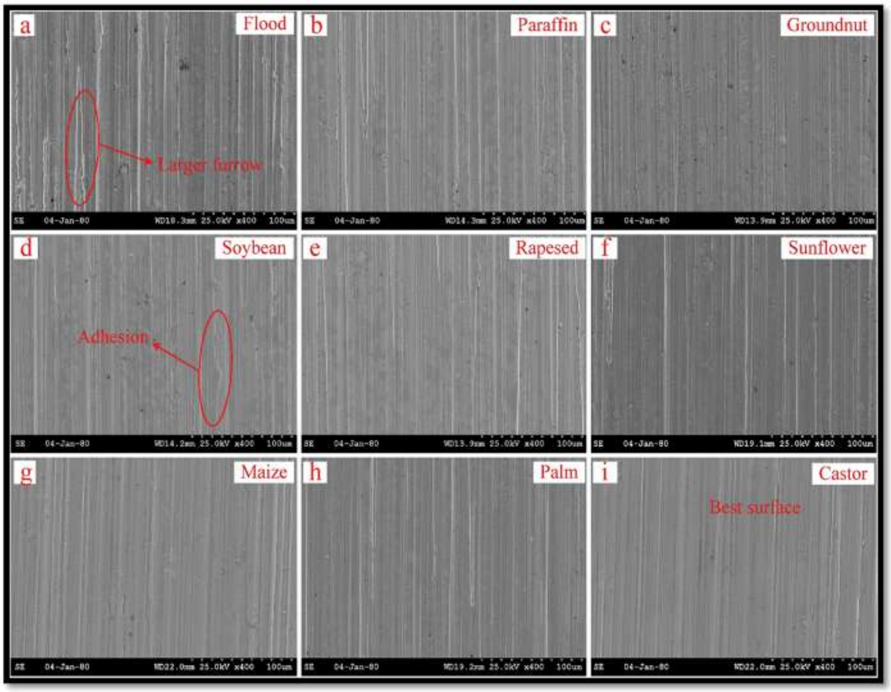

FIG. 3. Comparative analysis of the surface morphology of GH4169 under lubri-cooling conditions.[38] [Reproduced with permission from Wang *et al.* J. Cleaner Prod. **127**, 487–499 (2016). Copyright 2016 Elsevier.]

B. Effectiveness of nanofluids

MQL is acknowledged as a highly effective alternative to conventional cooling methods. It offers manufacturers a practical solution when dry machining is impractical, particularly in scenarios where machining efficiency and the quality of the cutting surface are crucial. In addition, the integration of nanoparticles and nanoplatelets into MQL base fluids has demonstrated significant potential in minimizing friction during machining processes. These nano-additives are increasingly perceived as a sustainable and cost-effective substitute for conventional flood lubrication, especially in light of growing environmental concerns. Considering the vast array of research on nanofluids, a comprehensive review is warranted to capture the breadth of available studies. Therefore, this section presents a concise overview of MQL systems enhanced with nanofluids to align with the objectives of the work.

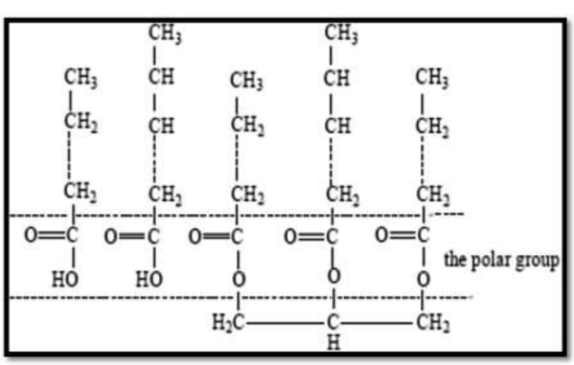

FIG. 4. Vegetable oil molecule with polar characteristics.[39] [Reproduced with permission from Debnath *et al.*, J. Cleaner Prod. **83**, 33–47 (2014). Copyright 2014 Elsevier.]

A few years ago, Vasu and Pradeep Kumar Reddy[41] conducted an experimental study to assess the influence of diverse lubricating media, including green oils, nanofluids, and dry conditions, on the machinability improvement. The findings revealed that the synergistic use of vegetable oil combined with Al_2O_3 nanoparticles significantly reduced cutting zone temperature and machining forces relative to other lubrication methods. Subsequently, Mandal *et al.*[42] investigated the impact of nanoparticle volume fractions on MQL in grinding processes, utilizing AISI 52100 as the workpiece material. They synthesized nanofluids containing Al_2O_3 nanoparticles of 40 and 80 nm diameters at concentrations of 1%, 3%, and 5%. Their findings revealed that increased nanoparticle volume fractions adversely affected machining performance relative to lower fractions. Setti *et al.*[43] investigated the impact of CuO and Al_2O_3 nanoparticles on the machining of Ti–6Al–4V, revealing that Al_2O_3 nanofluids produced the lowest frictional coefficient compared to other environments. Similarly, Mao *et al.*[44,45] concentrated on the efficacy of Al_2O_3-based nanofluids in the machining of AISI 52100. Both studies demonstrated that the alumina-reinforced deionized water substantially reduced grinding forces and the coefficient of friction; however, it was noted that larger nanoparticle diameters adversely affected surface finish quality. Furthermore, Sharma *et al.*[46] formulated nanofluids by blending a 1% volumetric concentration of Al_2O_3 into an emulsion, which served as the lubricant during machining operations on AISI 1040. Their experimental results indicated reductions of 25.5% in surface roughness, 5.27% in tool wear, and 28% in cutting force compared to traditional flood machining methods.

In a comprehensive research study by Padmini *et al.*,[47] a hybrid suspension of micro as well as nanoparticles comprising boric acid and MoS_2 was formulated in coconut and sesame oils for use as lubricants. The findings revealed that nano-fluids exhibited a markedly superior performance compared to their micro-fluid counterparts, effectively minimizing cutting temperatures, reducing cutting forces, and enhancing surface finish during machining operations. The research group of Zhang *et al.*[48] examined how MoS2 nanoparticles work with palm, soybean, and rapeseed oils when used in MQL-assisted grinding processes. Adding MoS2 to soybean oil generated the best results for grinding operations. During the machining of AISI 1040 steel, Padmini *et al.*[49] evaluated MoS2 applicability in sesame, coconut, and canola oils by performing thorough evaluation tests. They discovered that a 0.5% concentration of MoS_2 in coconut oil markedly improved operational efficiency, yielding reductions in machining responses when contrasted with traditional dry machining practices.

Nam *et al.*[50] undertook a comprehensive investigation into the utilization of diamond nanoparticles measuring 30 nm in diameter, which were dispersed in vegetable oil and paraffin oil, serving as distinct base fluids. These nano-fluids were utilized as lubricants in the machining process of Al-6061. The experimental results indicated a significant reduction in drilling torque when employing both types of nano-fluids. Notably, the nano-fluid based on paraffin oil demonstrated enhanced lubrication performance compared to its vegetable oil counterpart. In a follow-up investigation, Nam *et al.*[51] found that diamond nanoparticles with a larger diameter were less effective in drilling applications.

Sarhan *et al.*[52] conducted milling operations utilizing SiO_2 nanofluid as a lubricant, revealing through their experimental investigations a marked reduction in both cutting forces and specific energy consumption when contrasted with conventional oil. Similarly, Sayuti *et al.*[53] studied the influence of silica nanofluids on the machining performance of AISI 4140. Their findings indicated that optimal surface roughness was achieved with a 300° nozzle angle in an MQL setup, accompanied by a 0.5% weight concentration of SiO_2 and low air pressure. In addition, they observed that tool wear was minimized at a 600° MQL nozzle angle, with the same SiO_2 concentration maintained under an air pressure of 2 bar. Furthermore, Ooi *et al.*[54] investigated milling processes involving the Al-6061-T6 alloy lubricated with SiO_2 nanofluid and developed a fuzzy model to elucidate the results, attaining an impressive accuracy range of 91.37%–98.27% when juxtaposed with the actual experimental data.

