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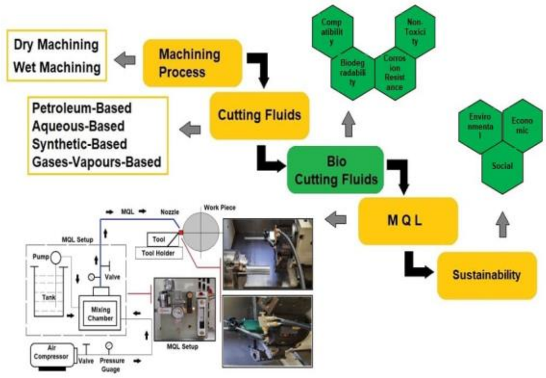
The role of bio-based cutting fluids for sustainable manufacturing and machining processes: A holistic review

Arun Kumar Katam[1,3], Ramesh Chandra Mohanty[2], Aditya Kolakoti[3] *

[1] Research Scholar, Department of Mechanical Engineering, Centurion University of Technology and Management, Odisha 752050, **India**
[2] Department of Mechanical Engineering, Centurion University of Technology and Management, Odisha 752050, **India**
[3] Department of Mechanical Engineering, Raghu Engineering College(A), Visakhapatnam, Andhra Pradesh 531162, **India**
✉ aditya.kolakoti@gmail.com

This article contributes to:
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
SUSTAINABLE DEVELOPMENT GOALS



Highlights:
- Role of Metal Cutting fluids (MCFs) in machining.
- Predominance of conventional MCFs in the industry.
- Environmental and health hazards associated with conventional MCFs.
- Recent developments in eco-friendly cutting fluids.
- Recommendations for implementing sustainable manufacturing methods.

Abstract
Metal cutting fluids (MCFs) play a significant role in cooling and lubricating the cutting zones during various machining operations. The commercially available MCFs like mineral and petroleum oils cater to approximately 75% of the market needs. However, these MCFs harm the worker's health and environment. Therefore, sustainable and eco-friendly MCFs are gaining widespread acceptance in industries. This study critically analyses the recent improvements in metal cutting fluids in drilling, milling, and turning operations with the prospect of accomplishing green and sustainable manufacturing. Furthermore, this study highlights the role of bio-based cutting fluids in the manufacturing industry and the effect of non-bio-based coolants on the environment, and human health hazards are highlighted. In addition, this study analyses minimum quantity lubrication (MQL) techniques applied in various metal-removing operations. Finally, this review article recommends that bio-based cutting fluids combined with MQL techniques can achieve the sustainability goals of the manufacturing industry.

Keywords: Cutting fluid; Machining; Manufacturing; Minimum quantity lubrication; Sustainability

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1. Introduction

Machining operations encompass a variety of processes that remove material from a workpiece to achieve desired shapes and dimensions. These processes include turning, milling, drilling, grinding, and more. Cutting fluids plays a crucial role in achieving optimum machining parameters, ensuring efficient and precise results.

Cutting fluids serve multiple purposes, such as removing heat, reducing friction, and aiding in chip evacuation during machining operations. By reducing the heat generated during machining, cutting fluids prevent thermal deformation and tool wear, thereby prolonging tool life [1]. As a lubricant, they minimize the friction between the cutting tool and workpiece, resulting in a smoother surface finish and reduced energy consumption.

According to the surveys, approximately 30-40 million tons of lubricants are used annually, with 20 million tons returning to the environment [2]. Over 95% of these lubricants are petroleum-based and non-biodegradable [3]. The improper disposal of petroleum-based cutting fluids harms the environment, while prolonged exposure to their emissions leads to cancer and respiratory diseases [4]. Additionally, their nonrenewable nature raises global concerns about environmental hazards. As a result, scientists and tribologists have suggested the use of bio-based or plant-derived cutting fluids (CFs) as a viable substitute for petroleum-based CFs [5]–[7]. Vegetable oils have garnered increased attention due to their noteworthy properties, such as high viscosity and flash points, reduced toxicity, renewability, and biodegradability [8].

This study aims to provide a comprehensive overview of the advancements in MCFs, considering recent progress in bio-based CFs, minimum quantity lubrication (MQL) methods, human health risks, and environmental challenges as reported by various researchers. The methodology of this literature review is depicted in Figure 1.

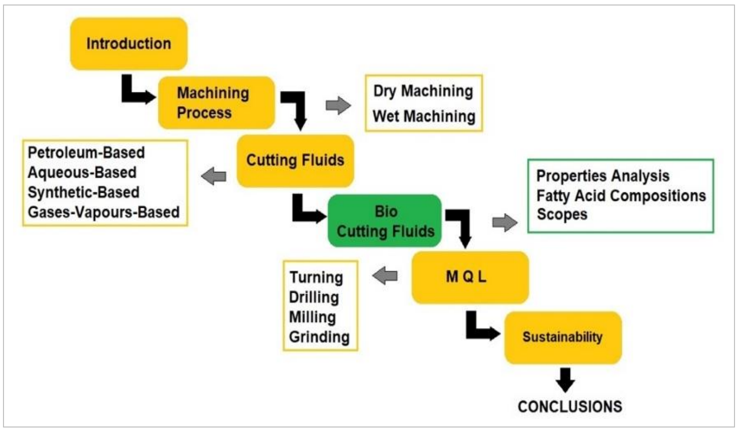

Figure 1. Process flowchart of the present study

2. Evolution of Metal Cutting Fluids in Machining Operation

Cutting fluids are indispensable in machining operations, contributing to enhanced precision, improved surface quality, and extended tool life. Their role in maintaining optimum machining parameters is vital for achieving high-quality, cost-effective results in the manufacturing industry. Better cooling and lubrication are achieved with the application of CFs and the timeline of various heat removal techniques from 1906 to the present day is shown in Figure 2.

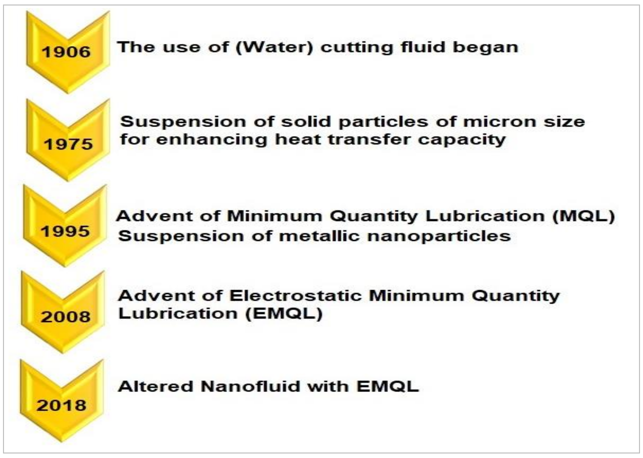

Figure 2. Evolution of metal cutting fluids

2.1. Dry Machining Operation

Dry machining is an environmentally friendly alternative to traditional metal cutting processes that rely on the use of cutting fluids. This technique avoids the application of lubrication and cooling agents, resulting in a more sustainable manufacturing method. In his groundbreaking work, F.W. Taylor [9] said, "Under certain conditions, the cutting tool operates efficiently without the need for lubrication or cooling agents". These observations by Taylor have paved the way for further research and innovation in dry machining, offering industries the potential to reduce their environmental impact while maintaining efficient production processes. The absence of coolant in dry machining lowers production costs by 16-20% and leads to economic and ecological achievements [10]. Some of the recent experimental studies by various researchers on different machining operations are summarized in Table 1.

