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REVIEW ARTICLE

Progress for sustainability in the mist assisted cooling techniques: a critical review

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Abstract

The proper implementation of sustainable manufacturing processes is an effective step towards a clean environment. The modern cooling strategies applied in the manufacturing sector have presented promising solutions that enable economic growth and ecological environment. In machining operations, cryogenic cooling and minimum quantity lubrication (MQL) have been extensively utilized to replace conventional cooling techniques. Thus, this work offers a detailed review of major works focused on manufacturing processes that use some of these sustainable cooling/lubrication modes (i.e., MQL, nanocutting fluids, nanofluid-based MQL strategy, and other miscellaneous MQL upgrades). The main driver of this study is to create a bridge between the past and present studies related to MQL and MQL upgrades. In this way, a new guideline can be established to offer clear directions for a better economic vision and a cleaner manufacturing process. Thus, this review has mainly focused on the machining of the most commonly used materials under MQL-related methods in conventional operations including turning, milling, drilling, and grinding. Current work provides a detailed insight into the major benefits, limitations, as well as mechanisms of cooling strategies that directly affects the machinability performance from a sustainable point of view. In summary, further potential upgrades are indicated so that it will help to drive more sustainable approaches in terms of cooling and lubrication environment during machining processes.

Keywords Sustainability · Minimum quantity lubrication · Nanofluids · Green machining · Cooling · Lubrication

1 Introduction

The employment of cooling agents, natural or synthesized, during machining processes was reported to improve the overall cutting performance; however, they were criticized, too, for being unhealthy and dangerous for the natural environment. This is because the majority of such fluids contain potentially harmful chemicals. In addition, the recycling cost

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of such fluids is very high, and their disposal poses several issues. Operators handling such chemicals over a long period are bound to suffer from skin or lung-related diseases. In the past two decades, researchers have focused on dry or near-to-dry machining processes that bypass the use of hazardous chemicals. Due to its simple application and eco-friendly features, minimum quantity lubrication (MQL) has emerged as one of the best solutions to tackle this challenge. It has been widely used in most of the machining operations ranging from turning to grinding [1, 2]. The results obtained after investigating these processes clearly indicate the benefits of using the MQL process while machining of various materials such as steel, aluminum, Inconel, titanium, composite etc. [3–7]. The primary benefit of this review is an in-depth analysis of the main MQL strategies used in different machining operations. It can be used later as a resource for significant improvements in the existing machining process such as turning, grinding, milling, drilling, etc.

In today's competitive world, sustainability and harmony with the environment in the manufacturing industry are closely related to economic production with very high quality. One of the primary factors that trigger the abundance of labor costs in any manufacturing process is the repetitive replacement of damaged tool inserts. The main cause of this issue is rapid tool wear that takes place during machining processes. The work-tool friction engenders a very high wear rate corroborated with high cutting temperature, which further aggravates the rate of tool failure [8]. In order to reduce the cutting forces and the cutting temperatures, the utilization of cutting fluids has become a necessity in various machining operations [9]. These cutting fluids aid lubricate the cutting area along with heat removal. In addition, they allow improvement in surface quality and chip breakability [10]. Selecting the appropriate cutting fluid is an essential task because their performance may vary from one process to another. Moreover, washing away the chips generated is another vital task performed by cutting fluids [11].

The types of cutting fluids are divided into three major categories: neat cutting-oils, cold gases, and water-soluble fluids, as shown in Fig. 1. The straight oil is well known as neat oil or cutting oil. It is considered as the oldest class of metal cutting fluid. These types of fluids are derived from petroleum or animal origin. The application of straight oil is valuable only within very light duty machining operations [13]. Soluble or emulsifiable oils are such types of oil formed as droplets suspended in the emulsifier agent. Synthetic or chemical fluids are generally mixed with different chemical agents in water. The chemical agent includes amines, nitrites phosphates, glycol, and germicides. The use of a chemical agent helps to improve the lubrication functions and decrease the surface tension. The synthetic fluids possess the best coolant potential; however, they lag in terms of lubrication abilities when they are compared to other capable coolants. Sometimes, 2 to 10% concentrations of chlorine, sulfur, or other additives are added to both synthetic and semi-synthetic fluids, which permit to induce extreme pressure as well as boundary lubrication effects. Hence, these fluids are used in more difficult machining and grinding applications [14]. Choosing a suitable coolant is paramount importance because it improves the machinability characteristics without affecting the operator's health. The customary inhalations of such harmful mists often lead to serious health conditions [15, 16]. Table 1 shows the comparison of different cutting fluids.