You and Gao[55] conducted an investigation into the incorporation of carbon nanotube (CNT) particles in the context of nano-machining. Research data revealed that grinding wheels containing CNTs reach superior performance levels, which makes them suitable as cutting edge materials. Rao *et al.*[56] executed a specific experimental research where they investigated turning process changes through different CNT nanoparticle volumes added to the base fluid. The addition of 2% CNTs in the mix led to diminished tool wear while simultaneously decreasing cutting temperature levels. The depiction of AISI D3 steel grinding using atomic force microscopy (AFM) was achieved by Prabhu and Vinayagam[57] while they utilized Taguchi's methodology for designing and optimizing grinding parameters. The researchers performed regression analysis to establish predictions about the final machining results. Research findings showed that CNT nano-fluids create superior performance in micro-cracking and surface roughness reduction within dry machining operations. The influence of silica nanofluids on AISI 4140 steel during machining procedures was evaluated by Sayuti *et al.*[58] Surface roughness reached its lowest point when researchers used 0.5% SiO2 weight concentration in their MQL nozzle setup designed at 30° while maintaining low air pressure levels. Tool wear reached its best state when combined with a 60° nozzle angle along with 2 bar air pressure and 0.5% weight concentration of silica nanofluid.

Hybrid nanofluids that combine two or more nanoparticles suspended inside a base fluid receive tremendous interest in MQL-assisted machining because they raise thermal conductivity levels and enhance lubrication performance while decreasing tool wear. The combination of multiple nanoparticles in MQL leads to superior heat management along with minimized cutting tool-workpiece contact friction that yields both enhanced surface finishes and extended tool duration and better machining effectiveness. Ti–6Al–4V represents a machining problem that Lotfi *et al.*[59] examined because of its poor thermal conductivity properties. Their study demonstrated that Al_2O_3 and CuO nanofluids, in both individual and hybrid forms, outperformed pure-MQL, conventional fluids, and dry machining, improving cutting forces, surface roughness, microhardness, and surface finish. Ma *et al.*[60] investigated the machinability of the nickel-based superalloy GH4169, commonly used in aerospace. Their GnP-ZrO_2 hybrid nanofluids improved lubricity, cooling, and machining performance, reducing friction and enhancing surface roughness, cutting temperatures, and tool life compared to other cooling conditions. Li *et al.*[61] investigated the properties and performance of nanofluids containing GnPs, Al_2O_3, and a hybrid nanofluid. The study revealed that the incorporation of nanoparticles improved thermal conductivity, viscosity, and contact angle, with GnPs showing better thermal conductivity and Al_2O_3 providing superior surface quality. Hybrid nanofluids combined the advantages of both, performing better in grinding force, energy consumption, and surface roughness. Recently, Hakki Namlu *et al.*[62] combined Ultrasonic Vibration-Assisted Machining (UVAM) with Al_2O_3–CuO hybrid nanofluid for machining Inconel 718. UVAM reduced cutting forces and improved surface quality, while the hybrid nanofluid further optimized machining performance, leading to better surface finishes, cutting efficiency, and overall machinability of Inconel 718.

The research community strongly pursues graphene nanoplatelets (GnPs) because they show excellent lubrication performance and excellent thermal conducting ability. Extensive scientific research dedicated in part to GnP applications for MQL technologies has been ongoing for the past ten years. Huang *et al.*[63] performed a laboratory study that proved the significant increase of paraffin oil's anti-wear performance when GnP was added to the mixture according to their research. Similarly, Marcon *et al.*[64] explored the integration of GnP into cutting fluids during micro-milling operations, demonstrating that these GnP-enhanced fluids effectively reduced both tool wear and cutting temperature.

In a related study, Alberts *et al.*[65] assessed the efficacy of GnP in grinding applications, revealing that GnP-enriched cutting fluids conferred distinct advantages in the grinding of D2 steel. Furthermore, Ravuri *et al.*[66] utilized GnP-embedded grinding wheels for machining Inconel 718, reporting significant improvements in wheel durability and machinability. More recently, Pavan *et al.*[67] conducted an experimental study in an MQL-supported machining framework, concluding that the addition of optimal GnP to the MQL fluid markedly improves the surface morphology of superalloy. Moreover, Kwon and Drazel[68] patented a GnP-based technology, demonstrating its efficacy in diminishing chipping and extending tool longevity. In a separate investigation, Wang *et al.*[69] indicated that alumina nanoparticles exhibited excellent lubrication characteristics paralleled to other nanoparticle alternatives. Their experiments on superalloy, utilizing palm oil, ranked the lubricating effectiveness of various nanoparticles in the following order: ZrO_2 < CNT < ND < MoS_2 < SiO_2 < Al_2O_3. Figure 5 illustrates the surface quality of ground materials in varying conditions. In addition, a number of researchers, including Beyth *et al.*,[70] Marsalek,[71] Salehi *et al.*,[72] and Tseng *et al.*,[73] have substantiated

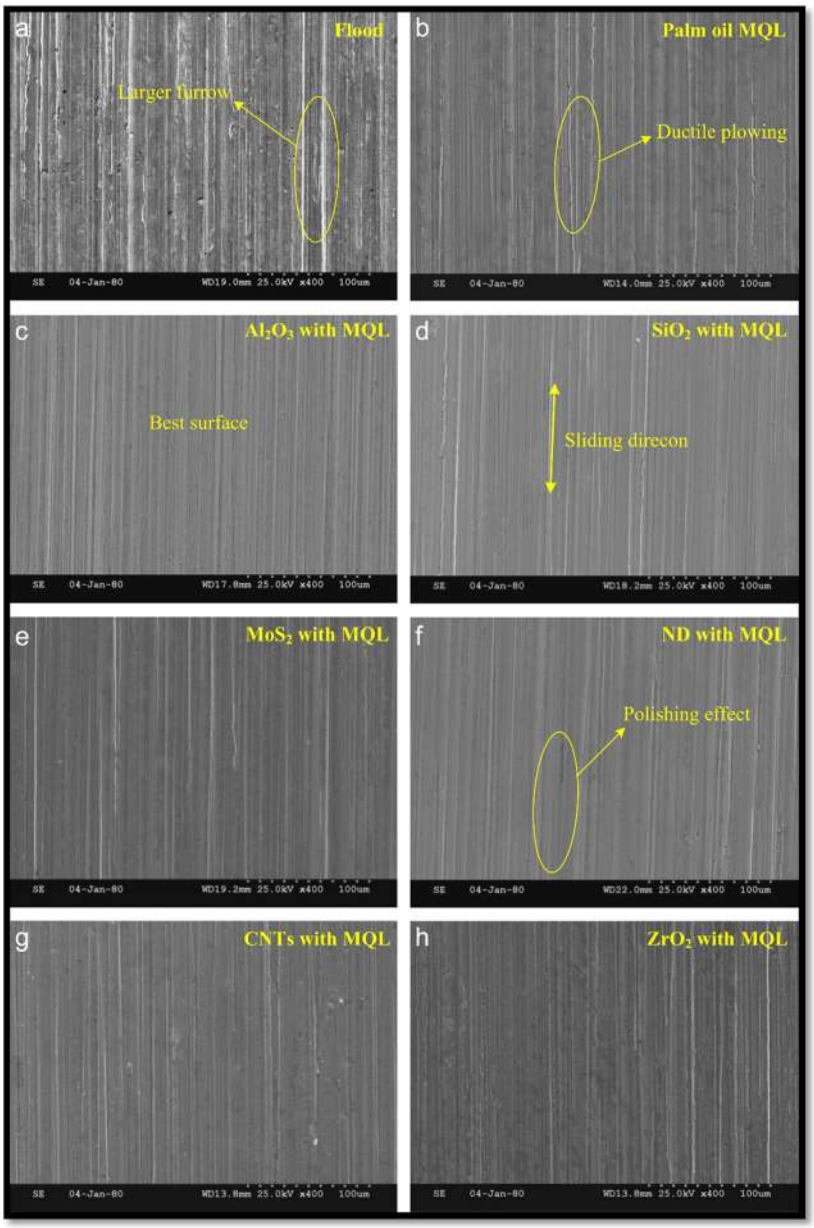

FIG. 5. SEM micrographs showcasing the surface of the GH4169 workpiece in diverse MQL conditions.[69] [Reproduced with permission from Wang *et al.*, Tribol. Int. **99**, 198–210 (2016). Copyright 2016 Elsevier.]