2.2. Wet Machining Operation

Wet machining operations make use of CFs primarily to control temperature in the work zones and to provide cooling and lubrication to the workpiece as well as the cutting tool. Water is one of the best coolants used in machining operations [8]. A good coolant maintains a temperature below the thermal softening temperature of the tool material, thereby extending its life. Fluids possess high specific heat, which enables them to carry away a large amount of heat. Initially, water is considered one of the ideal cutting fluids due to its excellent cooling ability. Despite its advantages, water is being gradually replaced with other mineral oils or petroleum products. This is due to the corrosive nature and inadequate lubricating properties of water.

Table 1. Various experimental findings for dry machining operations

Ref.	Type of machining	Tool used	Workpiece used	Main findings
[11]	Dry cutting	PVD TiAlN tools	IN718	The impact of Ti-Al-N coating thickness on the cutting temperature in dry turning of Inconel 718 was examined. The research found that coated tools outperformed uncoated tools in terms of anti-friction, thermal barrier effect, and tool life.
[12]	Dry milling	Uncoated tungsten carbide	Titanium alloy Ti-6Al-4V	Wear Mechanism reduced in Extreme High Vaccum (XHV) environment. Reduced workpiece adhesion on the tool and cutting forces compared to machining in air.
[13]	Dry turning	Uncoated WC tool	IN718	According to the findings of their research, the surface quality of the workpiece deteriorates as the flank wear depth increases, and it was also found that dry machining accelerates the oxidation of a few elements of the work material.
[14]	Dry whirling milling	TiAlSiN	AISI 420 martensitic stainless steel	The primary goal of the researchers was to evaluate the effectiveness of TiAlSiN coated inserts in dry machining of martensitic stainless steel and also to optimize the process variables. The microhardness of coated inserts was found to be 43.34% greater than that of pure inserts.
[15]	Dry turning	HSS	EN AW- ALLOY	Average surface roughness and cutting force are found to be highest in dry cutting compared to other cutting processes.

3. Overview of Cutting Fluids

The use of cutting fluids is inevitable for any machining process, and their applications in industrial manufacturing are gradually increasing. Over many decades, there has been a tremendous change in the CFs in industrial applications, including the evaluation of rheological, tribological, thermal, anti-corrosion, biodegradation, and storage stability characteristics. Initially, water is one of the most widely used CFs in many metal removal operations. For instance, the initial grinding fluid consisted of water, which was employed as the primary medium for removing metal during the well-known practice of sharpening a knife on a whetstone [16]. However, due to its corrosive nature and insufficient lubrication, petroleum-based oils emerged in the market, offering better cooling and lubrication, thus replacing water. Currently, a wide variety of CFs are being used in metal removal operations, and the significant classification is illustrated in **Figure 3**.

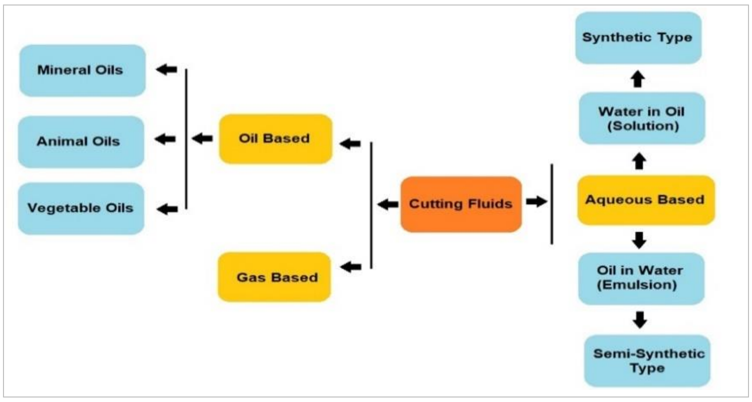

Figure 3. Classification of cutting fluids

3.1. Petroleum-Based Cutting Fluids

Petroleum-based CFs (mineral oils) are water-insoluble and are widely used in metal removal operations due to their desirable lubricating characteristics, approximately they make up 85% of the world's lubricants [17]. The mineral oils possess excellent lubrication and corrosion resistance properties but fail to provide enough cooling in the working zones viz. tool and workpiece contact. The experimental findings from different research groups on mineral oil-based CFs are reported in **Table 2** and some of the advantages and limitations of their applications are reported in **Table 3**.

3.2. Aqueous-Based Cutting Fluids

The aqueous-based CFs are available in concentrated form, which is generally mixed with water before their application. The aqueous-based products are mixed with water to form an emulsion and solution. Usually, the emulsion is formed by blending mineral oil in water with an emulsifying agent, and the typical ratio of water to oil is maintained as 20:1 or 30:1 [18]. The presence of water helps the emulsion for better cooling, while the oil lowers the tendency of oxidation caused by water. However, the presence of water in emulsion leads to the growth of infestation by microorganisms like bacteria, fungi, and yeasts [19]. This micro-organism growth will weaken the emulsion's cooling and lubrication properties and also lead to corrosion. While traditional bactericides may enhance the biological stability of cutting fluids, their environmental toxicity remains a concern [20].

3.3. Synthetic-Based Cutting Fluids

Synthetic-based CFs are chemical-based and are completely free from mineral oil. They appear clear and watery; therefore, dyes are often added to make them visible in clear green or yellow colours [19]. Synthetic CFs are good at removing heat at work zones during the machining

Table 2. Experimental findings of mineral oil-based CFs

Ref.	Type of machining	Tool used	Workpiece used	Main findings
[21]	Milling	Carbide	AISI 8640 steel	The effectiveness of synthetic, semi-synthetic, and mineral oil emulsions as CF was studied. Examined that the synthetic oils produced high cutting temperatures, followed by the mineral oil emulsion, and then the semi-synthetic oil.
[22]	Slot milling	Micro-grained carbide cutting inserts	IN718	The impact of MCF flood cooling on surface integrity was studied considering dry, mineral, and biodegradable oil. Proposed that biodegradable cutting fluid improves surface integrity and is more ecologically friendly than mineral oil-assisted wet cutting.
[23]	Turning	AISI D2 (heat treated) (55±1 HRC) steel	Uncoated carbide tool	Applied novel method of spray impingement cooling environment using Taguchi-based L16 orthogonal array. They found that feed and depth of cut are the most significant factors in surface roughness and chip reduction coefficient, while the cutting speed is the most significant factor in flank wear and chip-tool interface temperature.
[24]	Turning	Mixed alumina inserts	hardened AISI 4340 steel	The authors compared two emulsions and one synthetic cutting fluid to dry cutting for tool life, surface quality, tool wear mechanisms, and chip formation. Emulsion-based fluid (without mineral oil) and dry cutting performed best, followed by synthetic fluid and mineral oil-based emulsion.