In terms of research motivation, this work offers the reader adequate information about the details of the significant benefits/limitations in many respects when such cooling approaches are employed in machining operations. The current work does not only refer to the limitations and advantages of such cooling and lubrication techniques but also discuss the tribological and heat transfer mechanisms behind applying MQL or nanofluid-based MQL to evaluate the machining process performance. In addition, this review aimed to identify the future perspectives that can be implemented by using MQL and nanofluid-based MQL techniques, and therefore, producing directions for an economical manufacturing process and environmentally friendly approaches. This review has been organized based on the primary cutting operations and most machined materials that are performed by using the cooling and lubrication techniques mentioned above. The complete framework of this review is presented in Fig. 2.

2 MQL

This practice represents to change the traditional cooling strategy with a modern mist assisted lubri-cooling strategy. It has become prevalent from the past few years because researchers apply it to obtain superior results regarding cutting forces, surface roughness, temperatures, tool wear, tool life, etc. This process mainly focuses on the use of a minimal lubricant amount mixed with air outlet released from an air compressor. The employment of negligible quantities of lubricant leads to an immense cost reduction. From the sustainability point of view, it is indisputable that the process is extremely safe for both the environment and worker health. Mulyadi et al. [17] made milling operations on AISI H 13 steel using MQL by considering an electrical energy input. The total consumption was determined and compared for all three environments (i.e., dry, MQL, and flood) as is shown in Fig. 3. They presented the environmental aspects as well as energy benefits associated with the application of MQL system. The results obtained through MQL are precious as it allows improving the tool life as well.

Ginting et al. [18] organized a series of experiments to highlight the potential benefits associated with MQL compared to traditional techniques. Several calculations were done

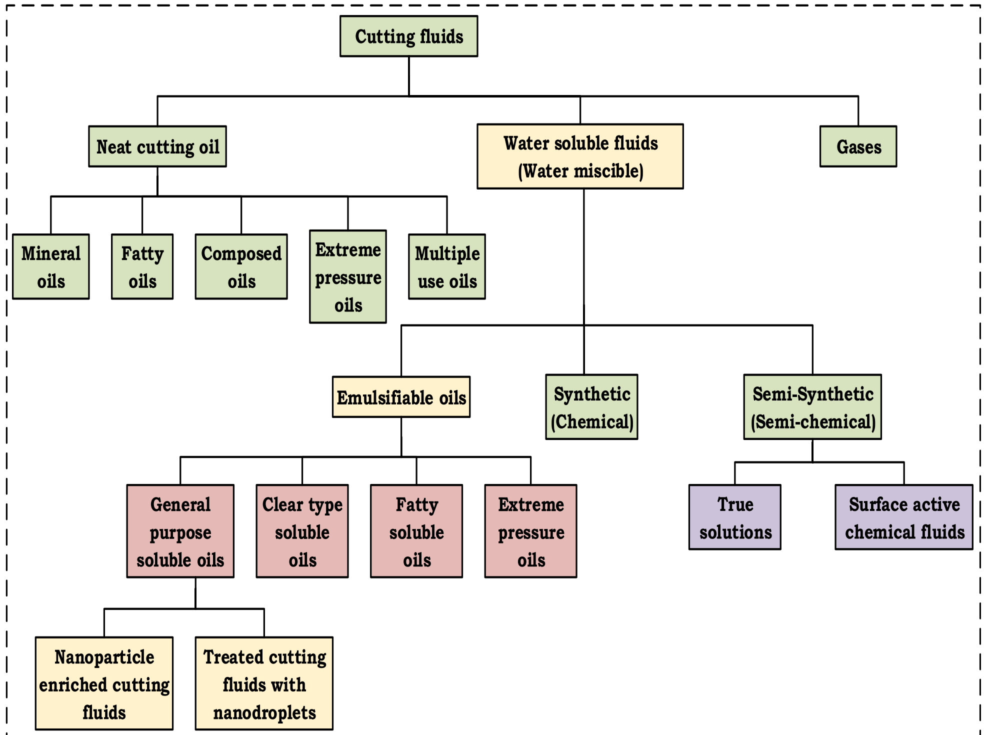

Fig. 1 Cutting fluid classification [12]

for cost and energy generation when using different cooling techniques (i.e., MQL vs. traditional). Table 2 shows the comparison of life cycle inventory in manufacturing using different cooling techniques. It was noticed that some hazardous environmental impacts such as human toxicity, eutrophication, and global warming could be reduced with MQL by 87, 32, and 21%, respectively, compared to flood cooling. The data from Table 3 proves the possibility of replacing the flood cooling technique with MQL. In addition, Campatelli and Scippa [19] performed a comprehensive study to detect the environmental impact on the machining process. Dry, flood cooling, and MQL techniques were compared by determining the energy rate released within each lubrication process. Further, the environmental impact was calculated in terms of CO_2 equivalent for machining of 1 kg of material. It was detected that MQL has a minimum environmental impact. In another recent work, Mia et al. [20] machined the AISI 1060 steel in turning process using the MQL system and other available techniques. The Pugh matrix for the sustainability assessment was developed to compare these techniques in terms of different machining performance measures (i.e., temperature, surface roughness, cutting force, etc.). In addition to these measured outputs, other responses (i.e., the ecological effect, coolant cost, operator health, and part cleaning cost, etc.) were investigated. The results are depicted in a Kiviat diagram, as shown in Fig. 4. When dry cutting and cold air are applied, if the possible high temperature and friction in the cutting zone do not have a negative effect on performance outputs, these can be a practical application as cost and environmental effects are considered. It can be clearly said that the MQL is a more appropriate alternative to sustainability production since it can decrease production cost, negative effects on environment and worker health, and finally productivity will rise. However, it should be kept in mind that MQL