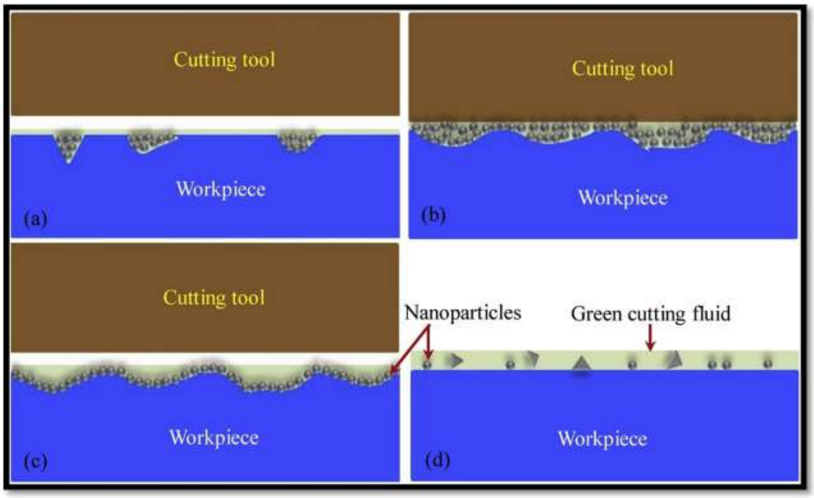

FIG. 6. Nanoparticles at the tool-workpiece interface showcasing several benefits: (a) mending, (b) rolling, (c) lubricating film formation, and (d) polishing.[74] [Reproduced with permission from Gajrani *et al.*, J. Mater. Process. Technol. **266**, 125–139 (2019). Copyright 2019 Elsevier.]

the antimicrobial, antibacterial, non-toxic, and deodorizing properties of nanoparticles, thereby reinforcing the principles of green manufacturing.

Nanoparticles possess inherent instability and unsaturation due to the existence of unoccupied bonds, rendering them susceptible to easy attachment to surrounding atoms. When these nanoparticles are introduced into polar molecules in vegetable oil, they produce elevated surface energy, thereby enhancing their interactions within lubrication contexts. The distinctive surface characteristics of nanoparticles play a pivotal character in their performance in cutting environments. The addition of diverse nanoparticles into MQL fluids has demonstrated a significant reduction in friction and wear rates, resulting in improved tribological attributes of lubricants. Furthermore, nanoparticles are known to form a protective surface film, contributing to enhanced lubrication efficiency. During machining operations, circularly shaped nanoparticles promote the transition from sliding to rolling–sliding friction at the boundary between the tool and workpiece. In addition, these nanoparticles exhibit self-repairing properties, which can further augment machining efficiency. Their capacity to withstand substantial contact pressure facilitates an even distribution of compressive forces, thereby minimizing stress concentrations.[74] The lubrication mechanism of nanofluids is further illustrated in Fig. 6, highlighting the various interactions and advantages they offer in machining processes.

IV. THE ROLE OF MQL IN VARIOUS MACHINING OPERATIONS

The manufacturing operation known as turning is commonly used for making cylindrical objects, and researchers are increasingly adopting MQL methods for these applications. The process applies evenly to numerous types of materials. Mia *et al.*[75] conducted research on hardened steel turning with the MQL method to evaluate material removal rate alongside surface finish and tool degradation. The Taguchi signal-to-noise (S/N) ratio method enabled effective optimization of the variables. Researchers from Dhar *et al.*[76] carried out experimental tests to demonstrate MQL's benefits when used for turning AISI 1040 through decreased cutting temperatures and tool-workpiece friction. The traditional dry machining methods had lower secondary flank wear when compared to the findings reported by researchers. An experimental study by Thakur *et al.*[77] showed MQL as an effective process for working with Inconel superalloys by finding the best machining parameters. According to CheHaron *et al.*,[78] the plastic deformation from high-speed cutting became parallel with the cutting direction when they conducted a microstructural analysis. Mia *et al.*[79] evaluated the surface roughness changes that occur when fluid impingement flow rates fluctuate throughout MQL turning procedures. Researchers discovered that using a suitable coolant flow rate improved surface quality because it properly lubricated the cutting area. In their study of titanium-based alloys, Liu *et al.*[80] implemented a vortex tube in the MQL system for cooling, demonstrating that this configuration positively influenced machining responses, resulting in reduced surface roughness. Nevertheless, it was observed that cutting forces in the vortex tube-assisted MQL setting were marginally elevated compared to those encountered during conventional flood cutting. Liu *et al.*[81] further discerned that the feed rate emerged as the pivotal parameter influencing the outcomes of machining. Stephenson *et al.*[82] reported that the application of supercritical CO_2-based MQL technology significantly enhanced material removal rate (MRR) during turning operations, achieving an impressive 40% increase in MRR relative to traditional flood cooling while concurrently prolonging tool life. Finally, Sarıkaya and Güllü[83] implemented vegetable oil as the base fluid within their MQL process, employing Taguchi-based gray relational analysis for optimization. Their findings revealed that a cutting speed of 30 m/min and a flow rate of 180 ml/h minimized both tool wear and surface roughness effectively.

Although grinding is not the primary method for material removal, its significance is paramount in the production of high-performance components. To improve the quality of the results, the application of MQL in grinding processes has gained considerable attention. Khan *et al.*[84] led an experimental investigation into the machining of AISI D2 steel in MQL conditions, comparing it with traditional dry and wet machining techniques. Their research emphasized surface topography and optimization, ultimately concluding that MQL provided superior machinability compared to the other cooling methods. Similarly, Sadeghi *et al.*[85] examined the grinding of Ti alloy, utilizing artificial ester and green oil as base fluids in their MQL application. Their results revealed that synthetic ester outperformed vegetable oil in MQL applications. Barczak *et al.*[86] performed a comparative analysis of grinding across three machining environments: dry, flooded, and MQL. The findings indicated that the surface quality achieved through MQL-assisted grinding significantly surpassed that of the other techniques. Oliviera *et al.*[87] conducted a comprehensive investigation into the machining of tempered and quenched steel utilizing a cubic boron nitride grinder, augmented by MQL techniques and an air jet strategically positioned within the machining zone to enhance cleaning efficacy. The study aimed to evaluate several key performance of both the ground surface and subsurface. It underscored the advantageous role of the cleaning jet system as a noteworthy technological advancement in MQL, which effectively reduces lubricant consumption. In a related inquiry, Li and Lin[88] explored the effects of MQL in micro-grinding operations, demonstrating its effectiveness in reducing tool wear and surface roughness in micro-machining environments. Furthermore, Balan *et al.*[89] examined the impact of MQL parameters on the machining of nickel alloy, concluding that increased MQL pressure substantially enhanced machining outcomes, particularly regarding surface roughness and cutting forces. In the realm of MQL-assisted machining of 100-Cr-6, Hadad and Hadi[90] reported remarkable surface quality. However, they also highlighted certain limitations associated with the application of MQL technology in the grinding of 42-Cr-Mo4 steel. Furthermore, Rabiei *et al.*[91] validated the efficacy of MQL-assisted grinding for hard steel applications. Figure 7 illustrates the surface morphology of hard and soft steels subjected to different lubrication conditions, emphasizing variations in surface texture.

