

Cutting fluids in metalworking: A comprehensive review of types, applications, and environmental considerations

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ABSTRACT

Cutting fluids play a crucial role in machining processes by cooling the cutting tool and workpiece, reducing friction at the tool-workpiece interface, and facilitating chip removal from the cutting zone. The primary objective of cutting fluid application is to minimize heat generation and frictional wear, thereby enhancing tool life, improving surface finish, and ensuring process stability. The effectiveness of cutting fluids is highly dependent on machining conditions, fluid composition, and the method of application. However, the improper selection, use, and disposal of cutting fluids can lead to serious health risks for operators and significant environmental concerns, including soil and water contamination. Therefore, sustainable alternatives such as minimum quantity lubrication (MQL), dry machining, and biodegradable cutting fluids have gained increasing attention. This review article provides a comprehensive analysis of the types of cutting fluids, various cooling and lubrication techniques, and recent advancements in their application. Additionally, it highlights the challenges associated with conventional cutting fluids and explores environmentally friendly alternatives to promote sustainable manufacturing practices.

Keywords: cutting fluids, machining processes, cooling and lubrication, tool wear reduction, surface finish improvement, minimum quantity lubrication, dry machining, biodegradable cutting fluids, environmental impact, sustainable manufacturing.

INTRODUCTION

In modern machine-building industries, lubricating-cooling fluids (LCFs) are widely utilized in machining operations to enhance the cutting process and minimize tool wear [1]. This excessive heat can deteriorate the final workpiece quality by increasing surface roughness and affecting dimensional accuracy [2]. It can also accelerate tool wear through mechanisms such as crater and flank wear, reducing cutting tool life [3]. Moreover, inadequate cooling and lubrication can exacerbate tool wear and surface damage, particularly when machining difficult-to-cut alloys, highlighting the importance of advanced methods

like minimum quantity lubrication (MQL) [4]. Supporting these observations, turning experiments on Ti-6Al-4V have shown that adjusting Al₂O₃ nanoparticle concentration in MQL fluids significantly influences tool-wear behavior, with 0.5–0.75 wt% yielding the lowest flank and crater wear among the tested conditions [5]. Insufficient heat dissipation can compromise both tool flank durability and workpiece surface finish, whereas effective cutting fluids improve penetration into the cutting zone and mitigate wear mechanisms [6]. Additionally, overheating can alter the mechanical properties [7] and microstructure [8] of the processed metal, negatively impacting its performance and durability.

To mitigate these adverse effects, the application of LCFs is essential across a broad spectrum of machining processes. For example, in turning operations, internal cooling strategies and improved coolant delivery systems have been shown to significantly reduce tool temperatures and wear, thereby enhancing process efficiency [9]. Other studies on turning highlight the role of externally applied cutting fluids – particularly when combined with novel enhancement techniques such as static magnetic fields – in improving chip formation and reducing chip shrinkage during cutting with HSS tools [10].

In milling and related machining of high-strength or difficult-to-cut materials, recent work emphasizes the benefits of advanced and environmentally safer LCF formulations. For instance, fire-resistant, hydrogen-containing lubricant-cooling liquids derived from vegetable oils have demonstrated improved performance in the machining of rotor steels, influencing chip morphology and facilitating the destruction of structural components through hydrogen-assisted mechanisms [11]. Additionally, comprehensive reviews of metal-working fluids (MWFs) in the milling of aerospace alloys underscore the effectiveness of high-performance vegetable-oil-based fluids in improving machinability, reducing environmental impact, and supporting sustainable production practices [12].

Other metal-cutting operations also benefit from enhanced lubrication and cooling strategies. In the finishing of difficult-to-cut alloys, hybrid approaches that combine MQL with cryogenic cooling agents such as liquid nitrogen or carbon dioxide have been shown to substantially reduce thermally activated wear mechanisms and improve surface integrity [13]. Vegetable-oil-based fluids delivered through MQL systems have likewise been investigated as environmentally friendly alternatives, exhibiting strong cooling and lubricating effects during turning and demonstrating tool life improvements comparable to conventional fluids [14]. Broader analyses of alternative cooling and lubrication techniques – such as the integration of compressed cold air with MQL – indicate promising directions for achieving higher machining efficiency while meeting sustainability requirements [15]. Comparative face-milling experiments on D2 steel have shown that Al_2O_3 -based nanofluid MQL can further reduce cutting temperature compared with conventional MQL, highlighting the potential of nanoparticle-enhanced lubricants to improve thermal control

in machining [16]. Overall, these advancements in LCF technology, delivery methods, and hybrid lubrication-cooling strategies continue to enhance tool life, reduce frictional heat, and improve workpiece quality, while simultaneously pushing the field toward more sustainable and cleaner manufacturing solutions [17]. Furthermore, emerging approaches such as minimum quantity lubrication and environmentally benign alternatives are increasingly gaining attention for their potential to combine high machining performance with reduced ecological impact [18].