Table 1 Cutting fluid classification [15]

Type	Pros			Cons		
Straight cutting oil	Better lubrication	Corrosion protection	–	Poor cooling	Mist formation	Fire hazard
Soluble-cutting fluids	Good lubrication and cooling	Non-poisonous	–	Corrosion problem	Bacterial growth	Quick evaporation
Semi-synthetic fluids	Good cooling	Microbe control	Corrosion protection	Quick foaming	Easily polluted	–
Synthetic fluids	Better cooling	Corrosion protection	Non-inflammable	Poor lubrication	Easily polluted	–

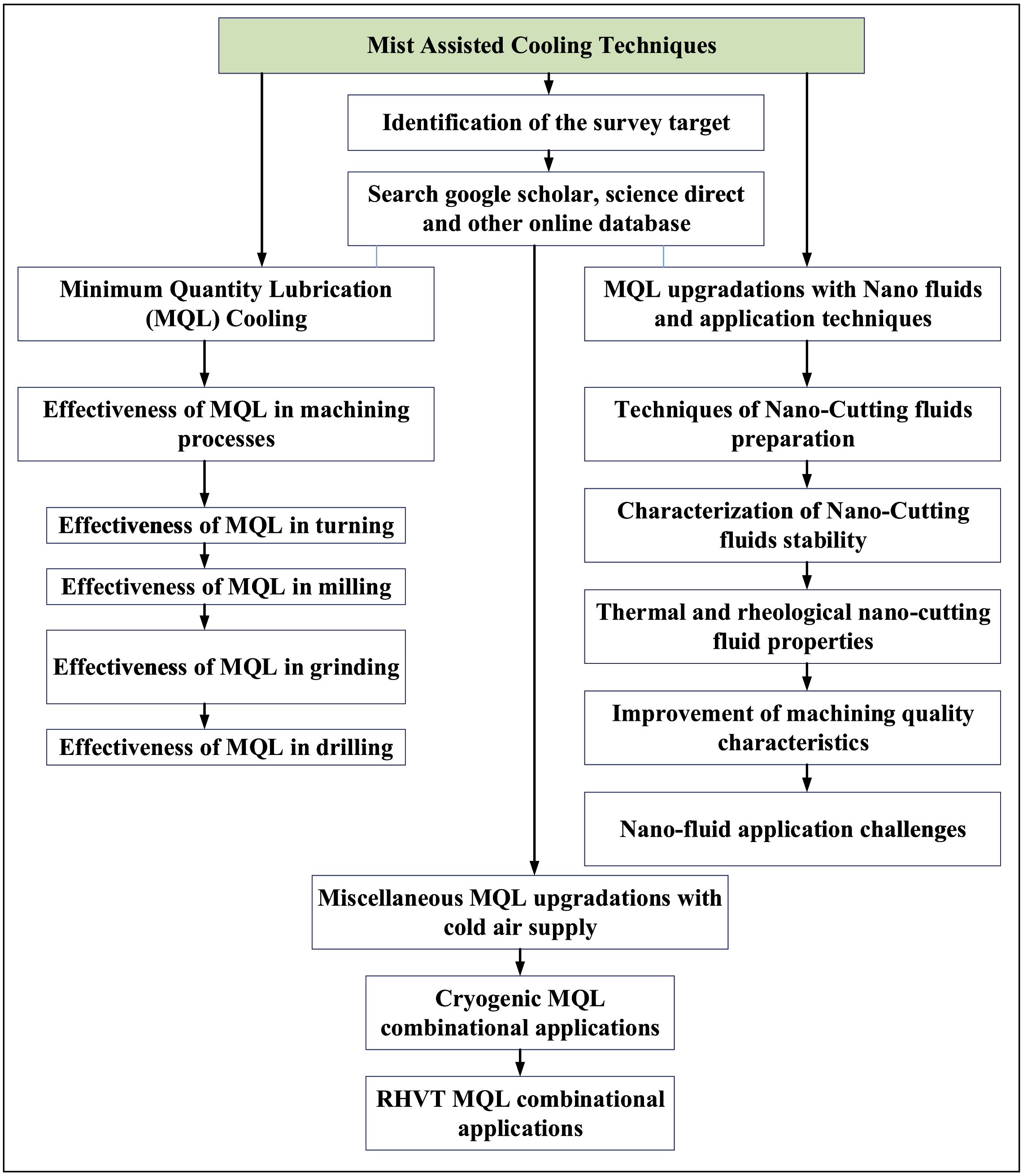

Fig. 2 The organization of the topics

method may cause errors induced by thermal damage on the workpiece material, considering that highest temperature under MQL was nearly four times more than traditional liquid especially in grinding operation [9].