The milling process is extensively researched due to its diverse applications in high-performance engineering fields, including aerospace, automotive, and modern electronics. Effective cooling in the cutting zone has become essential, prompting numerous studies in this domain. For example, Sun *et al.*[92] conducted an investigation into milling operations employing MQL and compared their results with those derived from dry and wet cooling methods. Their findings revealed that MQL substantially enhanced lubrication within the cutting zone, resulting in improved tool longevity and a reduction in cutting forces relative to other cooling techniques. In a related study, Li *et al.*[93] examined milling operations on Inconel 718 using coated carbide tools, reporting a significant reduction in both tool wear and cutting forces. Their research

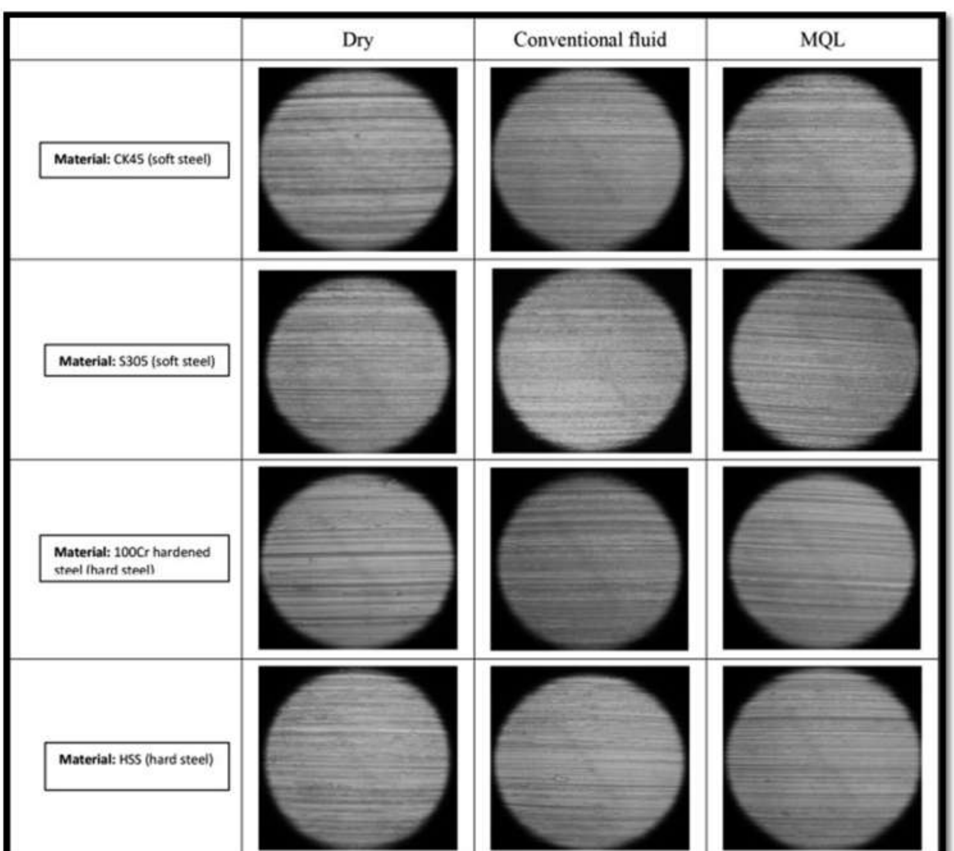

FIG. 7. Examining the surface morphology of hard and soft steels under different lubricating conditions.[91] [Reproduced with permission from Rabiei *et al.*, J. Cleaner Prod. **86**, 447–460 (2015). Copyright 2015 Elsevier.]

highlighted flank wear as a pivotal factor contributing to decreased tool lifespan. Furthermore, Da Silva *et al.*[94] undertook an analysis of different cooling conditions. They discovered that a reduced flow rate of MQL led to increased MRR and prolonged machining lengths, underscoring MQL's effectiveness in mitigating thermal cracking in hardened materials.In a separate investigation, Liu *et al.*[95] tested the machinability of titanium under MQL conditions while varying the parameters of the MQL system. They found that alterations in these input parameters significantly impacted cutting temperature and force, with an increase in lubricant supply from 2 to 14 ml/h leading to a marked reduction in the roughness of the machined surface. Wang *et al.*[96] conducted an extensive evaluation of the influence of MQL fluid flow, determining that flow rates of up to 10 ml/h yielded particularly advantageous outcomes. Zhang *et al.*[97] identified that the primary cause of tool wear during machining is severe chipping at the cutting edge. However, they reported a remarkable increase in tool longevity under MQL conditions, achieving one and a half times greater life of cutting tool compared to a conventional dry environment. Singh *et al.*[98] developed an intelligent predictive model for tool wear in Inconel machining utilizing MQL-assisted end milling, demonstrating that the MQL environment significantly outperformed both flooded and dry machining in mitigating tool wear. Furthermore, Mia[99] undertook a study examining surface roughness and specific cutting energy across various MQL flow rates, concluding that MQL substantially influenced both energy consumption and the quality of the machined surface. Xiang *et al.*[100] highlighted the challenges of achieving optimal tool life, surface quality, and residual stresses in the micro-machining of difficult-to-cut materials, particularly titanium alloys. Known for their poor thermal conductivity and high hardness at elevated temperatures, titanium alloys cause premature tool wear. Additively manufactured titanium alloys present even greater challenges due to their increased hardness. In micro-milling, the application of minimal cooling/lubrication is essential to mitigate heat generation, reduce tool wear, and prevent surface burning. This study focuses on evaluating the effectiveness of MQL in enhancing performance during the micro-milling of Ti–6Al–4V using coated tungsten carbide micro end mills under various cutting conditions. Recently, Li *et al.*[101] investigated the effects of machining parameters on the surface quality of titanium alloy holes formed by laser powder bed fusion (L-PBF). They compared dry and MQL medium in milling operation. The study revealed that L-PBF holes were smaller than theoretical dimensions, primarily due to collapsed areas and powder adhesion. MQL-assisted cutting improved surface quality, with minimal burrs and a dimensional error of 77 μm at a 20 mm/min feed rate. MQL reduced cutting forces, especially radial forces, and significantly decreased tool wear by forming an oil film on the machined surface.

Drilling is widely acknowledged as one of the most commonly employed manufacturing techniques, utilized across a broad spectrum of applications, from routine tasks to sophisticated engineering settings. The adoption of MQL in drilling processes has been examined to improve lubrication efficiency. The study conducted by Davim *et al.*[102] evaluated the impact of different cooling conditions on the machining of AA1050. The findings revealed that the enactment of MQL was comparable to that of conventional flooded methods. In addition, Bhowmick *et al.*[103] reported significant improvements in tool longevity when employing MQL in the drilling of magnesium alloys. Bhowmick and Alpas[104] further illustrated that drilling operations utilizing MQL required less torque than both dry and wet drilling approaches. In a distinct study, Rahim and Sasahara[105] conducted drilling experiments on nickel alloy, employing palm oil and ester as base fluids for MQL. Their findings demonstrated that both fluids successfully reduced surface roughness, surface defects, and micro-cracking. Similarly, Fox-Rabinovich *et al.*[106] evaluated the impact of coatings on tool longevity using flooded and MQL methods. The outcomes of the study indicated that the MQL cooling approach markedly improved tool longevity. Kilickap *et al.*[107] accomplished drilling operations on the aluminum alloy, reporting favorable machining outcomes attributed to the adoption of the MQL method. Finally, Brinksmeier *et al.*[108] examined the effects of MQL on drilling processes, concluding that an internally lubricated MQL system resulted in cutting temperatures that were 50% lower than those observed in an externally lubricated MQL system.