In most hard-to-machine alloys, LCFs are essential during machining, providing lubrication at the workpiece-tool interface, dissipating heat from the cutting zone, and removing abrasive particles from the chip-tool contact area [19,20]. In the context of titanium machining, recent work has shown that sustainably formulated water-based cutting fluids containing polyol esters can markedly improve lubricity, as their molecular structure promotes the formation of a stable organic film on the metal surface, thereby reducing torque increases associated with tool wear and enhancing the overall efficiency of machining Ti6Al4V and similar difficult-to-machine alloys [19]. Complementing these findings, investigations into the use of super palm olein during the turning of mild steel demonstrate that this vegetable-oil-based fluid can deliver superior surface roughness and competitive cutting-force performance compared with mineral-oil coolants and dry machining, with statistical analyses confirming its effectiveness across a range of cutting speeds, feed rates, and depths of cut [20].

The effectiveness of cutting fluids depends not only on their chemical and physical properties but also on the type of material being machined. For example, in woodworking, the surface quality produced during CNC turning of hardwoods is influenced by insert geometry, which interacts with lubrication and heat dissipation at the tool-workpiece interface [21]. In contrast, for metals such as 1.4301 stainless steel, milling operations are sensitive to feed rate, depth of cut, and cutting speed, which in turn affect the fluid's ability to control temperature and friction and maintain desired surface finish [22]. Such comparisons underscore the importance of tailoring cutting fluid strategies to both the workpiece material and the specific machining process.

The development of water-based coolants faces increasing challenges as manufacturers

demand higher performance, extended service life, and improved stability under more extreme conditions [23]. To address these challenges, vegetable oils and their synthetic ester derivatives are now emulsified as additives in water-based LCFs, offering improved lubrication and environmental benefits [24]. Additionally, advanced optical techniques, such as photon correlation spectroscopy (PHS), are emerging as promising methods for analyzing the composition and stability of these lubricant-enriched fluids [25].

Traditional metalworking fluids consist primarily of mineral oils, which have long been used in commercial formulations despite their environmental and health drawbacks [26], and they also rely heavily on chemically synthesized surfactants whose molecular structure – such as charge type, hydrocarbon chain length, and degree of ethoxylation—critically influences film-forming ability and lubricity during machining processes [27]. While these formulations are widely used globally, their negative environmental impact and health risks for workers have raised significant concerns, necessitating the search for safer and more sustainable alternatives [28]. In response to these issues, research has led to the development of a “green” lubricant-coolant (GCF), which has demonstrated superior characteristics compared with conventional commercial lubricant-coolants (COMs) used in industrial machining processes [29].

As a water-soluble lubricating additive, synthesized proton-type ionic liquids (PILs) offer several advantages, including simple synthesis [30], excellent solubility stability [31], and superior corrosion resistance [32]. These properties make PILs a promising solution to the limitations of traditional water-based additives. The physicochemical properties of these additives have been examined in studies showing that applying a static magnetic field to the lubrication–cooling medium can improve cutting-tool wear resistance and enhance machining conditions through the use of newly developed magnetizing devices such as the UMD-1 and SMD-2 [33]. Their lubrication performance has also been investigated using electrostatic minimum quantity lubrication systems, where graphene-enhanced nano-lubricants demonstrated reduced friction, smaller wear scars, and superior machining performance due to improved droplet penetration and deposition at the rubbing interface [34]. Additional evaluations in high-speed machining have shown that water-based MWFs exhibit performance strongly influenced

by emulsion type, particle-size distribution, and boundary-lubricant formulation, which affects machinability, tool wear, and cutting forces across a range of materials and cutting speeds [35]. Tribological trials on mineral-oil-based and surfactant-modified coolant formulations have characterized their frictional behavior and corrosion resistance, leading to recommendations for selecting high-performance cutting fluids for metal-cutting applications [36]. A deeper understanding of their lubricating mechanisms has been obtained using advanced analytical techniques such as quartz crystal microbalance (QCM), transmission electron microscopy (TEM), time-of-flight secondary ion mass spectrometry (TOF-SIMS), X-ray photoelectron spectroscopy (XPS), and molecular dynamics (MD) simulations [29]. The findings demonstrate that PILs exhibit exceptional friction-reducing and anti-wear properties while enhancing the load-bearing capacity of water-based lubricants. This performance is primarily attributed to the formation of a protective tribofilm on the friction surface [37].

In today’s manufacturing industry, growing attention is being directed toward mitigating the negative social, health, and economic impacts associated with machining processes [38]. Sustainable manufacturing emphasizes the adoption of alternative cooling, flushing, and lubrication techniques that significantly influence all aspects of machining, including social, economic, and environmental factors [15,39]. One of the critical challenges in machining titanium alloys is excessive cutting temperature, which leads to rapid tool wear and reduced machinability [40]. Therefore, implementing an efficient cooling strategy is essential to reducing cutting temperatures and friction, as cutting fluids play a central role in lowering thermal loads, extending tool life, and improving surface quality through their combined cooling, lubrication, and cleaning functions [41]. Moreover, the general characteristics and documented benefits of lubricating-cooling liquids – supported by both experimental data and widespread literature – further underscore their importance in enhancing machining performance across various metal-cutting operations [42].