3 Effectiveness of MQL in machining processes

There have been numerous studies conducted to evaluate the effectiveness of MQL by corroborating different machining performances on several materials. The prime motive of these studies was to obtain the desired combination of working parameters in relationship to superior values of measured response. The following subsections list the literature work connected with the effectiveness of the MQL process in various machining processes for example milling, turning, drilling, and grinding.

3.1 Effectiveness of MQL in turning operations

Turning is a machining process used for producing a desirable cylindrical shape by the assistance of a suitable cutting tool.

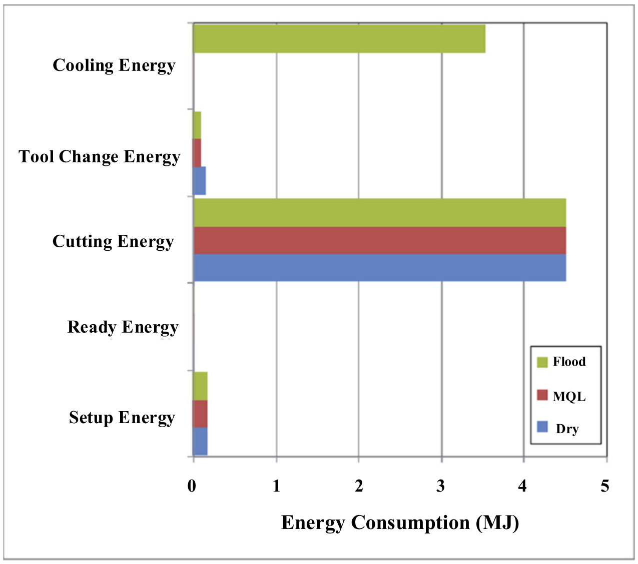

Fig. 3 Relative energy consumption in different cooling regimes [17]

The single point cutting tool is generally used for this purpose. This process can be done under various cooling/lubrication conditions to raise the quality of the product and maintain the cutting tool lifespan. Dhar et al. [21] have reported the influence of MQL on the formation and morphology of the chips, generated temperature, and surface quality whan turning AISI 1040 material. The experiments were performed using carbide inserts by varying cutting speed and feed rate. Dry turning has been compared with soluble oil-based machining as coolant. It was concluded that MQL highly improves the dimensional accuracy, and make a substantial decline in the cutting temperature. They concluded that not only the MQL helps to improve the process parameters, but also works in resonance with the environment protection. Ondin et al. [8] compared the nanoparticles assisted MQL with dry turning of PH 13–8 Mo stainless. The authors have concluded that nanoadditives assisted MQL has provided excellent surface finish and tool life. This case can be associated with great lubrication and behaving like spacers has generated excellent surface finish and less wear by preventing direct contact of tool main cutting edge. Prasad [22] performed turning

Table 2 Life cycle inventory comparison between TFC (traditional flood cooling), MQL and CA (cold air) techniques [18]

Input	TFC	MQL	CA
Cutting energy (Wh)	323	295	223
Pumping energy (Wh)	5.12×10^{-2}	0	0
Compressor energy (Wh)	0	51	72
Coolant (gm)	1.970	0.150	0
Cutting tool (gm)	0.150	0.140	0.150
Disposal (gm)	1.970	0.150	0