Ultrasonic-assisted machining (UAM) and MQL have emerged as promising strategies for enhancing the machinability of difficult-to-cut materials like titanium alloys and superalloys. Hakki Namlu *et al.*[109] highlighted the challenges in machining Ti–6Al–4V and explored the combined application of UAM and MQL during end-milling operations. Their results demonstrated significant reductions in cutting forces and surface roughness, particularly in rough cutting operations, compared to conventional methods. The study concluded that integrating UAM and MQL improves overall cutting performance, underscoring its potential in machining applications where precision and efficiency are critical. Similarly, Khanna *et al.*[110] investigated the ultrasonic-assisted turning of Inconel 718 using various sustainable cooling strategies, such as electrostatic MQL (EMQL) and liquid carbon dioxide (LCO_2). The novel combination of LCO_2 and EMQL showed considerable reductions in tool wear, power consumption, and specific cutting energy without compromising surface quality, achieving sustainability in machining processes. Further research by Hoanga *et al.*[111] introduced a method for deep hole drilling in AISI SUS 304 stainless steel using MQL and ultrasonic vibrations, resulting in improved cutting performance, longer tool life, and higher production rates. The integration of graphene nanoparticles in the MQL system further enhanced lubrication efficiency. Meanwhile, Ni and Zhu[112] provided theoretical and experimental insights into the simultaneous application of UAM and MQL for milling TC4 alloy. Their findings revealed substantial improvements in cutting force characteristics, chip morphology, and surface quality, with surface roughness reductions of 30%–50% compared to conventional milling. These studies collectively emphasize the efficacy of combining UAM and MQL, offering sustainable and high-performance solutions for machining difficult materials. A summary of the materials, machining processes, lubrication methods, and key findings from each study is presented in Table I.

V. ADVANTAGES AND DISADVANTAGES OF MQL TECHNOLOGY

MQL has gained significant attention in modern machining processes due to its potential to enhance performance while aligning with environmental and economic sustainability goals. However, the adoption of MQL is accompanied by a range of advantages and

TABLE I. Summary of materials and findings.

Author(s)	Material(s) machined	Machining process	Lubrication method	Key findings
Mia *et al.*	Hardened steel	Turning	MQL	Optimized tool wear, surface roughness, and MRR using the Taguchi S/N ratio method
Dhar *et al.*	AISI 1040	Turning	MQL	Decreased friction, lower cutting temperatures, and diminished flank wear in contrast to dry machining
Thakur *et al.*	Inconel alloys	Turning	MQL	Identified optimal parameters for MQL turning of heat-resistant superalloys
CheHaron *et al.*	Inconel alloys	Turning	High-speed cutting	Found plastic deformation aligned with cutting direction during high-speed cutting
Mia *et al.*	Hardened steel	Turning	MQL with varying fluid flow rates	Noted significant effects on surface roughness and suggested an optimal flow rate for surface quality
Liu *et al.*	Ti-based alloys	Turning	Vortex tube-assisted MQL	Demonstrated reduced surface roughness, though slightly higher cutting forces than flood cooling
Stephenson *et al.*	Steel	Turning	Supercritical CO2-based MQL	Achieved a 40% increase in MRR and enhanced tool longevity compared to flood cooling
Sarıkaya and Güllü	Steel	Turning	Vegetable oil-based MQL	Optimized cutting speed and flow rate to minimize tool wear and surface roughness
Khan *et al.*	AISI D2 steel	Grinding	MQL	Provided superior surface quality compared to wet and dry machining techniques
Sadeghi *et al.*	Ti alloy	Grinding	Synthetic ester and vegetable oil	Under MQL conditions, synthetic esters demonstrated superior performance compared to vegetable oils
Barczak *et al.*	Steel	Grinding	MQL	Demonstrated superior surface quality under MQL-assisted grinding compared to dry and flooded conditions
Oliviera *et al.*	Quenched and tempered steel	Grinding	MQL with air jet cleaning	Improved roundness, surface roughness, and reduced lubricant usage with air jet assistance
Balan *et al.*	Inconel 751	Grinding	MQL	Increased MQL pressure improved surface roughness and cutting forces significantly
Hadad *et al.*	100-Cr-6 and 42-Cr-Mo4 steel	Grinding	MQL	Achieved excellent surface quality for 100-Cr-6 but observed adverse effects on 42-Cr-Mo4
Sun *et al.*	Steel	Milling	MQL	MQL enhanced tool life and reduced forces compared to wet and dry milling
Li *et al.*	Inconel 718	Milling	MQL	Reduced tool wear and cutting forces with flank wear as a major contributor to tool life decline

TABLE I. (*Continued*.)

Author(s)	Material(s) machined	Machining process	Lubrication method	Key findings
Da Silva *et al.*	Steel	Milling	MQL	MQL mitigated thermal cracking and increased MRR with reduced flow rates
Liu *et al.*	Titanium	Milling	MQL with varying parameters	Found that increased lubricant supply significantly decreased surface roughness
Cai *et al.*	Steel	Milling	MQL	To achieve effective outcomes, MQL fluid flow rates of up to 10 ml/h are favorable
Singh *et al.*	Inconel	End milling	MQL	Developed predictive models for tool wear, showing MQL outperforming dry and flood cooling
Mia	Steel	Milling	MQL with varying flow rates	MQL influenced specific cutting energy consumption and surface quality significantly
Davim *et al.*	AA1050	Drilling	MQL	MQL performance was comparable to flooded cooling in terms of tool life and surface quality
Bhowmick *et al.*	Magnesium alloys	Drilling	MQL	Enhanced tool life and reduced torque under MQL conditions
Rahim and Sasahara	Inconel 718	Drilling	Synthetic ester and palm oil	Both lubricants reduced surface defects and roughness in MQL drilling
Fox-Rabinovich *et al.*	Steel	Drilling	MQL	Tool coatings significantly extended tool life under MQL cooling compared to flood conditions
Kilickap *et al.*	Al-7075	Drilling	MQL	Observed favorable machining outcomes using MQL technology for Al-7075 alloy drilling
Brinksmeier *et al.*	Steel	Drilling	Internal vs external MQL systems	It was observed that internally lubricated MQL systems generated cutting temperatures that were 50% lower than those produced by externally lubricated systems
Hakki Namlu *et al.*	Ti–6Al–4V	End milling	MQL	Significant reductions in cutting forces and surface roughness compared to conventional methods
Khanna *et al.*	Inconel 718	Turning	EMQL	Reduced tool wear, power consumption, and specific cutting energy without compromising surface quality, achieving sustainability
Hoanga *et al.*	AISI SUS 304 stainless steel	Deep hole drilling	MQL	Improved cutting performance, longer tool life, higher production rates, and enhanced lubrication efficiency with graphene nanoparticles in MQL
Ni *et al.*	TC4 alloy	Milling	MQL	Improved cutting force characteristics, chip morphology, and surface quality, with surface roughness reductions of 30%–50% compared to conventional milling

TABLE II. Advantages and disadvantages of MQL technology in machining operations.