Experimental results have been obtained on the effects of different grinding methods (up-grinding and down-grinding) and cooling strategies – including emulsion cooling, minimum quantity lubrication (MQL), cryogenic cooling with liquid nitrogen (LN_2), and a combined

approach (MQL + LN₂) – on sidewall wear, chip morphology, and surface roughness during peripheral high-speed side milling of Inconel-718 [43]. The findings indicate that down-milling consistently produces lower maximum flank wear than up-milling across all cooling strategies, thereby enhancing machinability during peripheral high-speed milling of Inconel-718 [44]. Additionally, cryogenic cooling with liquid nitrogen has been shown to further improve tool life and workpiece performance by maintaining significantly lower cutting-zone temperatures and reducing thermal impact, with inner injection strategies offering particularly efficient LN₂ consumption and extended tool durability [45].

Additionally, the impact of emulsion type and particle-size distribution of metalworking fluids as well as the effectiveness of high-temperature boundary lubricants in high-speed machining (HSM) are presented [46]. Furthermore, using a face milling operation on Al6Si3.5Cu alloy, the influence of MWFs on insert wear and cutting forces at increasing cutting speeds is discussed [41].

HSM [35] of compacted graphite iron and ductile cast iron necessitates the use of advanced, highly engineered metalworking fluids. Water-based cutting fluids (WCFs) are increasingly being adopted in modern metal processing to meet the demands of advanced manufacturing [47]. However, the effectiveness of water-based cutting fluids can be limited by low wettability, which leads to unstable lubrication and inconsistent machining performance [48]. To address this issue, functional additives such as graphene oxide have been incorporated to form Pickering emulsions, significantly enhancing film formation, reducing friction and wear, and improving the overall lubrication performance of WCFs [49].

To address this problem, a novel graphene oxide (GO)-based Pickering emulsion was developed as a WCF, leveraging the exceptional lubricating properties of GO [49]. Graphene oxide-based Pickering particles were incorporated into water-based cutting fluids to enhance tribological performance, inspired by studies showing that GO/SiO₂ hybrid nanoparticle lubricants in MQL systems can form protective films at the rubbing interface, significantly reducing friction and wear while improving machining outcomes [50]. Additionally, nanohybrid additives such as MoS₂/Bentonite have demonstrated that functional nanoparticles can be combined with water-based lubricants to create low-shear-strength tribofilms,

further enhancing anti-wear properties and stability under challenging machining conditions [51]. Experimental results demonstrated that the prepared WCFs were uniform and highly stable, with the emulsion containing e-GO exhibiting the most significant improvements in friction reduction, tapping torque reduction, and extreme pressure performance [52].

In modern metal cutting processes, the primary objective is to produce high-quality components by optimizing surface finish and dimensional accuracy, which can be achieved through the use of advanced cutting fluids with enhanced tribological properties [53]. Another key goal is to minimize energy consumption during machining, a task supported by techniques such as electrostatic minimum quantity lubrication (EMQL) that reduce friction and tool wear while maintaining efficient metal removal [54]. These fluids play a crucial role in providing effective lubrication and cooling during metal removal operations. Additionally, their minimal and optimized application can significantly reduce machining costs and overall energy consumption [55].

This paper specifically focuses on techniques to enhance the machinability of difficult-to-cut materials, such as steel alloys, Ni-based superalloys, Ti-based alloys, and composites – materials widely used in the aerospace manufacturing industry [56]. Given the growing industrial demand for high-performance and sustainable machining of advanced superalloys and composites, optimizing machining processes is essential to maintaining a reasonable profit margin [57]. Key areas of interest include the development of high-performance vegetable oil-based MWFs [12], environmentally conscious machining strategies for hard-to-machine materials, and future prospects for biodegradable MWFs in aerospace manufacturing.

Furthermore, the study examines the chemical cleaning of polyvinylidene fluoride (PVDF) hollow fiber ultrafiltration (UF) membranes irreversibly fouled by cutting fluids containing anionic emulsifiers [58]. The cleaning efficiency of anionic, cationic, and non-ionic surfactants was primarily assessed through pure water permeability tests, which demonstrated that anionic surfactants achieved superior removal of emulsified cutting oils from PVDF ultrafiltration membranes [59]. Additionally, these results were supported by morphological surface analysis and molecular vibrational spectroscopy, confirming the effectiveness of membrane-based cleaning methods

for recovering lubricating-cooling fluids [60]. These findings highlight the importance of reconditioning and reusing lubricating-cooling fluids as an effective strategy for improving sustainability in machining operations.

USE OF CUTTING FLUIDS

Most metal-cutting operations require the use of metalworking fluids for cooling, lubrication, and the removal of metal fines [61]. These fluids are complex mixtures comprising base oils—such as mineral, vegetable, animal, marine, or synthetic oils—along with various additives, including biocides, corrosion inhibitors, and antifoaming agents [62]. Additionally, substances such as metal chips, nitrosamines, and microorganisms can develop during use, further altering fluid composition over time [63]. Studies have shown that microbial growth within metalworking fluids can significantly degrade fluid quality and negatively affect tool performance, which emphasizes the need for more stable and environmentally benign fluid formulations [64]. Cutting fluids play a crucial role in machining by reducing cutting forces and temperatures, thereby extending tool life and improving overall machining efficiency [65]. Table 1 shows the physical properties of the coolant.