Table 3. General features of various types of CFs

Cutting fluid	Advantages	Limitations	Effect on the environment due to disposal into air, water, and soil	Effect on health due to prolonged exposure
Straight/Neat oils	Excellent lubrication and rust protection.	Poor cooling produces mist and smoke. Appropriate for machining at moderate speeds. Surface cleanliness issues.	Contaminate the soil and water. Contains toxic compounds such as polycyclic aromatic hydrocarbons (PAHs) that can be harmful to living organisms.	Skin irritation and dermatitis coughing, wheezing, and shortness of breath dizziness, headaches
Soluble oil	Ample lubrication. Good cooling. Protection from corrosion by leaving a thin film of oil on the surface of the workpiece.	Easily contaminated by bacteria. Loss due to evaporation. Inclination to precipitate. Misting issue.	Contributes to greenhouse gas emissions. Easily contaminates water bodies and is not easily biodegradable, and can persist in the environment for a long time.	Skin and lung cancer. Shortness of breath. Headaches. Dryness of skin etc.
Semi-synthetic oil	Better cooling and wetting capabilities. Good antibacterial properties. Excellent for ferrous and nonferrous substances. Reduced viscosity facilitates cleaning.	Less base oil than soluble oils, thus less lubricity. Foaming problem. Incompatible with hard water. Easy cross-contamination of other fluids. May create deposits	MoS2 is a known hazardous material and can be toxic and pose a health risk to wildlife and humans. Damages soil quality and reduces the fertility of the land.	Eye irritation, redness of eyes. Digestive problems like stomach cramps. Skin irritation and respiratory problems.
Synthetic oil	Outstanding cooling. Exceptional microbial control. Noninflammable. Extremely high flashpoint. Less foaming. Excellent corrosion resistance Loss of minimum drag out	Lack of lubrication owing to a lack of lubricants. Contamination from other machine lubricants. Mist formation. Gummy residue after contact with machine lubricants.	Causes harm to aquatic life and disrupts the natural balance of the ecosystem. Contaminates soil and may affect the growth of plants.	Eye irritation. Nausea and diarrhea when ingested accidentally. Headaches and dizziness.

process but are incapable of providing sufficient lubrication compared to other types of CFs. This is due to the lack of oiliness in synthetic CFs. However, they provide good corrosion resistance, water softening, and reduction of surface tension with the addition of organic and inorganic chemicals [25]. Another classification for synthetic-based CF is the semi-synthetic type, it is a combination of synthetic chemicals and mineral oil diluted in water with additives. The additives help to create a more stable emulsion with smaller droplets, enhancing lubrication [19]. Both the synthetic and semi-synthetic CFs perform reasonably well in cooling performance with a low corrosion rate and low vulnerability to bacterial growth. Though widely used, synthetic-based oils have a severe environmental impact. These oils should be handled with high precaution as they are toxic, non-biodegradable, challenging for disposal, and harmful to the working environment. Therefore, a green and sustainable machining process with the implementation of bio-cutting fluids has an increasing demand.

4. Vegetable Oils as Bio-Cutting Fluids

The challenges in petroleum-based CFs can be overcome with the implementation of bio-based cutting fluids (BCFs), which are renewable and bio-degradable. The biodegradable potential of BCFs is very promising. They are 96.67% biodegradable, compared to mineral oils which are only

18.32% biodegradable [26], [27]. These BCFs are not only eco-friendly and biodegradable but also promote to achieve enhanced machinability during usage. They are primarily obtained from plants and vegetable oils. Different researchers have investigated a wide variety of edible and non-edible vegetable oils, and some of them are; palm, rapeseed, sunflower, soybean, canola, neem, karanja, cottonseed, coconut, pongamia, jatropha, palm kernel, groundnut, mustard, castor, olive melon seed, etc.

Mannekote et al. [28] categorize various vegetable oils that are popularly used in industrial applications into three categories, as shown in **Figure 4**. These categories are based on availability and sources from which the oils can be extracted and the type of oil, i.e. edible or non-edible. The market share of various CFs in the United States has been displayed in **Figure 5** which reveals the increasing trends for BCFs in upcoming years [29].

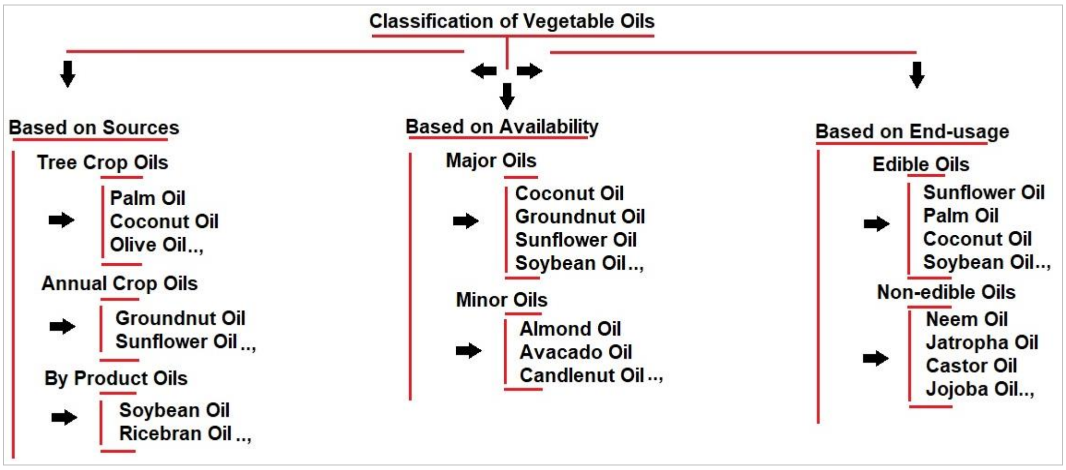

Figure 4. Classification of vegetable oils

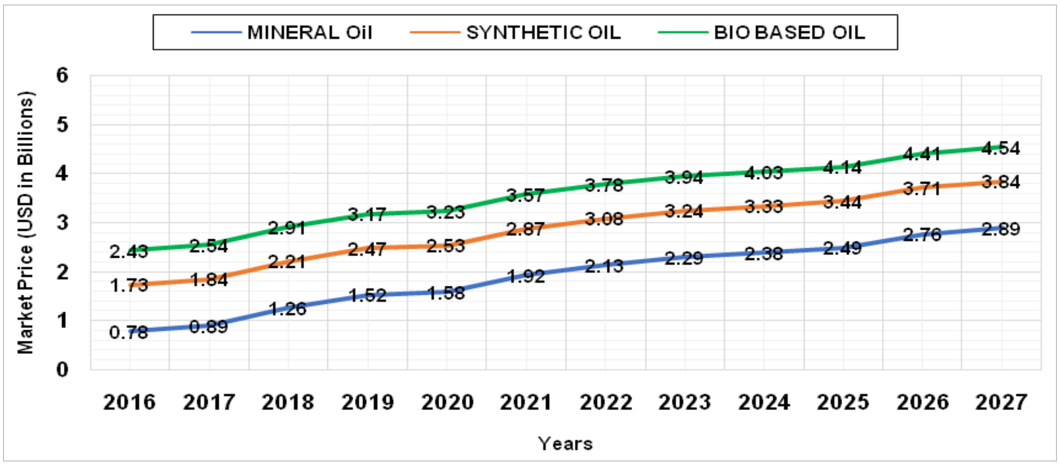

Figure 5. Market share of CFs with respect to years

These features made the researchers further investigate the compatibility of vegetable oils as BCFs during machining operations in terms of performance, environment, and economic aspects. The performance of the BCFs during the metal cutting operations mainly depends on the significant physiochemical oil properties like viscosity, density, flash point, pour point, and saponification values. Significant oil properties obtained from the available literature have been summarized in **Table 4**. All the physiochemical properties of the vegetable oils are equally significant during metal cutting operations. However, kinematic viscosity and flash points are of particular interest. The tribology of CFs, which includes friction, wear, heat transfer, and lubrication at the interacting surfaces, plays a predominant role in metal removal operations [7].