Category	Machining operation	Advantages	Disadvantages
Environmental aspects	Turning	Reduces waste disposal and minimizes ecological footprint due to minimal cutting fluid use	MQL's inability to provide adequate corrosion resistance can lead to increased waste generation for some materials
	Grinding	Generates fewer harmful residues, promoting environmental sustainability	Ineffective for wheel dressing, potentially leading to more waste generation over time
	Milling	Minimal harmful by-products make disposal easier and environmentally friendly	System complexity and initial investment costs could impact sustainability efforts
	Drilling	Reduces coolant waste compared to traditional methods	MQL may be less effective in deep hole applications, leading to potential inefficiencies and increased waste
Economic aspects	Turning	Improves machining efficiency by reducing cutting forces, leading to cost savings	Struggles to clear chips from the machining zone, which could lead to tool wear and operational downtime
	Grinding	Reduces coolant usage, promoting cost savings	MQL is not suitable for wheel dressing, leading to potential increased costs for wheel maintenance
	Milling	Reduces harmful by-products, lowering disposal costs	Maintaining consistent fluid concentration across multiple nozzles can complicate machining setup, increasing costs
	Drilling	Reduces need for large amounts of coolant, reducing operating costs	MQL may not be suitable for deep hole drilling, requiring additional systems that could increase operational costs
Health aspects	Turning	MQL reduces exposure to harmful coolants and fluids	Oil mist generated by MQL poses health risks to operators, requiring safety measures
	Grinding	Less harmful by-products compared to conventional methods, contributing to safer working conditions	Requires proper ventilation to mitigate oil mist health risks
	Milling	Reduces harmful emissions, promoting a healthier work environment	Similar to grinding, oil mist can pose health risks, requiring effective filtration
	Drilling	Reduces exposure to harmful fluids by using minimal coolant	Oil mist exposure is a general concern in MQL, affecting operator health
Machining performance	Turning	Enhances tool life and surface finish, improving overall performance	Ineffective chip removal, which can cause tool damage and poor surface quality
	Grinding	Enhances surface finish and prevents clogging of grinding wheels	Inability to assist with wheel dressing reduces long-term performance
	Milling	Improves tool longevity, reduces cutting temperature, and enhances surface finish	The system's complexity and nozzle maintenance can interfere with optimal performance
	Drilling	Reduces friction, improving tool life and surface quality	Chip removal can be problematic, affecting hole quality and performance

limitations, which vary depending on the machining process and operational requirements. This section presents a comprehensive evaluation of the advantages and disadvantages of MQL technology, categorized into general aspects such as environmental, economic, and health impacts, followed by its specific effects on turning, grinding, milling, and drilling operations (Table II).

VI. RECENT BREAKTHROUGHS IN MQL TECHNOLOGY

Approximately two decades ago, the introduction of MQL marked a significant advancement aimed at mitigating the health and environmental hazards linked to machining processes.[113,114] In its early stages, MQL systems employed conventional cutting fluids combined with compressed air to supply lubrication to the cutting zone. However, contemporary applications increasingly favor the use of vegetable oils and nanofluids, attributed to their superior lubricating characteristics. Furthermore, ongoing research endeavors are focused on developing innovative strategies to improve the performance and efficacy of MQL systems.

Ionic liquids, which are organic salts characterized by their low melting points, have garnered significant interest due to their remarkable lubrication properties, rendering them highly effective for applications involving the interaction of two surfaces.[115] Their minimal volatility and exceptional thermal stability have prompted extensive investigations into their potential advantages.[116] Research indicates that the addition of ionic liquids can lead to a significant reduction in tool wear during the machining of titanium, compared to conventional cooling techniques.[117,118] The superior performance of ionic liquids in reducing tool wear can be attributed to their unique physicochemical properties. These include strong adsorption on metallic surfaces due to their polar structure, which forms a protective lubricating film at the tool-workpiece interface. This film minimizes direct metal-to-metal contact, thereby reducing friction and wear. In addition, ionic liquids exhibit excellent thermal conductivity and heat dissipation capabilities, which help to efficiently transfer heat away from the cutting zone, mitigating thermal stresses that contribute to tool wear. Furthermore, their ability to maintain stability under extreme pressure and temperature conditions ensures consistent lubrication during the machining process. For example, Goindi *et al.*[119] established that the effectiveness of ionic liquids in minimum quantity lubrication (MQL) was on par with conventional flood cooling techniques when milling AISI 1045 carbon steel. Similarly, Pham *et al.*[120] reported a significant improvement in surface quality during the micro-machining of aluminum 5052 when employing ionic liquids, attributing the enhancement to their ability to reduce cutting forces and tool wear. More recently, Abdul Sani *et al.*[121] illustrated the influence of ionic liquids on sliding surfaces in a schematic representation (Fig. 8), further emphasizing their role in enhancing tribological performance.

EMQL is an innovative enhancement in MQL technology, offering significant improvements in lubrication efficiency and machinability for difficult-to-cut materials.[122] EMQL employs an electrically charged lubricant aerosol that ensures precise and uniform application to the machining zone, providing superior cooling and lubrication. This electrostatic mechanism facilitates better adherence of lubricant particles to the cutting interface, reducing friction and wear more effectively than conventional MQL. Its advantages include enhanced machinability of superalloys and hardened steels, reduced tool wear, improved surface quality, and minimized lubricant consumption, aligning with sustainable manufacturing goals.[123] Lv *et al.*[124] proposed an EMQL technique using graphene nanoplatelets (GnPs) as nano-lubricant additives to enhance machining performance and reduce oil mist concentration. Their study demonstrated that EMQL significantly improved lubricant penetration and deposition, reducing friction and wear compared to conventional MQL. The results highlighted a lower coefficient of friction, smaller worn scar diameter, and enhanced machining efficiency. EMQL's superior tribological behavior underscores its potential for sustainable machining, offering both environmental and performance advantages in industrial applications. Bartolomeis *et al.*[125] investigated machining Inconel 718, highlighting challenges like short tool life and high costs. They proposed an innovative EMQL system, demonstrating its superiority over MQL in end milling through improved tool life, reduced specific cutting energy, and enhanced surface roughness. Last year, Khanna *et al.*[126] investigated sustainable machining techniques for drilling Ti6Al4V ELI, focusing on EMQL and cryogenic CO_2.

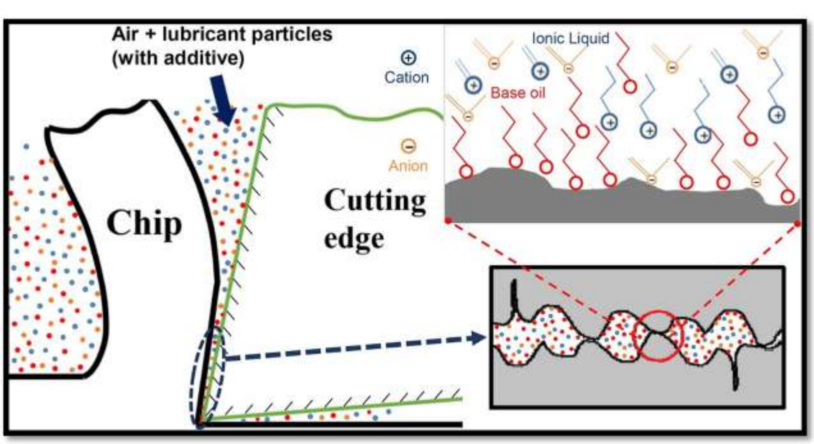

FIG. 8. Diagram illustrating the role of ionic liquid in MQL medium.[121] [Reproduced with permission from Abdul Sani *et al.*, J. Cleaner Prod. **209**, 947–964 (2019). Copyright 2019 Elsevier.]

The study revealed that LCO_2 outperformed EMQL regarding surface quality, tool life, and chip morphology. EMQL resulted in poor lubrication, higher surface roughness (42%–71% more), and severe tool wear, while LCO_2 improved tool life by 416% and effectively reduced defects. LCO_2, dissipating into the air, proved to be a sustainable, eco-friendly coolant for machining titanium alloys.