The increasing demand for environmentally friendly and sustainable products has motivated the metal-mechanic industry to seek alternatives to traditional mineral-based lubricants [66]. Vegetable-based oils have been explored as potential candidates for MWFs owing to their excellent lubricating properties and biodegradability [67]. Recent evaluations of vegetable-based cutting fluids have demonstrated that they can markedly improve surface finish and reduce cutting temperatures in turning operations, reinforcing their potential as high-performance sustainable substitutes for mineral oils [68]. Tribological tests using vegetable oils derived from *Jatropha* and *Moringa* have demonstrated reduced wear compared with both emulsifiable and integral commercial oils, highlighting their effectiveness as sustainable lubricants [69]. However, one of the major challenges in machining is heat dissipation. The

low thermal conductivity of certain materials hinders heat transfer from the cutting zone to chips, causing localized temperatures to rise as high as 1000 °C. This extreme heat accelerates tool wear and promotes various wear mechanisms [70].

An emerging approach to addressing friction and wear issues in machining is the use of solid lubricants – small particles dispersed within an oil base [71]. Depending on the working conditions, solid lubricants can significantly reduce friction between contact surfaces, contributing to more sustainable machining practices for advanced engineering materials [39].

Recent research has provided an overview of vegetable oils as base oils for lubricant production, examining their prospects, challenges, and ongoing efforts to overcome their limitations [72]. Compared with mineral oils, vegetable oils generally exhibit a high flash point [73], a high viscosity index [74], superior lubricity [75], low evaporative loss [30], renewability [76], and environmental friendliness [77]. These characteristics position vegetable oils as promising candidates for the production of industrial lubricants, aligning with global sustainability goals.

STRUCTURE OF CUTTING FLUIDS

Numerous scientific studies have explored the effects of magnetic fields on the physical and chemical properties of water [33]. When liquids are exposed to magnetic fields, they undergo structural changes, becoming magnetized liquids [78]. This phenomenon has garnered increasing interest because of its potential applications in various industrial processes [79].

In recent decades, MQL technology has gained significant academic and industrial attention as an environmentally friendly alternative to conventional lubrication methods [34]. Concurrently, extensive research efforts have been dedicated to identifying eco-friendly substitutes for mineral-based lubricants and halogen-containing working fluids [80]. Among these alternatives, dry machining has been widely recognized as a viable and sustainable option [36].

Table 1. Physical properties of the cutting fluid

Type of concentrate	Specific gravity at 20 °C	pH (in Use)	Refractive index	Type of emulsion
Brown butter	0.93	8.9–9.5	1	Milky white

The lubricating properties of different cutting fluids vary depending on their viscosity, which directly influences both heat transfer and lubrication effectiveness at the tool-chip interface [23]. The formulation and characteristics of the green cutting fluid used in this study are presented in Table 2.

Higher viscosity fluids tend to provide better lubrication, while lower viscosity fluids enhance cooling efficiency. Table 3 illustrates the viscosity of several common vegetable oils at 40 and 100 °C, highlighting their potential as sustainable metalworking fluid alternatives.

A study conducted as reported by Belluco [81] evaluated the performance of various mineral and vegetable oil-based cutting fluids in different machining operations. The results indicated that the vegetable oil formulation performed as well as or better than the commercial mineral oil in all tested operations. Despite its excellent lubricating properties, vegetable oil is highly susceptible to oxidation, which can lead to a decline in processing efficiency over time [72].

Oxidation adversely affects the extreme pressure properties of vegetable oils, yet the precise oxidation mechanism remains unclear. To mitigate these challenges, ongoing research is focused on enhancing the stability and effectiveness of vegetable oil-based cutting fluids through chemical and physical modifications [19,32,82]. The overall structure of this study is outlined in Figure 1.

For a qualitative assessment of the penetrating power of aqueous coolants, it is essential to determine the particle size of their dispersed

phase. Currently, optical methods are widely used for such measurements, with photon correlation spectroscopy (PCS) emerging as a particularly promising technique [25].

PCS is a non-contact method based on analyzing the temporal autocorrelation function of scattered light intensity fluctuations. It is specifically designed to measure the sizes of nano- and sub-micron dispersed particles undergoing Brownian motion. One of its key advantages is that it introduces no perturbations into the medium under study, making it a reliable tool for assessing the properties of coolant formulations [20].

While the metal cutting industry is a crucial driver of global economic growth, it also has significant environmental and resource implications. Key factors such as cutting tools, cooling and lubrication environments, and optimized cutting parameters directly affect natural resources and ecosystems [83]. The rising global demand for goods and services has led to an unsustainable linear production and consumption model [26]. Transitioning to green or sustainable manufacturing is imperative, not only owing to regulatory and occupational health concerns but also to address hazardous working conditions and environmental legislation [84].