4.1. Fatty acid Profiles of Vegetable Oils

The Fatty Acid Compositions (FAC) play a significant role in analyzing the bio-oil properties and the FAC are always varied from oil to oil, and it also depends on seed quality, weather, and cultivation lands. Most BCFs have almost similar molecular structures. Triglycerides with long-chain fatty acids linked to the hydroxyl group via an easter link can be observed primarily in most vegetable oils [7]. The FAC can be determined with the position of carbon-to-carbon double bonds and their ratio.

Table 4. Significant properties of various vegetable oils [8], [18]

Type of oils	Viscosity (mm^2/s)	Density (g/ml)	Flash point (°C)	Pour point (°C)	Iodine value	Thermal conductivity (W/mK)
Palm	40.72	0.918	315	12	51-54	0.171
Coconut	30.12	0.917	245	19	9-11	0.148
Sunflower	39.13	0.896	278	-15	113-148	0.168
Castor	250.12	0.986	280	-32	89-92	0.160
Neem	50.14	0.898	252	7	93-34	0.156
Jatropha	37.85	0.916	276	-3	82-91	0.157
Rapeseed	43.22	0.915	316	-20	40-41	0.170
Groundnut	36.45	0.916	321	3	84-94	0.162
Rice bran	40.06	0.920	319	-30	93-94	0.155
Karanja	12.54	0.912	219	-6	86-87	0.154
Jojoba	21.78	0.845	298	9	91-92	0.147
Palm	40.72	0.918	315	12	51-54	0.171

The deserving property of cutting fluid is the lubricity and it can be achieved with the triglyceride's structure in vegetable oils. Furthermore, vegetable oils possess low volatility and hence they are more suitable as a metalworking fluid. The oiliness and anti-wear in vegetable oils are due to the polarity of fatty acids which produces oriented molecular films. Therefore, FACs is believed to be a significant element of lubricity and hence their analysis is also significant in the characterization of different vegetable oils as MCFs. The manufacturing industries are gradually inclined towards green and sustainable manufacturing. Environmental legislation series by Occupational Safety and Health Administration (OSHA) and other international agencies played a vital role in pushing the manufacturing sector towards green and sustainability.

Most vegetable oils are served as good lubricants and MCFs. However, there are still a few disadvantages existing in vegetable oils in terms of oxidation stability and low thermal stability when compared to regular petroleum fluids. These shortfalls can be mitigated with the proper modification of vegetable oils. Some of the popularly used techniques to improve poor oxidation stability and low-temperature properties are the reformulation of additives, chemical modification, and genetic modification. Some major advantages and drawbacks are presented in **Table 5** [30].

Table 5. Advantages and drawbacks of vegetable oils as MCFs

Advantages	Drawbacks
Low production cost due to availability	Poor thermal conductivity
Environment-friendly and biodegradability	Oxidation stability is very low
Improved fuel properties of high flash point and viscosity	Anti-corrosion protection is poor
Low toxicity and volatility	High freezing points
High production possibilities	-

5. Minimum Quantity Lubrication (MQL)

Tools wear and heat generation at the tool-tip and workpiece interface are one of the most challenging issues in machining, particularly in hard-to-cut materials. At high speeds, the heat liberation is high and the coolant may not reach the desired areas resulting in poor cooling of the interface [31]. Flood cooling techniques are considered the most effective to regulate tool wear and remove unnecessary heat [32]. However, there are many associated problems with flood cooling in terms of disposal, pollution, health hazards, etc. Therefore, minimum quantity lubrication (MQL) techniques emerge as a possible alternative. MQL is considered an environmentally friendly method where the quantity of cutting fluid used is 21.27% compared to the flood lubrication system. Thus, the quantity of coolant used in MQL is very less due to the fine mist lubrication effect [33]. It has better reachability on the cutting zones and also reduces cost by minimizing its consumption [34]. The required pressures for mist formation in an MQL system vary from 2 to 6 bar [35], [36]. **Figure 6** represents the schematic layout of an MQL setup.

The major benefits of the MQL system over other cooling/lubrication systems include a decrease in environmental and worker health hazards, minimum utilization of cutting fluid, relatively low cost and less tool wear, improved surface roughness, and better lubrication than conventional systems. The less utilization of CF helps to regulate the CF disposal problems. In addition, the convection and evaporation heat transfer modes in MQL and the way that pressurized liquid breaks the evaporation zone made the metal removal process more attractive [37]. Due to the benefits, the successful application of MQL in different metal removal operations like turning, drilling, milling, and grinding are investigated by the researchers, and concluded that MQL results in improved surface finish, less cutting forces, lower chip breakability, and better tool life. A summary of significant findings from the different researchers using MQL in various metal removal operations is presented in **Table 6**.

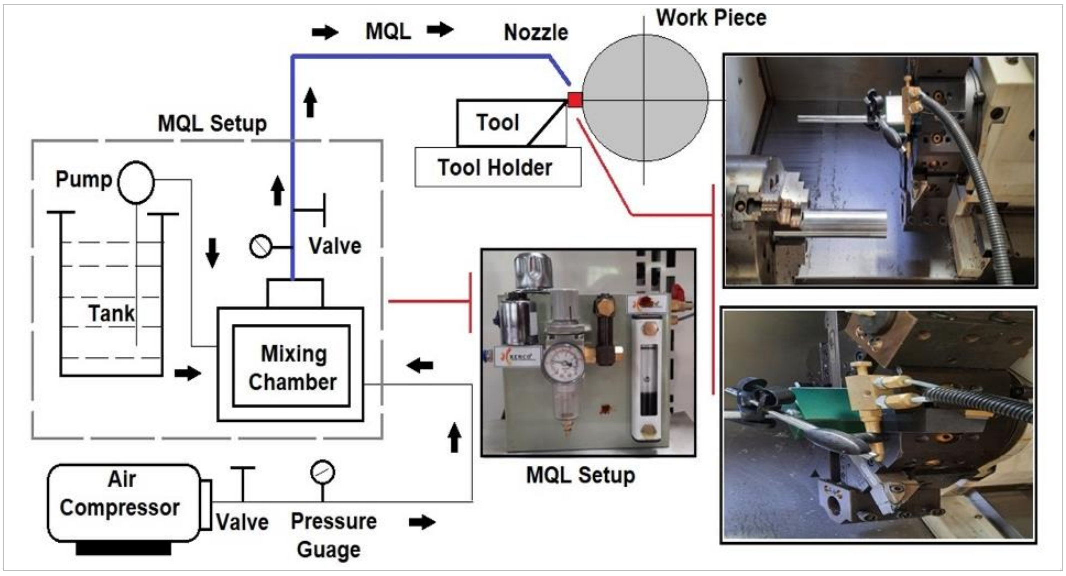

Figure 6. Schematic layout of MQL setup

6. Nano-Additives in Cutting Fluids

The role of nano-additives in cutting fluids has emerged as a significant area of research in recent years, primarily due to their potential to improve the performance of conventional and bio-based coolants. Nano-additives, such as nanoparticles of metals, metal oxides, or carbon-based materials, can impart enhanced tribological properties, better heat transfer capabilities, improved tool life, superior surface finish, and improved stability to cutting fluids [38]. The effect of graphene nanoplatelets on the performance of cutting fluids found that the addition of graphene resulted in reduced cutting forces, lower tool wear, and improved surface finish [39]. In another study, Kumar et al. [40] investigated the influence of zinc oxide nanoparticles on the lubrication and cooling properties of cutting fluids and reported that the addition of nanoparticles enhanced the heat dissipation capacity and reduced the coefficient of friction.