The Ranque–Hilsch Vortex Tube (RHVT) is a mechanical device that separates compressed gas into hot and cold streams without any moving parts or external power. It operates on the principle of vortex motion. Compressed gas is injected tangentially into a cylindrical chamber, creating a high-speed vortex. Centrifugal forces separate the gas into hot outer layers and cold inner cores, which exit through separate outlets.[127] Research conducted

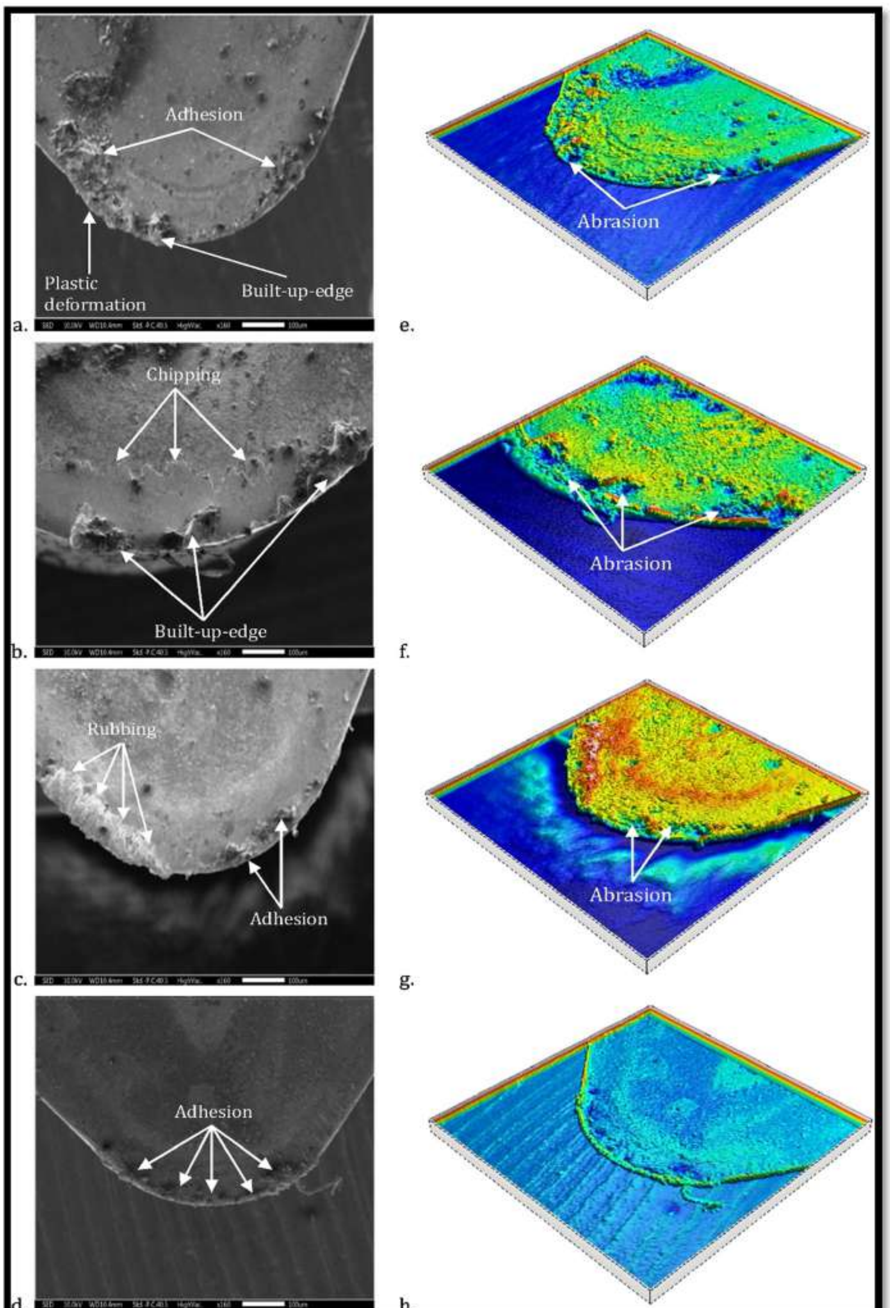

FIG. 9. Worn tools and 3D surface topography: (a) and (e) Air cooling, (b) and (f) N2 cooling, (c) and (g) NGMQL, and (d) and (h) RHVT-NGMQL.[130] [Reproduced with permission from Mia *et al.*, Precis. Eng. **53**, 289–299 (2018). Copyright 2018 Elsevier.]

TABLE III. Comparative analysis of advanced MQL techniques.[140]

MQL techniques	Tool wear	Tool life	Surface quality	Cutting forces
Nanofluid assisted MQL	✓	✓	✓	✓
Ionic liquid assisted MQL	✓	...	✓	✓
EMQL	✓	✓	✓	✓
RHVT assisted MQL	...	✓	✓	...
Cryo-MQL (MQL + LN2)	✓	✓	✓	✓
Cryo-MQL (MQL + SCO2)	...	✓	✓	...

by Liu and Chou[128] demonstrated that the application of RHVT led to a significant reduction in tool wear. In addition, experiments by Boswell and Islam[129] indicated that the implementation of RHVT resulted in improved surface finishes and decreased cutting forces during machining of aluminum alloys. Moreover, Mia *et al.*[130] observed a significant reduction in both surface roughness and tool wear when employing RHVT in conjunction with nitrogen gas in the context of MQL-assisted turning, highlighting the promising potential of advanced cooling technologies in the machining process. Figure 9 illustrates the worn tools alongside their respective 3D surface topographies across different cooling conditions. Ji *et al.*[131] investigated the turning of Ti–3Al-2.5 V with coated carbide tools under various cooling/lubricating environments to identify sustainable technologies. The study compares five conditions: dry, pressurized compressed air-assisted wet cooling, RHVT, conventional MQL, and wet oil cooling. Results show that MQL provided the lowest tool wear and surface roughness but generated concerning levels of PM2.5 particulate matter. MQL and RHVT demonstrated the lowest energy consumption and carbon emissions, with RHVT offering a 45%–56% reduction in carbon emissions. RHVT emerged as a viable, sustainable alternative in terms of environmental, economic, and technological benefits. Gupta *et al.*[132] explored the use of RHVT-MQCF as an eco-friendly alternative to traditional MQL for machining hard-to-cut materials like pure titanium. The study compared RHVT-MQCF with conventional MQL under varying cutting parameters and analyzed sustainability indicators such as cutting force, power consumption, and surface quality using statistical modeling and desirability functions. Life Cycle Assessment (LCA) revealed RHVT-MQCF's superior performance, making it a promising sustainable option for the manufacturing industry.

Cryogenic MQL is an advanced cooling and lubrication technique that combines the benefits of cryogenic cooling and MQL. In this process, gases like CO_2 or N_2 are cooled to liquid form at temperatures below $-150\,^{\circ}C$ and atomized with minimal cutting fluid using specialized nozzles.[133] This method has been increasingly applied in machining processes like turning, milling, grinding, and drilling. Pusavec *et al.*[134] explored the sustainable manufacturing of Inconel components, highlighting the benefits of MQL and cryogenic systems, and developed predictive models to enhance sustainability. Su *et al.*[135] reported a 124% improvement in tool life when machining Inconel 718 under cryogenic MQL, a finding corroborated by other studies. Busch *et al.*[136] found CO_2 aerosol lubrication to be highly effective when optimized.