One of the most pressing concerns in the metal cutting sector is the high cost associated with excessive cutting fluid consumption and waste generation [28]. To address these challenges, this article explores sustainable manufacturing strategies within the metal cutting industry, providing

Table 2. Formulation and characteristics of the green cutting fluid

Component	Subcategory	Content (mass%)
Base oil	Coconut oil	50
Emulsifiers		40
	EF-1	77
	EF-2	20
	EF-3	3
Additives		10
	A-1	1
	A-2	3
	A-3	3
	A-4	3

Table 3. Viscosity of some common vegetable oils at 40 and 100 °C

Viscosity (mPa·s)	Oil type						
	Rapeseed	Corn	Soybean	Peanut	Olive	Linseed	Castor
At 40 °C	31	29	27	32	35	25	50
At 100 °C	8	7	6	9	8	5	15

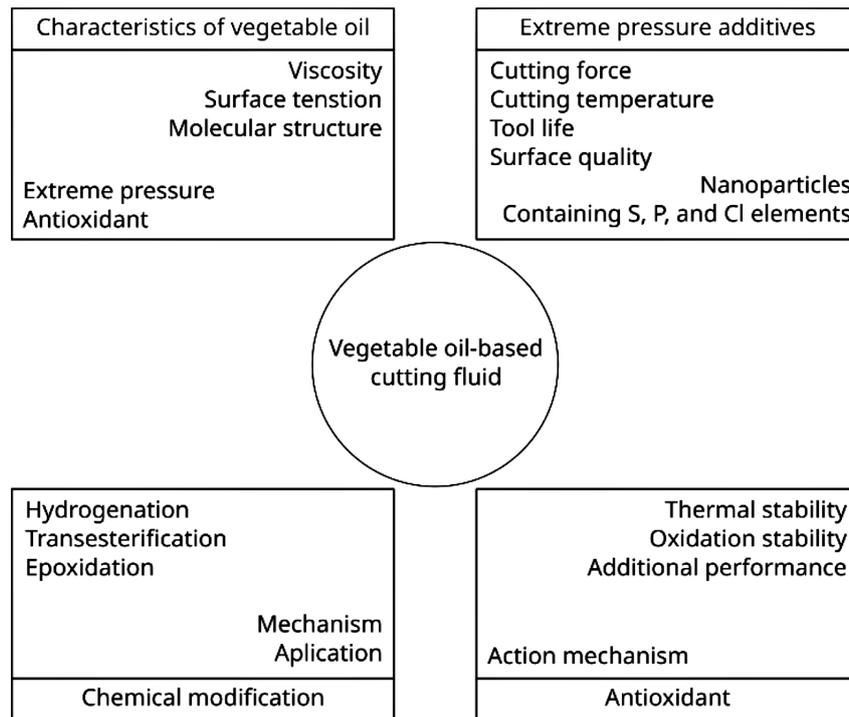


Figure 1. The overall structure of the study on vegetable oil-based nanolubricants [19]

a comprehensive guide for industrial applications [85]. Through an in-depth analysis, it highlights green processing techniques already implemented across various machining operations to ensure a cleaner and safer work environment [86]. Special attention is given to organizational strategies, key performance indicators, and potential barriers to implementation, offering valuable insights for researchers and industry professionals seeking to adopt more sustainable machining practices.

RECENT DEVELOPMENTS

Minimum quantity lubricant milling (MQLM) [87], combined with nanofluids [88], is one of the key processing methods in sustainable green manufacturing. Nanoparticles [89] can significantly enhance the heat transfer capabilities of metalworking fluids, making nanofluid-based coolants highly effective in milling applications. Despite their potential, limited research has been conducted on the impact of different nanoparticles on the cooling mechanisms of nanofluids [90].

The experimental results demonstrated that EMQL technology delivered superior performance [54]. This improvement is attributed to the presence of ultra-high electrostatically charged mist particles, which enhance droplet uniformity

and significantly improve fluid penetration into the cutting zone. These characteristics contribute to better lubrication, reduced cutting temperatures, and more effective chip evacuation. Figure 2 illustrates the operating principle of electrostatic EMQL technology.

Several studies have investigated the effects of environmentally friendly cutting conditions on the machining performance of Inconel X-750 superalloy during milling operations [91]. To address this, a total of 14 different eco-friendly cutting conditions [92] were tested, including dry cutting, base fluid application, and three distinct nanofluids at four different concentrations. Key performance indicators such as surface roughness [93], cutting temperature [94], cutting force [95], tool wear [96], and tool life [97] were evaluated.

The results demonstrated that the use of base fluid significantly improved machining performance compared with dry cutting. However, the most favorable outcomes across all performance criteria were achieved under nanofluid cutting conditions [98], which highlights their potential for optimizing machining efficiency and sustainability.