Other researchers have explored the potential of different types of nano-additives, such as silver nanoparticles [41], carbon nanotubes [42], and alumina nanoparticles [43] in enhancing the properties of cutting fluids. These studies have reported improvements in properties such as thermal conductivity, viscosity, and wear resistance. Nano-fluid MQL exhibited improvement in surface finish by 34.72% and 7.59% over dry and flooded coolant environments, respectively [44].

However, there are also challenges associated with the use of nano-additives in cutting fluids like the stability of nano-fluids [45], potential health risks associated with exposure to nanoparticles, necessitate proper handling and disposal procedures [46], and the increased cost of production due to the use of nanoparticles and the need for specialized equipment to disperse them in the coolant [47].

7. Safety and Environmental Challenges

Metal cutting fluids are widely used in manufacturing industries to improve surface finish and provide better cooling and lubrication in the working zones. Moreover, machining is a high-energy consuming method with multiple operations and any small decrease in the machining power in each operation can add to a significant cost-benefit and a positive impact on the environment [48]. Unfortunately, MCFs harm the health of the worker and the environment. The MCFs have a high risk of causing diseases like cancer and respiratory problems and most of the MCFs cause skin irritation or allergies when they are exposed to the work zones [49]. According to reports, approximately 80% of occupational diseases among operators can be attributed to skin contact with cutting fluids [50]. Constituents in cutting fluids like nitrates and amines [51], hetero-cyclic and poly aromatic hydrocarbons [52], [53], biocides [54] are potential carcinogenic agents, and sulfur, chlorine, and phosphorus cause respiratory problems [55], chlorinated paraffin [56], aromatic hydrocarbons, etc. cause skin diseases. The MCFs may enter the body when the mist, aerosols, or vapors are inhaled during metal removal operations. Therefore, wearing a safety mask and enclosing the machine is highly recommended. Skin irritation or allergic contact dermatitis is reported if the worker is exposed to synthetic, semisynthetic, and soluble MCFs.

Table 6. Various experimental findings for MQL in machining operations

Ref.	Machining	Tool	Workpiece material	Findings
[57]	Turning	Tungsten carbide turning insert	Ti-6Al-4 V	The effects of MQCL treated with soluble oil, aqueous alumina, and hBN nanofluids on machinability were studied. MQCL mode provided promising results in feed force, primary cutting force, radial thrust, and friction-to-normal force ratio.
[58]	Turning	Sintered carbide	316L stainless steel	Observed that cutting tool wear was reduced by around 21% by the MQL approach in comparison to dry machining.
[59]	Turning	Uncoated tungsten carbide	Precipitated hardened stainless steel (PH SS)	A rise in MQL flow rate is found to considerably decrease surface roughness and tool wear.
[60]	Drilling	HSS drill tool	Stainless steel (AISI 321)	MQL improved drilling performance over dry and flood drilling. Thrust force, torque, surface roughness, and friction coefficient decreased by 21.27, 25.49, 30.72, and 5.35 %.
[61]	Drilling	HSS drill coated with titanium nitride (TiN)	Electrolytic copper	The MQL system created the least specific cutting pressure. Compared to dry and flood machining, there is a decrease in the feed force and burr height through MQL.
[62]	Milling	High-speed steel	AISI 1045	The milling parameters (milling force, friction coefficient, surface roughness, surface morphology of chips and workpiece) are examined. Palm oil based on MQL outperformed synthetic oils.
[63]	Milling	Coated carbide inserts	Carbon steel (SA516)	When milling with dry and MQL vs conventional flood coolant, there have been noticeable enhancements in surface finish and tool life. Compared to flood coolant, measured energy footprints for dry and MQL were considerably reduced.
[64]	Milling	High-speed steel	Super duplex stainless steel (SDSS)	The authors examined tool wear, cutting force, surface quality, chip shape, residual stress, and low surface fracture density. Overall machinability studies showed that MQL performed superior to alternative coolant and lubrication techniques.
[65]	End milling	Coated carbide cutting tool	Aluminium alloy AA6061-T6	Used MQL with hybrid Nano coolant (TiO_2 and ZnO particles). Found that the material removal rate during the machining of aluminum alloys is most influenced by the depth of cut and feed rate, followed by spindle speed, This technique offers economic benefits through reduced machining costs and improved machinability.
[66]	Milling	High-speed steel	Inconel 718 alloy	Tool flank wear was compared under dry, flood, and MQL machining conditions. The MQL has outperformed the other two, keeping the tool wear below the ISO3685 rejection threshold.
[67]	Grinding	Hauni-Blohm HFS 204 surface grinding machine	Ceramic matrix composites	Grinding pressures and specific grinding energy were lowered using MQL grinding. As a consequence, wheel wear was reduced while the G-ratio was raised. Furthermore, the surface produced by MQL grinding was smoother than that produced by fluid grinding and much better than that produced by dry grinding.
[68]	Grinding	Aluminum oxide grinding wheel	AISI 4340 steel	The MQL with the cleaning jet was compared to both the traditional flood application and the MQL without the cleaning jet. Compared to MQL and flood lubrication, the (MQL+WCJ) method led to less surface roughness and roundness deviation, more G-ratio, less tangential grinding force, less chip adhesion, and less specific energy.

Respiratory problems like asthma, respiratory tract irritation, and difficulty in breathing are commonly observed in workers exposed to the MCFs [69]. Continuous exposure to aerosol, mist, and vapour may lead to respiratory problems like chronic obstructive pulmonary disorders (COPD) or aggravate the existing ones [70]. The presence of bacteria can aggravate asthma, irritate the eyes, nose, and throat, and create irritation to the respiratory tracts, which can cause flu-like symptoms such as wheezing, shortness of breath, sore throat, and runny nose [69]. For instance, hypersensitivity pneumonitis, often known as HP, is a form of allergic reaction that can occur in the lungs and is aggravated if exposed to microbial products leading to bacterial pneumonitis. The symptoms of HP are wheezing shortness of breath, and persistent cough. If it is not treated, it can lead to lung damage that cannot be reversed [71]. The international agency for research on cancer reveals that hydrocarbon mineral oils that are used in metal removal operations as MCFs are carcinogenic, and can cause cancers. The cancers like rectum, pancreas, skin, esophagus, bladder, and larynx are commonly reported with exposure to MCFs.

With the advancement of science and technology, the manufacturing sector's growth rate has increased significantly by utilizing the most recent technologies. Nanotechnology, among others, has played an important role in improving the desired properties in CFs and improving surface quality, and lowering tool wear. However, nanoparticles harm working environments, especially health. The National Institute for Occupational Safety and Health (NIOSH) report showed that workers exposed to metal removal operations are highly at risk of severe skin and inhalation health issues [49]. Statistical results also reveal that huge tonnes of petroleum-based MCFs are being consumed every day and are unable to dispose of them scientifically, which results in polluting the environment. Therefore, the main functions of CFs should not only focus on cooling and lubrication but also their biodegradability and sustainability.