experiments using HSS and cemented carbide tools with nanofluids. The particle size was taken in the size of 80 nm and applied slowly to the cutting zone using the MQL technique. Variations in the fluid flow rates were made and the results were compared with the simple dry turning as well as with flooding technique. The inclusion of nanopowders into to the base-liquid permits to improve several fluid properties namely viscosity and thermal conductivity. The results displayed a promising reduction in the roughness as well as in the flank wear values. In another study, Ozbek and Saruhan [23] worked the impression of the MQL on the surface characteristics and wear modes driven by the turning of AISI-D2 steel. Positive results were obtained in both roughness and tool wear values. Sarikaya and Gullu et al. [24] emphasized the findings on the optimal value of MQL fluid flow rate along with the optimized parameters of the cutting speed and fluid type. The experimental design was made using the Taguchi's orthogonal arrays. The optimum levels of cutting parameters were accomplished at an MQL flow rate of 180 ml/h, and cutting speed of 30 m/min. In addition, Sreejith [25] studied the relative influences of the different lubrication strategies while turning aluminum 6061 alloy using a diamond-coated carbide insert. Different comparisons were made between dry, MQL, and flooded assisted turning. Cutting forces, flank wear as well as the surface roughness were investigated as measured machining outputs. The results support the fact that MQL leads to a significant improvement when compared with dry turning. It offers similar results as compared to flood cooling conditions. Furthermore, it has been found that the environmental burden could be reduced substantially as well. Khan et al. [26] turned AISI 9310 steel to evaluate the effectiveness of vegetable oil-based MQL, and a comparison was carried out using dry and wet cooling to study the critical machining performance measures. The responses such as chip morphology, surface properties, wear, etc., were evaluated. The MQL performance was much better compared to other alternatives in terms of reducing the amount of heat produced. A lower frictional force between the workpiece-tool interfaces accompanied this. In addition, the verification indicates that the MQL leads to a much safer workplace with less heat and fumes. Thus, besides improving the machinability characteristics, MQL also improves the sustainability-related parameters. Sarikaya et al. [27] used a particular cutting fluid to lower the rate of tool wear that further permits to improve the surface roughness. These series of experiments aimed to enhance the machinability characteristics while turning Haynes 25 superalloy. The lubricant was introduced to the machining zone in a small quantity via a specifically designed nozzle at a fixed flow rate. The main emphasis during this experimentation laid to endorse a better performance for the MQL, which enables a significant diminution in both tool wear and surface roughness when compared to other conventional techniques. Yazid et al. [28] turned Inconel-718 to evaluate the effect of working

Table 3 Environmental impacts and benefits associated with MQL [18]

Impacts	TFC	MQL	CA	% Savings (MQL)
Global Warming (kg CO_2-eq)	0.38	0.30	0.21	21
Eutrophication (kg PO_4-eq)	5.26×10^{-4}	1.01×10^{-4}	8.23×10^{-5}	81
Human toxicity (DAILY)	3.11×10^{-8}	4.06×10^{-9}	3.28×10^{-9}	87

parameters on the surface properties. The machining was performed under dry, flood as well as near dry machining conditions. The MQL fluid flow rates were varied for two different levels 50 ml/h and 100 ml/h, respectively. The SEM images gathered from the workpiece after machining reveal many deformations and changes in the microstructure. It was noticed that MQL could be useful for surface integrity characteristics. Ali et al. [29] studied different parameters including chip thickness ratio and cutting temperature to investigate the MQL effects. Responses such as flank wear as well as cutting forces were analyzed. The work was conducted on medium carbon steel at a pre-determined speed and feed combinations. The analysis of the results proved that MQL provides much better features. Improvements in productivity were also reported when considering all design-related costs. Ozcelik et al. [30] worked the impact of the vegetable-based cutting fluid (VBFC) blend of two distinct oils (i.e., canola and refined). It includes the high-pressure additives mist and commercial type of cutting fluids (i.e., mineral and semi-synthetic). Machining operations were performed with various machining parameters on AISI-304 L. The results revealed that the canola cutting fluid containing 8% of EP additives allows improving the surface quality. It was concluded that the VBFC could replace the mineral and semi-synthetic based cutting fluid and allows it to decrease the health hazards. Borkar et al. [31] performed experiments using the MQL process assisted by the soluble oil. Flood cooling and dry machining were utilized to develop a relationship between the work-tool interface, tool wear, and surface finish. The optimal operating parameters were chosen with the assistance of the Taguchi method. The significant improvements in roughness values have been recorded when using soluble oil under the MQL system. Besides, it was possible to obtain a significant improvement in the machinability characteristics. Sivalingam [32] carried out tests under two different cooling regimes, namely dry and MQL reinforced with molybdenum disulfide and graphite nanopowders at 0.2 wt% concentrations in turning of nickel alloy 718 with ceramic cutting tools. A remarkable decline in flank wear, surface roughness, and vibration was recorded, which facilitate the improvement of environmental sustainability due to the use of nanoparticle-based MQL process. Amrita et al. [33] executed several trials to analyze the performances of mist and flood cooling while the turning process of AISI 1040 material. The misting fluid was enriched with nanosized particles to improve the lubricating properties of the base fluid. The data was measured as the interface temperature, cutting forces and tool wear. Immense improvements were recorded in terms of cutting temperature, cutting forces and tool wear when using nanoparticle enriched fluids.