The primary functions of a cutting fluid include cooling the cutting zone, reducing friction by providing lubrication at the tool-chip interface, removing chips from the cutting zone, and enhancing machining efficiency by prolonging tool life

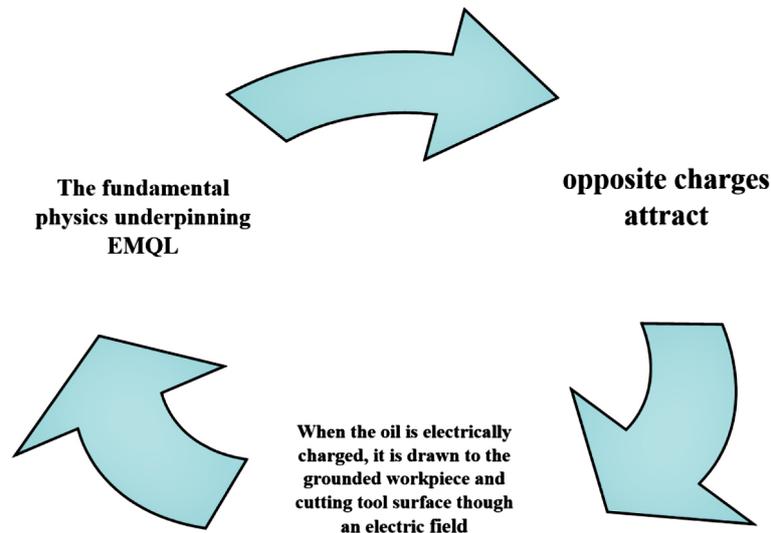


Figure 2. Schematic representation of the operating principle of EMQL technology

[99]. However, more than half of the lubricants used globally are petroleum-based, posing significant environmental challenges due to high disposal costs, toxicity, and non-biodegradability [100].

As a result, manufacturers and researchers are making substantial efforts to minimize the use of conventional cutting fluids [101]. To enhance machining performance while promoting sustainable manufacturing, the adoption of innovative and eco-friendly cooling-lubrication methods is essential [102]. A shift toward sustainable manufacturing in the metalworking industry can be achieved by reducing reliance on traditional coolants [103].

Environmentally conscious alternatives such as dry machining and nano-cutting fluids offer promising solutions. While dry machining is an effective method in terms of cost reduction and environmental impact, its efficiency remains limited, particularly in heavy machining conditions where lubrication and cooling are critical [104].

As an alternative machining technique, MQL involves delivering a small amount of cutting fluid – typically around 0.2 L/h – combined with compressed air to the cutting zone in the form of a fine mist [105]. Often referred to as “semi-dry machining,” MQL has gained increasing popularity in industrial applications owing to its balance between performance and environmental sustainability [95].

In this method, biodegradable oil droplets are atomized and transported by compressed air to the tool-workpiece interface, effectively reducing cutting temperatures and minimizing tool wear [106]. Unlike conventional flood cooling, where large volumes of fluid are used, MQL

significantly lowers the physiological and environmental risks associated with excessive coolant exposure in manufacturing settings [107]. The biodegradable oils used in MQL are typically non-toxic, help reduce cutting forces compared with dry machining, extend tool life, and enhance surface finish quality [92].

Furthermore, MQL presents a practical compromise that addresses the drawbacks of both traditional flood cooling and dry machining [108]. This method has proven effective across a wide range of machining operations, including turning [7], milling [109], drilling [110] and grinding [111].

Experimental findings indicate that, across all cooling strategies, downward milling consistently results in lower maximum side surface wear compared with upward milling, thereby enhancing overall machinability [44]. Among the tested approaches, MQL combined with downward milling yielded the lowest maximum lateral surface wear of just 0.072 mm after eight passes, which makes it a highly recommended method for machining Inconel-718 [112]. In contrast, liquid nitrogen (LN₂) cooling combined with upward milling led to the highest lateral wear of 1.984 mm after a single pass [113]. The significant difference in tool wear can be attributed to varying wear mechanisms: upward milling is dominated by adhesion wear, resulting in chipping and plastic deformation as common failure modes [114], which contribute to accelerated tool degradation. Downward milling, on the other hand, primarily exhibits abrasive wear, leading to more gradual and predictable tool wear [115]. Emulsion cooling with step-up milling achieved the lowest surface roughness of 0.29

μm, highlighting the role of water-based cutting fluids in maintaining high surface quality while addressing concerns over fluid stability and microbial growth [116]. In contrast, step-down milling combined with emulsion, MQL, or hybrid MQL + LN₂ cooling produced slightly higher but still low roughness values of 0.34 μm, demonstrating the effectiveness of sustainable and hybrid cooling-lubrication strategies in optimizing surface finish [117]. These results underscore the importance of both milling direction and cooling method in optimizing surface quality.

Additionally, the application of MQL in machining Inconel-718 not only enhances stability but also presents significant cost-saving opportunities [118]. Cutting fluids enhance machining efficiency by reducing friction and lowering cutting temperatures, as demonstrated in MQL with nano-Al₂O₃ additives, which improved surface finish and decreased crater wear in hot work tool steel [119]. They also help stabilize cutting forces and improve dimensional accuracy, as observed in bi-directional helical milling of CFRP, where controlled lubrication reduced tool wear and minimized surface damage [120]. Typically, CFs are water-diluted in the range of 92–97%, depending on the machining operation, to balance these dual functionalities effectively [121].