8. Conclusion

The primary objectives of cutting fluids are to dissipate excess heat from work zones and create an optimal cooling environment for efficient machining operations. Metal-cutting fluids have been traditionally used to achieve these goals; however, they pose environmental and safety concerns due to their non-biodegradable nature. The use of bio-cutting fluids and related technologies such as nano-additives and minimum quantity lubrication has shown significant potential in promoting sustainable and environmentally friendly manufacturing practices. In this review, various experimental studies on different metal removal operations have been critically analyzed, and based on the observations, the following are the key conclusions:

a. Dry machining operations are considered environmentally friendly, but huge heat will be generated during dry operation, resulting in decreased tool life and poor surface finish. Furthermore, dry operations are limited to easy-to-cut materials.
b. MCFs like mineral and synthetic oils have emerged as a promising solution to remove excess heat and provide better lubrication. Unfortunately, they are toxic and non-biodegradable.
c. Bio-based oils obtained from different feedstocks of edible and non-edible oil possess high biodegradability compared to mineral and synthetic base oils.
d. The physicochemical properties of bio-based oils exhibit superior viscosity and flash points, but poor oxidation stability and low thermal conductivity are the major drawbacks.
e. Compared to Bio-based cutting fluids, conventional cutting fluids are often toxic and non-biodegradable. Utilizing them in large quantities is a major environmental and health concern. Employing Minimum quantity lubrication (MQL) is an effective way to minimize environmental problems.
f. MQL finds applications in all metal removal operations, and MQL techniques are the best alternatives to conventional wet metal removal operations due to their ecological and economic advantages. Moreover, MQL techniques help in the reduction of friction coefficient and cutting force which results in achieving prolonged tool life and low surface roughness.

From the above discussions, it is evident that BCFs with MQL are possible solutions to achieve sustainable manufacturing goals. It is also estimated that the future directions of green and sustainable manufacturing will be focused on the improvement of bio-based coolant properties and tribological behavior with the addition of nanoparticles.

Authors' Declaration

Authors' contributions and responsibilities - Arun Kumar Katam: Writing original draft, conceptualization, visualization, methodology, and investigation; Ramesh Chandra Mohanty: Conceptualization, investigation, supervision, review, and editing; Aditya Kolakoti: Writing original draft, Conceptualization, investigation, supervision, review, and editing.

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References

[1] K. S. Woon, "High Performance Machining of Metal Matrix Composites," *Encyclopedia of Materials: Composites*, vol. 1, pp. 512–524, 2021, doi: 10.1016/B978-0-12-803581-8.11831-4.

[2] T. Mang and W. Dresel, *Lubricants and lubrication*. John Wiley & Sons, 2007.

[3] M. P. Schneider, "Plant-oil-based lubricants and hydraulic fluids," *Journal of the Science of Food and Agriculture*, vol. 86, no. 12, pp. 1769–1780, 2006, doi: 10.1002/jsfa.2559.

[4] K. K. Gajrani and M. R. Sankar, "Past and current status of eco-friendly vegetable oil based metal cutting fluids," *Materials Today: Proceedings*, vol. 4, no. 2, pp. 3786–3795, 2017, doi: 10.1016/j.matpr.2017.02.275.

[5] R. Somashekaraiah, D. P. Gnanadhas, S. V. Kailas, and D. Chakravortty, "Eco-friendly, non-toxic cutting fluid for sustainable manufacturing and machining processes," *Tribology Online*, vol. 11, no. 5, pp. 556–567, 2016, doi: 10.2474/trol.11.556.

[6] P. Nagendramma and S. Kaul, "Development of ecofriendly/biodegradable lubricants: An overview," *Renewable and sustainable energy reviews*, vol. 16, no. 1, pp. 764–774, 2012, doi: 10.1016/j.rser.2011.09.002.

[7] J. C. J. Bart, E. Gucciardi, and S. Cavallaro, *Biolubricants: Science and Technology*, 1st ed. Philadelphia, USA: Woodhead Publishing Series in Energy, 2012.

[8] R. Sankaranarayanan and G. M. Krolczyk, "A comprehensive review on research developments of vegetable-oil based cutting fluids for sustainable machining challenges," *Journal of Manufacturing Processes*, vol. 67, pp. 286–313, 2021, doi: 10.1016/j.jmapro.2021.05.002.

[9] F. W. Taylor, *On the art of cutting metals*. New York: American Society of Mechanical Engineers, 1907.

[10] F. Klocke, L. Settineri, D. Lung, P. C. Priarone, and M. Arft, "High performance cutting of gamma titanium aluminides: Influence of lubricoolant strategy on tool wear and surface integrity," *Wear*, vol. 302, no. 1–2, pp. 1136–1144, 2013, doi: 10.1016/j.wear.2012.12.035.

[11] J. Zhao and Z. Liu, "Influences of coating thickness on cutting temperature for dry hard turning Inconel 718 with PVD TiAlN coated carbide tools in initial tool wear stage," *Journal of Manufacturing Processes*, vol. 56, pp. 1155–1165, 2020, doi: 10.1016/j.jmapro.2020.06.010.

[12] H. J. Maier *et al.*, "Towards dry machining of titanium-based alloys: A new approach using an oxygen-free environment," *Metals*, vol. 10, no. 9, p. 1161, 2020, doi: 10.3390/met10091161.

[13] M. Rakesh and S. Datta, "Effects of cutting speed on chip characteristics and tool wear mechanisms during dry machining of Inconel 718 using uncoated WC tool," *Arabian Journal for Science and Engineering*, vol. 44, pp. 7423–7440, 2019, doi: 10.1007/s13369-019-03785-y.

[14] C. Moganapriya, R. Rajasekar, T. Mohanraj, V. K. Gobinath, P. S. Kumar, and C. Poongodi, "Dry machining performance studies on TiAlSiN coated inserts in turning of AISI 420 martensitic stainless steel and multi-criteria decision making using Taguchi-DEAR approach," *Silicon*, pp. 1–14, 2021, doi: 10.1007/s12633-021-01202-4.

[15] S. Jozić, I. Dumanić, and D. Bajić, "Experimental analysis and optimization of the controllable

parameters in turning of en aw-2011 alloy; dry machining and alternative cooling techniques," *Facta Universitatis, Series: Mechanical Engineering*, vol. 18, no. 1, pp. 13–29, 2020, doi: 10.22190/FUME191024009J.

[16] Mc Coy JS, "Introduction: Tracing the historical development of metalworking fluids," in *Metalworking Fluids*, 2nd ed., London: CRC Publishers, 2006, pp. 1–18.

[17] L. Pop, C. Puşcaş, G. Bandur, G. Vlase, and R. Nuţiu, "Basestock oils for lubricants from mixtures of corn oil and synthetic diesters," *Journal of the American Oil Chemists' Society*, vol. 85, pp. 71–76, 2008, doi: 10.1007/s11746-007-1156-z.

[18] E. Kuram, B. Ozcelik, M. Bayramoglu, E. Demirbas, and B. T. Simsek, "Optimization of cutting fluids and cutting parameters during end milling by using D-optimal design of experiments," *Journal of Cleaner Production*, vol. 42, pp. 159–166, 2013, doi: 10.1016/j.jclepro.2012.11.003.

[19] S. Kalpakjian and S. R. Schmid, *Manufacturing Engineering and Technology*, 6th ed. California, USA: Prentice Hall, 2010.

[20] L. Tang *et al.*, "Biological stability of water-based cutting fluids: progress and application," *Chinese Journal of Mechanical Engineering*, vol. 35, pp. 1–24, 2022, doi: 10.1186/s10033-021-00667-z.

[21] J. M. Vieira, A. R. Machado, and E. O. Ezugwu, "Performance of cutting fluids during face milling of steels," *Journal of Materials Processing Technology*, vol. 116, no. 2–3, pp. 244–251, 2001, doi: 10.1016/S0924-0136(01)01010-X.

[22] S. Zahoor, W. Abdul-Kader, and K. Ishfaq, "Sustainability assessment of cutting fluids for flooded approach through a comparative surface integrity evaluation of IN718," *The International Journal of Advanced Manufacturing Technology*, vol. 111, pp. 383–395, 2020, doi: 10.1007/s00170-020-06130-y.