Liu et al. [34] explored the wear resistance of cutting tools during machining titanium-based alloys. Several input variables such as coating types and cooling environments (dry and MQL) were tested. It was reported that the (nc-AlTiN)/(a-Si_3N_4)-coated tool under MQL exhibited better performance than (nc-AlCrN)/(a-Si_3N_4)-coated tool in the

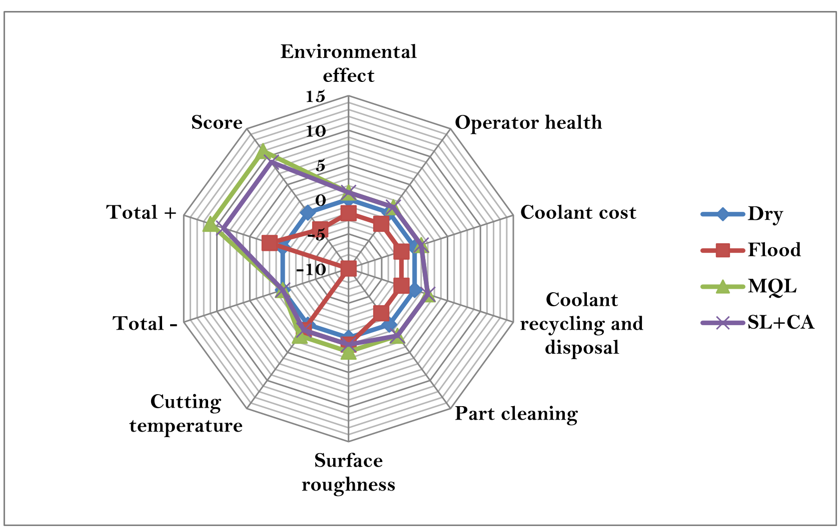

Fig. 4 The impact of several cooling regimes on ecology and worker health [20]

machining of Ti alloys. Hadad and Sadeghi [35] executed turning tests to highlight the influence of different input variables (i.e., the nozzle position) when applying some cooling regimes, namely dry, wet, and MQL while machining AISI 4140 steel. The cutting fluids were considered water-based ester, which mixed in a ratio of 10:1. The rate of fluid flow was kept constant at 30 ml/h, while the pressure of the air was fixed at 3 bars. The feed rate was imposed as 0.09 and 0.22 mm/rev. The importance of the MQL nozzle position was highlighted, as well. It reveals drastic reductions in the interface temperatures as well as cutting forces and surface roughness when using the oil mist process. Hence, temperature reduction as high as 350 °C was reported. Sanchez et al. [36] performed experiments in turning of SAE EV-8 steel by employing the triangular geometry cemented carbide cutting tool and using the conventional cooling, minimum quantity cutting fluid (MQCF), MQL and pulverization techniques. It was reported that the performance of the machining operation could be increased with the cutting fluid applications. Ramana et al. [37] worked to optimize the process parameters of machining titanium grade 5 alloy. The Taguchi principle was applied for the experimental design and the flank wear was chosen as the primary measured response. The results reveal that the MQL process with uncoated tool shows better machining characteristics as compared with the other conditions. Sharma and Sidhu [38] machined the AISI D2 steel to evaluate the performance of both MQL and dry machining techniques. Vegetable-based oil was used as a lubricant for developing the process of sustainability. The insert material used for turning was tungsten carbide. The results showed that MQL permits to improve surface roughness and tool wear. The minimal flow technique not only improves the machining process but also makes the process more sustainable. Deiab et al. [39] investigated the influential characteristics of several cooling techniques on different parameters while turning titanium Ti-6Al-4V with uncoated carbide tools. Relative effects on the roughness and energy consumption were recorded. The use of rapeseed oil was observed to improve the process of sustainability. Abhang and Hameedullah [40] conducted turning experiments on EN-31 steel, and the surface properties were studied based on several input parameters. It was concluded form statistical analysis that the cutting speed, feed rate, depth of cut, insert nose radius, and environment have impact on surface roughness. In some recent works, Rahim et al. [41] conducted different experiments by utilizing orthogonal cutting of AISI 1045 steel. The cutting environment was dry, and synthetic esters based MQL. The results from these two conditions were investigated to determine the best cutting temperature, chip thickness, tool-chip thickness and cutting force. It was reported that the synthetic ester-based MQL reduces cutting temperature by up to 30% and cutting force by up to 28%. It also allows enhancing the chip thickness in comparison to dry cutting environment. Sun et al. [42] focused on determining the usual input parameters while machining Titanium 5553 alloy. The comparisons were made between the cryogenic and MQL environment. It was observed that the machining of titanium alloy with liquid nitrogen reduces the cutting force by 30% when it is compared to the other techniques. In addition, it was found that the nose wear of cutting tools become better in cryogenic cooling. However, a higher surface finish was accomplished using the MQL technique due to a better penetration of the MQL mist.