A study conducted as reported by Emel Kuram et al. [122] focused on the development of vegetable-based oil emulsions intended to replace conventional semi-synthetic cutting fluids in milling operations [123]. These vegetable-based cutting fluids (VBCFs) are typically water-miscible and composed of a base oil derived from refined sunflower or canola oil, along with a blend of emulsifiers [124]. To improve functionality, additional components may be included, such as corrosion and rust inhibitors [125], neutralizing agents [126], extreme pressure (EP) lubricating additives [127], fungicides [128], biocides [129], and foam inhibitors [130]. To evaluate the performance and stability of these fluids, several physicochemical properties are

measured, including pH [131], density [132], viscosity [133], flash point, and refractive index [134]. Table 4 presents the detailed characterization of the tested cutting fluids [135]:

- pH values, determined using a Hach Lang HQ 40d pH meter, ranged from 8.92 to 9.18, aligning with the general acceptable range for cutting fluids (8.5–10). Maintaining appropriate pH levels is crucial to avoid health hazards for operators and environmental issues related to waste disposal;
- density, measured using a pycnometer, ranged from 0.96 to 0.98 g/mL, which is compatible with water and necessary for stable emulsion formation;
- viscosity, a critical parameter for lubrication and cooling performance, was measured using a Brookfield LDV-E viscometer, calibrated with pure water. The viscosity of base oils ranged from 75 to 110 mm²/s, while their emulsified forms ranged between 1.7 and 4.1 mm²/s;
- flash point, which indicates thermal usability under high-temperature machining conditions, was measured using a K16500 rapid flash closed-cup tester [136].

In manufacturing environments equipped with numerous machine tools, the high volume of hot chips generated during machining can cause cutting fluids to evaporate, leading to air contamination within the facility [137]. With increasing environmental awareness and the enforcement of stricter regulations [107], the adoption of green cooling and lubricating techniques has become a necessity.

One such approach is the cryogenic cooling method, which offers several benefits, including dry chip generation, significant reduction in cutting fluid consumption, and lower overall fluid costs [138]. As demonstrated by Pereira et al. [139], cryogens such as liquid nitrogen (LN₂) evaporate upon application, leaving no residual waste behind. Moreover, in MQL systems, the small quantity of oil used is typically biodegradable, which renders its environmental impact negligible [140].

Table 4. Characterization of vegetable-based cutting fluids.

Metal cutting fluid	pH (emulsion 8%)	Density (g/ml)	Viscosity 40 °C (mm ² /s)	Viscosity 40 °C (mm ² /s) (emulsion 8%)	Flash point (°C)	Refractive index
SCF-II	8.92	0.96	91	4.1	217	1.4775
SCF-II	9	0.97	110	3.9	232	1.477
CSSF	9.18	0.98	75	1.7	235	1.4825

Note: SCF-II: sunflower cutting fluid with 8% EP additive; CCF-II: canola cutting fluid with 8% EP additive; CSSF: commercial semi-synthetic cutting fluid.

Considering both technical and ecological factors [141], it has been concluded that the combined use of LN_2 and MQL achieves an effective balance between environmental sustainability and machining performance [142]. This hybrid approach is particularly valuable in modern manufacturing contexts where ecological impact and operational efficiency must be simultaneously optimized.

As a widely adopted alternative to mineral-based cutting fluids, MQL involves the use of a minimal amount of biodegradable oil delivered at a reduced flow rate [143]. Over the past two decades, it has become a standard lubrication technique across various machining industries owing to its effectiveness and environmental benefits.

Subhash et al. [144] investigated the effects of MQL and nanofluid-assisted MQL on the machinability of Nicrofer C263 during turning operations under three conditions: dry machining, MQL, and MQL combined with Al_2O_3 nanoparticles. The results revealed that the combination of nanofluids and MQL provided the best surface finish and superior heat dissipation in the cutting zone compared to other conditions.

The addition of nanoparticles – commonly referred to as nanoadditives – has a significant impact on enhancing the performance of MQL systems. These additives notably improve the thermal conductivity and lubrication characteristics of cutting fluids, making them highly effective for difficult machining operations [145]. Consequently, MQL using conventional or nanoparticle-enriched fluids has emerged as one of the most preferred sustainable lubrication techniques in precision manufacturing [146].

Dong et al. [147] further advanced this approach by applying minimum quantity cooling and lubrication (MQCL), a technique that integrates MQL with the Ranque-Hilsch vortex tube mechanism. When used in the machining of hard-to-cut materials such as SKD11 tool steel, MQCL with 0.5 wt.% MoS_2 nanofluid resulted in the best surface finish and significantly reduced burn marks.

Similarly, Huang et al. [148] demonstrated that the use of graphene-based nanofluids delivered via ultrasonic atomization MQL led to remarkable improvements in micro-milling of hardened SKH-9 high-speed steel. This advanced lubrication method resulted in reduced cutting forces, lower temperatures, and decreased tool wear.

Overall, numerous experimental studies affirm that MQL, particularly when enhanced with nanofluids, offers a viable and environmentally

sustainable alternative to conventional flood lubrication, promoting greener and more efficient machining processes.

FUTURE TRENDS OF METALWORKING FLUIDS

The future of MWFs is increasingly centered around the development of high-performance, vegetable oil-based formulations that prioritize both machining efficiency and environmental sustainability. Emerging trends focus on eco-friendly solutions for machining difficult-to-cut materials, particularly in aerospace and composite applications. These approaches align with the principles of sustainable manufacturing by addressing occupational health and safety, minimizing waste and effluent generation, and reducing environmental pollution during both the usage and disposal phases of MWFs.