[23] R. Kumar, A. K. Sahoo, P. C. Mishra, and R. K. Das, "Performance of near dry hard machining through pressurised air water mixture spray impingement cooling environment," *International Journal of Automotive and Mechanical Engineering*, vol. 16, no. 1, pp. 6108–6133, 2019, doi: 10.15282/ijame.16.1.2019.3.0465.

[24] R. F. Avila and A. M. Abrao, "The effect of cutting fluids on the machining of hardened AISI 4340 steel," *Journal of materials processing technology*, vol. 119, no. 1–3, pp. 21–26, 2001, doi: 10.1016/S0924-0136(01)00891-3.

[25] X. Wu *et al.*, "Circulating purification of cutting fluid: an overview," *The International Journal of Advanced Manufacturing Technology*, vol. 117, no. 9–10, pp. 2565–2600, 2021, doi: 10.1007/s00170-021-07854-1.

[26] K. K. Gajrani, D. Ram, and M. R. Sankar, "Biodegradation and hard machining performance comparison of eco-friendly cutting fluid and mineral oil using flood cooling and minimum quantity cutting fluid techniques," *Journal of Cleaner Production*, vol. 165, pp. 1420–1435, 2017, doi: 10.1016/j.jclepro.2017.07.217.

[27] M. C. de Souza, J. F. de Souza Gonçalves, P. C. Gonçalves, S. Y. S. Lutif, and J. de Oliveira Gomes, "Use of Jatropha and Moringa oils for lubricants: metalworking fluids more environmental-friendly," *Industrial crops and products*, vol. 129, pp. 594–603, 2019, doi: 10.1016/j.indcrop.2018.12.033.

[28] J. K. Mannekote, S. V Kailas, K. Venkatesh, and N. Kathyayini, "Environmentally friendly functional fluids from renewable and sustainable sources-A review," *Renewable and sustainable energy reviews*, vol. 81, pp. 1787–1801, 2018, doi: 10.1016/j.rser.2017.05.274.

[29] Market Research Report, "Natural Oil Polyols Market Size , Share & Trends Analysis Report By Product (Soy oil, Castor oil, Palm oil, Canola oil, Sunflower oil, Others), By Application (Furniture and Interiors, Construction, Electronics & Appliances, Others), By Region, And Segmen," 2022. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/natural-oil-polyols-nop-market.

[30] K. K. Gajrani and M. R. Sankar, "Sustainable cutting fluids: thermal, rheological, biodegradation, anti-corrosion, storage stability studies and its machining performance," *Encyclopedia of Renewable and Sustainable Materials*, vol. 1, pp. 839–852, 2020, doi: 10.1016/B978-0-12-803581-8.11152-X.

[31] U. S. Dixit, D. K. Sarma, J. P. Davim, U. S. Dixit, D. K. Sarma, and J. P. Davim, "Machining with minimal cutting fluid," in *Environmentally friendly machining*, Boston: Springer, 2012, pp. 9–

17.

[32] A. D. Jayal, A. K. Balaji, R. Sesek, A. Gaul, and D. R. Lillquist, “Machining performance and health effects of cutting fluid application in drilling of A390. 0 cast aluminum alloy,” *Journal of Manufacturing processes*, vol. 9, no. 2, pp. 137–146, 2007, doi: 10.1016/S1526-6125(07)70114-7.

[33] E. Abd Rahim and H. Dorairaju, “Evaluation of mist flow characteristic and performance in minimum quantity lubrication (MQL) machining,” *Measurement*, vol. 123, pp. 213–225, 2018, doi: 10.1016/j.measurement.2018.03.015.

[34] B. Boswell, M. N. Islam, I. J. Davies, Y. R. Ginting, and A. K. Ong, “A review identifying the effectiveness of minimum quantity lubrication (MQL) during conventional machining,” *The International Journal of Advanced Manufacturing Technology*, vol. 92, pp. 321–340, 2017, doi: 10.1007/s00170-017-0142-3.

[35] V. S. Sharma, M. Dogra, and N. M. Suri, “Cooling techniques for improved productivity in turning,” *International Journal of Machine Tools and Manufacture*, vol. 49, no. 6, pp. 435–453, 2009, doi: 10.1016/j.ijmachtools.2008.12.010.

[36] S. J. Skerlos, K. F. Hayes, A. F. Clarens, and F. Zhao, “Current advances in sustainable metalworking fluids research,” *International journal of sustainable manufacturing*, vol. 1, no. 1–2, pp. 180–202, 2008, doi: 10.1504/IJSM.2008.019233.

[37] A. S. Varadarajan, P. K. Philip, and B. Ramamoorthy, “Investigations on hard turning with minimal cutting fluid application (HTMF) and its comparison with dry and wet turning,” *International journal of Machine Tools and manufacture*, vol. 42, no. 2, pp. 193–200, 2002, doi: 10.1016/S0890-6955(01)00119-5.

[38] G. M. Krolczyk *et al.*, “Ecological trends in machining as a key factor in sustainable production–a review,” *Journal of Cleaner Production*, vol. 218, pp. 601–615, 2019, doi: 10.1016/j.jclepro.2019.02.017.

[39] M. Naresh Babu, V. Anandan, N. Muthukrishnan, A. A. Arivalagar, and M. Dinesh Babu, “Evaluation of graphene based nano fluids with minimum quantity lubrication in turning of AISI D3 steel,” *SN Applied Sciences*, vol. 1, pp. 1–15, 2019, doi: 10.1007/s42452-019-1182-0.

[40] V. P. S. Kumar, K. M. Subramanian, B. Stalin, and J. Vairamuthu, “Influence of ZnO nanoparticles on thermophysical and tribological properties of polyolester oil,” *Materials Research Express*, vol. 8, no. 4, p. 45502, 2021, doi: 10.1088/2053-1591/abf282.

[41] R. Robinson Gnanadurai and S. Mesfin, “Investigations on the effect of silver nanoparticles on performance of coconut oil based cutting fluid in minimal fluid application,” *Advances in Mechanical Engineering*, vol. 14, no. 1, p. 16878140211070444, 2022, doi: 10.1177/16878140211070445.

[42] H. Xie, Y. Wei, B. Jiang, C. Tang, and C. Nie, “Tribological properties of carbon nanotube/SiO2 combinations as water-based lubricant additives for magnesium alloy,” *Journal of Materials Research and Technology*, vol. 12, pp. 138–149, 2021, doi: 10.1016/j.jmrt.2021.02.079.

[43] A. K. Sharma, A. K. Tiwari, A. R. Dixit, R. K. Singh, and M. Singh, “Novel uses of alumina/graphene hybrid nanoparticle additives for improved tribological properties of lubricant in turning operation,” *Tribology International*, vol. 119, pp. 99–111, 2018, doi: 10.1016/j.triboint.2017.10.036.

[44] T. Singh, J. S. Dureja, M. Dogra, and M. S. Bhatti, “Machining performance investigation of AISI 304 austenitic stainless steel under different turning environments,” *International Journal of Automotive and Mechanical Engineering*, vol. 15, no. 4, pp. 5837–5862, 2018, doi: 10.15282/ijame.15.4.2018.10.0447.

[45] W. Yu and H. Xie, “A review on nanofluids: preparation, stability mechanisms, and applications,” *Journal of nanomaterials*, vol. 2012, 2012, doi: 10.1155/2012/435873.

[46] B. Nowack, H. F. Krug, and M. Height, “120 years of nanosilver history: implications for policy makers,” *Environmental Science & Technology*, vol. 45, no. 4, pp. 1177–1183, 2011, doi: 10.1021/es103316q.