Paturi et al. [43] carried out trials to survey the impact of MQL application on the surface finish of nickel alloy 718 while the turning. The composition of the cutting fluid consisted of an ester-based oil mixed with tungsten disulfide particles by 0.5% weight. The influence of different process parameters was studied using several statistical tools. The results showed a 35% improvement with solid lubricant-based MQL in the surface quality when compared to the MQL process without nanoadditives. Sharma et al. [44] showed the importance of cutting fluids during cutting operations in terms of cutting temperature and chip morphology. In order to safeguard the worker's health as well as the environment, the need for a particular type of cutting fluids was emphasized. It was recommended that fluid with better thermal and tribological properties is needed. The use of nanofluids was shown to be indispensable. The fluid preparation was done by mixing alumina nanoparticles with the base fluid using an ultrasonic agitator. The nanofluid was sprayed on the cutting zone during the turning of AISI 1040 steel. Much better results were recorded for the surface texture using nanofluid MQL when compared against traditional techniques. Akhtar et al. [45] prepared nanocutting fluid by mixing alumina and TiO2 nanosized particles in various proportions such as 0.05, 0.15, and 0.3 wt.%. The prepared solution was used in MQL technique while machining AISI 1018 alloy using carbide tools. It was concluded that the prepared solution had provided better spreadability and thermal conductivity, leading to a significant reduction in cutting temperature and surface roughness. As a result, the amount of coolant has been remarkably diminished with the use of nanofluid-MQL and the turning process performance has been improved. In another study performed by Chetan et al. [46], machining tests conducted on Nimonic-90, Ni-based alloy, and Ti-6Al-4V, titanium-based alloy, respectively. The turning tests were made in order to make comparisons between dry and MQL conditions for sustainable improvement. For sustainability, the MQL conditions were considered by using sunflower oil in water due to its biodegradable properties. Moreover, the use of a biodegradable emulsion led to outstanding results for wear of cutting tool and cutting force when turning of titanium alloy.

Kumar et al. [47] performed machining experiments while turning AISI 4340 steel with CBN cutting tool. The process parameters with a higher impact as speed, feed, hardness, etc.

were considered. The analysis of the results was performed by applying ANOVA calculations, while the mathematical models were determined using regression models. It was demonstrated that the MQL provides superior results in terms of surface roughness. Bagherzadeh and Budak [48] studied four kinds of cooling strategies to enhance the hard turning of titanium and nickel base alloys. They used carbon dioxide delivery system, modified carbon dioxide nozzle, a combination of carbon dioxide with MQL and CMQL techniques in order to generate good output variables (i.e., surface roughness, tool wear, and temperature). They revealed that the CMQL is a welcome technique that enhances the tool life up to 60% and 30% in the machining of Ti6Al4V and Inconel 718, respectively. Furthermore, it can generate better surface quality in contrast with other systems verified. The employment of MQL in turning process improves the machining performance especially with regard to tool war and surface finish of the cut surfaces in comparison to dry medium and flooding cooling. In addition, the performance of base fluid based MQL can be improved further with the addition of nanoparticles. It has been shown that MQL gives good results especially in the turning of steels compared to super alloys, which are difficult-to-machine materials. Therefore, MQL in turning operations can be an effective option to dry and flood cooling. The main machining works focused on MQL have been tabulated in Appendix Table 6.