Recent research has evaluated the influence of the tribological properties of vegetable oil-based MWFs on the thermophysical behavior of hard-to-machine materials [149]. These fluids not only provide an environmentally safer alternative but also demonstrate promising lubrication and cooling characteristics critical for high-performance machining.

MWF application techniques play a crucial role in determining their technical (cooling and lubrication), economic, and environmental effectiveness [150]. Common delivery methods include minimum quantity lubrication, flood cooling, cryogenic cooling, high-pressure cooling [151]. Each method presents trade-offs:

- Dry machining is generally preferred from socioeconomic and ecological perspectives, but it can lead to increased vibrations and higher surface roughness in metal cutting, limiting its suitability for precision operations [152].
- High-performance machining of advanced aerospace materials often generates excessive heat under dry conditions, reducing machinability and making alternative techniques such as cryogenic-assisted or hybrid machining more effective [153]. MQL offers reduced fluid usage and environmental impact but often falls short in heat dissipation, especially in high-speed operations, leading to increased tool wear and compromised surface quality [154].

- High-pressure cooling effectively reaches the tool–workpiece interface, especially in complex geometries, offering improved tool life and surface finish. Cryogenic cooling delivers excellent performance in terms of tool wear, thermal control, and part quality. However, its high capital, operational, and maintenance costs pose economic challenges, limiting its feasibility for widespread sustainable manufacturing [155].

Given the projected surge in demand for high-speed machining in the manufacturing sector, the importance of MWFs will continue to grow. However, this also raises concerns about the health, safety, and environmental impacts of conventional, mineral oil-based fluids. Regulatory frameworks are evolving to mitigate these risks, aiming to protect both workers and ecosystems during MWF usage and disposal phases [156,157].

MWFs play a critical role in reducing temperature and friction at the tool–chip interface, as well as minimizing tool wear during machining operations [158]. In addition to that, MWFs aid in efficient chip evacuation and help maintain the dimensional accuracy of machined components [159]. The effectiveness of a cutting fluid directly influences tool life, energy consumption, and overall machining performance [160].

To meet modern sustainability demands, researchers have increasingly turned to nontoxic, biodegradable vegetable oil-based MWFs. These fluids offer excellent lubrication and cooling properties, making them viable replacements for hazardous mineral oil-based alternatives. The triglyceride structure of vegetable oils contributes significantly to their performance, with long polar fatty acid chains enhancing lubricity and reducing friction and wear on contact surfaces.

In summary, the future of MWFs lies in advanced, bio-based formulations and optimized application techniques that balance machining performance with environmental responsibility.

CONCLUSIONS

This study focused on the development and application of vegetable-based cutting fluids (VBCFs) to promote environmentally friendly machining practices. Experimental investigations assessed the influence of key machining parameters—cutting speed, feed rate, and depth

of cut—alongside different cutting fluid formulations on the milling performance of stainless steel, with a particular focus on surface roughness, cutting forces, and tool wear.

In conventional machining, two primary types of cutting fluids are commonly used: neat oils and straight oils, both typically derived from mineral oil and enhanced with various performance additives. However, because of environmental and health concerns, vegetable oil-based alternatives have gained prominence.

Most conventional cooling and lubrication methods, despite their effectiveness, are often not economically or environmentally viable. In contrast, the MQL technique has emerged as a promising near-dry machining approach, using only a minimal volume of metalworking fluid (MWF) for lubrication and heat dissipation. The key advantage of MQL lies in its significantly reduced effluent generation, making post-machining fluid separation from chips unnecessary due to the use of fine mist spray. Additionally, MQL systems involve lower capital, operational, and maintenance costs compared with flood, cryogenic, or high-pressure cooling techniques. These factors contribute to the recognition of MQL as a socio-economically and environmentally favorable application method for MWFs.

Nevertheless, a notable drawback of MQL is the generation of aerosolized mist, which can impair air quality and affect operator health and visibility. This challenge can be mitigated using enclosed or semi-enclosed machining systems, which prevent mist exposure and ensure a safer working environment.

Despite its benefits, the limited fluid volume in MQL restricts its cooling capacity, especially during the machining of heat-resistant superalloys and composite materials. This limitation often results in elevated cutting temperatures, which can adversely affect tool life and surface quality. To overcome this issue, manufacturers have explored the use of enhanced performance cutting fluids within MQL systems. Furthermore, some studies have reported success by integrating cold air supply with MQL to improve thermal control and compensate for its lower cooling efficiency.

The tribological and cooling performance of the formulated VBCFs was also evaluated. The findings confirmed that the lubrication capability of the cutting fluids played a crucial role in minimizing surface roughness and cutting forces, thus improving overall machining efficiency.

Future work should explore the combined effects of advanced cutting fluid formulations, electrostatic enhancement, and hybrid cooling strategies across a broader range of workpiece–tool material combinations and process conditions. Such studies will help to fully quantify energy savings, tool life improvements, and environmental benefits associated with sustainable machining practices.

The findings support vegetable-based and electrostatic lubrication technologies as effective strategies for achieving high-performance, energy-efficient, and environmentally sustainable machining, which highlights their potential to replace conventional mineral-oil-based systems in modern manufacturing.

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