A key feature of cryogenic MQL is the solubility of oil in liquid CO_2, which is influenced by the oil's polarity. Polar oils mix better with liquid CO_2, resulting in a more uniform dispersion of the lubricant and improved lubrication efficiency. Non-polar oils may be less effective unless formulated with additives.[137] Chi *et al.*[137] investigated this solubility and its impact on oil droplet size, distribution, and tool life. Jamil *et al.* examined CO_2 snow and subzero MQL spray to improve heat transfer when machining Ti–6Al–4V, an aerospace alloy. Their study found that CO_2 snow had a higher heat transfer coefficient (1347 $W/m^2\,^{\circ}C$) compared to subzero MQL (486 $W/m^2\,^{\circ}C$), reducing tool wear and improving surface finish. Sterle *et al.*[138] explored the combined use of LCO_2 and MQL for drilling CFRP/Ti–6Al–4V stacks, showing that optimized flow rates of LCO_2 and MQL improved hole quality, reduced cutting forces, and enhanced surface quality. Sterle *et al.* focused on drilling using LCO_2 cooling and MQL, developing empirical models to optimize parameters like LCO_2 flow rates and cutting speed. These studies demonstrate that cryogenic MQL significantly enhances tool life,

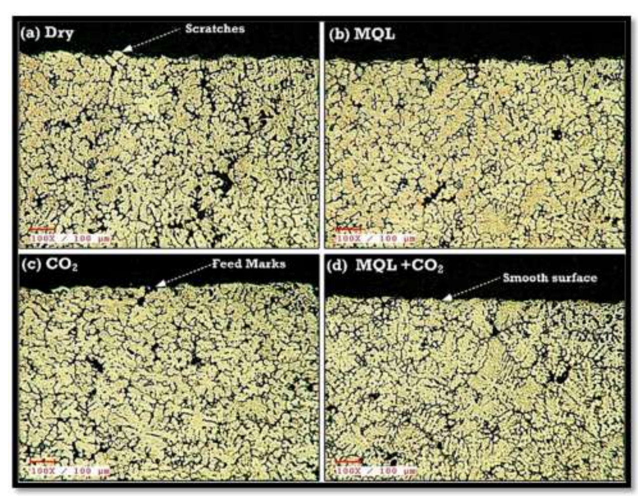

FIG. 10. Microstructure and cross-sectional view of the machined surface (cutting speed = 90 m/min and feed rate = 0.05 mm/rev).[141] [Reproduced with permission from Sivalingam *et al.*, Int. J. Adv. Des. Manuf. Technol. **132**(7), 3349–3361 (2024). Copyright 2024 Springer Nature.]

surface quality, and machinability, particularly for difficult materials such as CFRP and titanium alloys.

Sartori *et al.*[139] investigated the combination of MQL with liquid nitrogen (N_2), showing reduced tool wear and improved surface finish. Boswell *et al.*[140] compared various cooling methods, finding that nanofluid-based MQL systems outperformed other advanced cooling strategies in terms of tool wear, tool life, cutting forces, and surface roughness (Table III). Sivalingam *et al.*[141] showed that hybrid MQL and CO_2 cutting environments improved machinability, reducing cutting forces by 28%–39%, enhancing surface finish, and extending tool life by minimizing wear. Figure 10 illustrates the impact of different cutting environments on surface roughness: dry cutting leads to more scratches and a poorer surface finish due to higher cutting forces, while MQL with vegetable oil produces smoother surfaces. Cryogenic CO_2 results in fewer feed marks and burn marks, enhancing surface quality compared to dry cutting, with the best finish achieved when combining MQL with cryogenic CO_2. The interaction between LCO_2 and oil polarity further tailors lubrication properties for superior machining performance.

VII. SUMMARY OF THE REVIEW WORK

A sustainable manufacturing environment not only reduces machining costs but also enhances machining efficiency and improves business competitiveness. Considering these aspects, this review consolidates the findings of previously published studies on MQL-assisted machining operations, highlighting the advantages and limitations of MQL technology. The literature indicates that adopting MQL systems in machining is a promising alternative to conventional flood lubrication techniques. However, additional research is necessary to establish its feasibility for widespread industrial applications. The key insights from this review are summarized below:

a. The application of MQL technology significantly enhances machining performance by reducing parameters such as surface roughness, cutting forces, cutting temperature, and tool wear. However, critical factors like air pressure, air–oil mixture, nozzle configuration (number, distance, and angle), tool material/coating, as well as workpiece material, strongly influence its performance. To achieve optimal efficiency, a systematic selection of machining parameters is necessary, depending on the type of MQL working fluid used.
b. Compared to conventional flood lubrication, using vegetable oils in MQL systems has demonstrated superior performance, achieving lower surface roughness, cutting forces, and tool wear values. The polar functional groups (e.g., –COOH and –COOR) in vegetable oil molecules facilitate the formation of a molecular film on metal surfaces, thereby reducing friction and wear. Comparative analyses reveal that castor oil exhibits the highest lubricity among vegetable oils.
c. The integration of nanoparticles and nanoplatelets into MQL base fluids has proven to be an effective method for reducing friction during machining processes. With exceptional properties and cost-effectiveness, nanoparticles and nanoplatelets offer an environmentally friendly alternative to flood lubrication. Experimental studies highlight that Al_2O_3 nanofluids are particularly effective lubricants for machining operations. Spherical Al_2O_3 nanoparticles at the tool-workpiece interface transform sliding friction into rolling–sliding friction, further enhancing performance.
d. Numerous studies underscore the potential of MQL technology to improve machining processes such as turning, grinding, milling, and drilling. However, some research has identified limitations, particularly in grinding applications. Therefore, advancements in MQL systems are essential to enhance their compatibility for both lubrication and cooling purposes. Notably, comparative analyses indicate that nanofluid-based MQL systems outperform other advanced techniques such as MQL with ionic liquids, MQL with RHVT, cryogenic MQL, and MQL with supercritical CO_2.
e. The existing literature strongly advocates for dry machining and MQL as the most sustainable and environmentally friendly practices. However, when evaluating both sustainability and machinability, MQL emerges as the most viable option, striking a balance between environmental benefits and machining performance.

VIII. FUTURE RESEARCH POSSIBILITIES

MQL technology demonstrates significant potential in experimental studies; however, its long-term viability for large-scale industrial operations remains uncertain. Addressing this challenge requires more extensive industrial applications and large-scale production studies. This work identifies several research gaps in the existing literature and suggests these as future directions for further investigation, as outlined below:

a. Examining the toxicity of nanoparticles and ionic liquids is crucial to expanding the industrial applicability of MQL technology in the near future.
b. Recent studies have highlighted the benefits of hybrid nanoparticles, demonstrating their effectiveness in enhancing the lubricating properties of MQL base fluids. Further research is recommended to optimize and expand the use of hybrid nanoparticle-based MQL systems.
c. A comprehensive field survey on the industrial implementation of MQL is essential. Employing tools like Life Cycle Assessment (LCA) could provide valuable insights into the sustainability and feasibility of MQL in large-scale operations.
d. Investigating the droplet dynamics of MQL base fluids presents a new avenue for research. Integrating thermal analysis with sustainability studies can support the development of greener manufacturing technologies.
e. Considering the promising potential of nanofluids in MQL applications, additional studies are required to model key phenomena such as tribo-film formation, heat transfer, nanoparticle suspension, and the wetting behavior of sprayed droplets.
f. The emergence of advanced computational techniques and data science necessitates their integration with MQL-assisted machining and control parameters. This will facilitate the development of intelligent and smart manufacturing systems aligned with the goals of Industry 4.0. Research in this domain is crucial to advance MQL technology.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Abhijit Bhowmik: Conceptualization (equal); Formal analysis (equal); Methodology (equal); Resources (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Raman Kumar**: Conceptualization (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Ramachandran Thulasiram**: Conceptualization (equal); Methodology (equal); Visualization (equal); Writing – review & editing (equal). **Karthikeyan A**: Conceptualization (equal); Formal analysis (equal); Methodology (equal); Validation (equal); Writing – review & editing (equal). **Dhirendra Nath Thatoi**: Conceptualization (equal); Formal analysis (equal); Methodology (equal); Validation (equal); Writing – review & editing (equal). **Yashwant Singh Bisht**: Formal analysis (equal); Methodology (equal); Supervision (equal); Visualization (equal); Writing – review & editing (equal). **Priyaranjan Samal**: Conceptualization (equal); Formal analysis (equal); Methodology (equal); Supervision (equal); Writing – original draft (equal). **Tarun Kumar Kotteda**: Conceptualization (equal); Formal analysis (equal); Methodology (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Ghanshyam G. Tejani**: Conceptualization (equal); Methodology (equal); Visualization (equal); Writing – review & editing (equal). **A. Johnson Santhosh**: Conceptualization (equal); Methodology (equal); Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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