[47] R. R. Srikant, D. N. Rao, M. S. Subrahmanyam, and V. P. Krishna, “Applicability of cutting fluids with nanoparticle inclusion as coolants in machining,” *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 223, no. 2, pp. 221–225, 2009, doi: 10.1243/13506501JET463.

[48] P. Muthuswamy, "An environment-friendly sustainable machining solution to reduce tool consumption and machining time in face milling using a novel wiper insert," *Materials Today Sustainability*, vol. 22, p. 100400, 2023, doi: 10.1016/j.mtsust.2023.100400.

[49] NIOSH, "Criteria for a recommended standard occupational exposure to metalworking fluids." Department of Health and Human Services, 1998.

[50] S. A. Lawal, I. A. Choudhury, and Y. Nukman, "Application of vegetable oil-based metalworking fluids in machining ferrous metals—a review," *International Journal of Machine Tools and Manufacture*, vol. 52, no. 1, pp. 1–12, 2012, doi: 10.1016/j.ijmachtools.2011.09.003.

[51] B. Beekhuis, "Influence of solid contaminants in metal working fluids on the grinding process," *Advanced Materials Research*, vol. 769, pp. 61–68, 2013, doi: 10.4028/www.scientific.net/AMR.769.61.

[52] H. S. Abdalla, W. Baines, G. McIntyre, and C. Slade, "Development of novel sustainable neat-oil metal working fluids for stainless steel and titanium alloy machining. Part 1. Formulation development," *The International Journal of Advanced Manufacturing Technology*, vol. 34, pp. 21–33, 2007, doi: 10.1007/s00170-006-0585-4.

[53] C.-C. Wu and H.-M. Liu, "Determinants of metals exposure to metalworking fluid among metalworkers in Taiwan," *Archives of environmental & occupational health*, vol. 69, no. 3, pp. 131–138, 2014, doi: 10.1080/19338244.2012.750589.

[54] A. Shokrani, V. Dhokia, and S. T. Newman, "Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids," *International Journal of machine Tools and manufacture*, vol. 57, pp. 83–101, 2012, doi: 10.1016/j.ijmachtools.2012.02.002.

[55] S. Kalpakjian and S. R. Schmid, *Manufacturing Engineering and Technology*, 6th ed. California: Prentice Hall, 2010.

[56] Y. Shokoohi, E. Khosrojerdi, and B. H. R. Shiadhi, "Machining and ecological effects of a new developed cutting fluid in combination with different cooling techniques on turning operation," *Journal of Cleaner Production*, vol. 94, pp. 330–339, 2015, doi: 10.1016/j.jclepro.2015.01.055.

[57] N. Anand, A. S. Kumar, and S. Paul, "Effect of cutting fluids applied in MQCL mode on machinability of Ti-6Al-4V," *Journal of Manufacturing Processes*, vol. 43, pp. 154–163, 2019, doi: 10.1016/j.jmapro.2019.05.029.

[58] N. Szczotkarz *et al.*, "Cutting tool wear in turning 316L stainless steel in the conditions of minimized lubrication," *Tribology International*, vol. 156, p. 106813, 2021, doi: 10.1016/j.triboint.2020.106813.

[59] P. Sivaiah, "Experimental investigation and modelling of MQL assisted turning process during machining of 15-5 PH stainless steel using response surface methodology," *SN Applied Sciences*, vol. 1, pp. 1–13, 2019, doi: 10.1007/s42452-019-0827-3.

[60] A. Pal, S. S. Chatha, and H. S. Sidhu, "Performance evaluation of various vegetable oils and distilled water as base fluids using eco-friendly MQL technique in drilling of AISI 321 stainless steel," *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 9, no. 3, pp. 745–764, 2022, doi: 10.1007/s40684-021-00355-2.

[61] J. C. C. Rubio, B. A. Rezende, L. M. G. Vieira, H. M. Romero, and L. A. R. Brenes, "Comparative study on lubricating and cooling conditions in the drilling process of electrolytic copper," *The International Journal of Advanced Manufacturing Technology*, vol. 101, pp. 2633–2641, 2019, doi: 10.1007/s00170-018-3139-7.

[62] Q. Yin *et al.*, "Effects of physicochemical properties of different base oils on friction coefficient and surface roughness in MQL milling AISI 1045," *International Journal of Precision Engineering and Manufacturing-Green Technology*, pp. 1–19, 2021, doi: 10.1007/s40684-021-00318-7.

[63] A. Race *et al.*, "Environmentally sustainable cooling strategies in milling of SA516: Effects on surface integrity of dry, flood and MQL machining," *Journal of Cleaner Production*, vol. 288, p. 125580, 2021, doi: 10.1016/j.jclepro.2020.125580.

[64] J. Rajaguru and N. Arunachalam, "A comprehensive investigation on the effect of flood and MQL coolant on the machinability and stress corrosion cracking of super duplex stainless steel," *Journal of Materials Processing Technology*, vol. 276, p. 116417, 2020, doi: 10.1016/j.jmatprotec.2019.116417.

[65] N. S. M. Sahid, M. M. Rahman, K. Kadirgama, D. Ramasamy, and M. A. Maleque, "Experimental investigation on the performance of the TiO2 and ZnO hybrid nanocoolant in ethylene glycol mixture towards AA6061-T6 machining," *International Journal of Automotive and Mechanical Engineering*, vol. 14, no. 1, pp. 3913–3926, 2017, doi: 10.15282/ijame.14.1.2017.8.0318.

[66] G. Singh, M. K. Gupta, M. Mia, and V. S. Sharma, "Modeling and optimization of tool wear in MQL-assisted milling of Inconel 718 superalloy using evolutionary techniques," *The International Journal of Advanced Manufacturing Technology*, vol. 97, pp. 481–494, 2018, doi: 10.1007/s00170-018-1911-3.

[67] H. Adibi, H. Esmaeili, and S. M. Rezaei, "Study on minimum quantity lubrication (MQL) in grinding of carbon fiber-reinforced SiC matrix composites (CMCs)," *The International Journal of Advanced Manufacturing Technology*, vol. 95, pp. 3753–3767, 2018, doi: 10.1007/s00170-017-1464-x.

[68] R. L. Rodriguez *et al.*, "Evaluation of grinding process using simultaneously MQL technique and cleaning jet on grinding wheel surface," *Journal of Materials Processing Technology*, vol. 271, pp. 357–367, 2019, doi: 10.1016/j.jmatprotec.2019.03.019.

[69] J. Oudyk, A. T. Haines, and J. D'Arcy, "Investigating respiratory responses to metalworking fluid exposure," *Applied occupational and environmental hygiene*, vol. 18, no. 11, pp. 939–946, 2003, doi: 10.1080/10473220390237610.

[70] A. Zeka, D. Kriebel, S. M. Kennedy, and D. H. Wegman, "Role of underlying pulmonary obstruction in short-term airway response to metal working fluid exposure: A reanalysis," *American journal of industrial medicine*, vol. 43, no. 3, pp. 286–290, 2003, doi: 10.1002/ajim.10179.

[71] M. Ahamed, M. A. Siddiqui, M. J. Akhtar, I. Ahmad, A. B. Pant, and H. A. Alhadlaq, "Genotoxic potential of copper oxide nanoparticles in human lung epithelial cells," *Biochemical and biophysical research communications*, vol. 396, no. 2, pp. 578–583, 2010, doi: 10.1016/j.bbrc.2010.04.156.