3.2 Effectiveness of MQL in milling operations

Many researchers studied the turning process; however, extensive work has been focused on the milling process as well. Some studies are discussed in this section. For example, Sun et al. [55] observed the reaction of titanium (grade 5) alloy via a carbide tool. The different cooling regimes were developed considering the MQL approach in order to detect the behavior of the tool life. It was shown that the MQL process proved reliability due to its combinational aspects produced by its cooling and lubrication functions. Lacalle et al. [56] investigated the role of the cutting fluids on various machining outputs. Experiments were conducted while milling aluminum alloys. The relative impacts of MQL and flood cooling techniques were compared. The MQL flow rate was maintained at 0.06 ml/min while using a constant pressure of 10 bar. The application of spray cutting fluid made significant progress in reducing both tool wear and cost together. Liao and Lin [57] conducted high-speed machining (HSM) experiments with a vertical milling machine. The machining trials on a mold steel NAK80 were realized using dry and MQL conditions. The values of tool wear and milling forces were calculated based on the input parameter variation. The machining speed and feed rate were varied in the ranges 300 to 500 m/min and 0.1 to 0.20 mm/tooth. Likewise, the axial and radial depth of cut was set as 0.3 and 5 mm, respectively. The experimental results indicated that the MQL permits to improve the responses more efficiently as compared to dry machining. The MQL role over the HSM application is highlighted because it may generate extra oxygen in the middle of the chip-tool interface. Therefore, the tool life results have been improved. Thamizhmanii and Hasan [58] performed another research using a vertical milling machine. The process parameters were varied within different predefined levels, and the milling was performed using a hardened cobalt tool. The efficiency of MQL was tested keeping constant the flow rates of 12.5, 25, and 37.5 ml/h and using biodegradable vegetable oil. Different flow rates of the MQL had influenced the tool wear and surface roughness up to approximately 33% and 30%, respectively. It was also shown that the tool life results obtained using the MQL conditions were approximately 44% better than the dry machining. Thepsonthi et al. [59] investigated the metal cutting efficiency of the MQL process while milling ASSAB DF3 steel with a hardness of 51 HRC. The experiments were performed using three different cooling regimes with a TiAlN-coated milling insert. The variations in the speed, feed, cutting depth as well as in the cooling condition were made to obtain superior outputs parameters. The findings prove that the MQL process offers better results when compared to other cooling strategies. Besides, the investigation demonstrated that most of the negative effects on the environment can be eliminated with the use of MQL. Li and Chou [60] performed milling operation on SKD 61 steel by using uncoated carbide tool in dry and MQL conditions. Small-tools with a diameter of 600 μm were used. The milling process was carried out imposing a speed between 20,000 and 40,000 rpm, and the cutting depth was kept constant at 0.3 mm. The feed rate, air supply rate, as well as the lubricant supply rates were also varied. The observations with regard to burr formation, surface texture, and tool wear were evaluated. It was proved that the MQL helps to improve the above characteristics and allows a higher quality manufacturing process. Silva [61] has chosen various different compact graphite cast irons as work material. The cutting tool geometry and its coating, cutting environment including dry and MQL and milling parameters (cutting speed and feed rate) were considered as inputs, while the tool life, wear behavior, surface quality and electric current consumption was taken as outputs. Comparisons were made with the classical cooling techniques to demonstrate the effectiveness of MQL process. It was concluded that with MQL medium, perfect tool life and less electric current consumption were achieved in 200 m/min cutting speed. Taylor et al. [62] conducted a group of experiments in order to compare the traditional cooling techniques with the MQL approach when milling of tool steel that has 53 HRC hardness. While the life of the milling tool was 73 min during dry cutting, this time was increased to 120 min when MQL strategy was applied. As a result, the tool life was improved by 60% with the MQL. Zhang et al. [63] compared the relative effectiveness of dry and MQL techniques. The MQL fluid-applied was biodegradable oil and was mixed in small quantities with a large proportion of water. Milling test was performed on Inconel 718 alloy. The machining of this alloy may be greatly influenced by the addition of a mist cooling process, which further enables the superior performance of the machining outputs. Shahrom et al. [64] performed milling process on an aluminum workpiece within three distinct ecological conditions (wet, dry, and MQL). The actual operating variables, i.e., cutting speed, feed rate, and depth of cut were varied by applying four predefined levels of them. It was reported that MQL produced better product quality in comparison to the traditional machining. Moreover, it revealed that the error between experimentation and calculated responses is considerably higher by applying wet machining in comparison to MQL machining. Do et al. [65] realized hard-milling trials AISI H-13 steel. Some statistical tools were utilized to analyze the various studied responses. The use of the dry medium, MQL, and 2 wt% SiO_2 nanoparticles with the size of 100 nm incorporated in MQL was performed by varying different levels of speed, feed, and other vital parameters. A low flow rate of cutting liquid (90 ml/h) was applied by MQL approach. The improvements in surface roughness were recorded at a satisfactory level as a result of using the MQL process. It enables ecological as well as financial viability when using the MQL technique. Wang et al. [66] performed the milling of Inconel 182 alloy using different types of cutting inserts. Different comparisons between the PVD-coated as well as an uncoated insert were done for some variable nozzle locations relative to the cutting zone. The uncoated inserts failed the test in milling of Inconel 182 alloy as a result of their extremely high wear rates. Thus, based on the experimental work, the importance of using coated tools was highlighted. Priarone et al. [67] observed and reported the role of cooling techniques of different responses such as surface quality and sustainability etc. A titanium-based alloy was employed in the experimental work. The results proved that MQL is a much better alternative. Soman et al. [68] conducted a series of experiments in order to detect the superior process parameters and a comparison between the dry, flood, and MQL was implemented in milling Monel 400 alloy. Besides, the measured outputs (i.e., roughness, wear rate, etc.) were optimized with respect to the input parameter settings. MQL showed much better results when compared to conventional techniques. Jang et al. [69] studied the possibility to obtain environmental conscious manufacturing (ECM) for milling processes. The amount of cutting fluid was minimized by applying the MQL process. The input parameters were varied to find their effects on the output responses. Firstly, pilot test was conducted to decide the ranges of various input parameters that permit to implement a model related to the cutting energy. ANN technique was employed to enable the model generation.

In milling proces, the employement of cutting fluid is not as common as in a process turning, due to the fluctuations (because of the intermittent cutting) in temperature leading to thermal cracks in the cutting tool. For this reason, dry cutting is the ideal choice when high temperatures do not cause problems during milling process. When milling hardened steels and superalloys at high speed, high temperatures occured at the machining area are the main reason for rapid insert wear. Therfore, it can be clearly said MQL (also called as near-dry machining) is the best alternative option in the intermittent cutting operations. Appendix Table 7 presents the literature review of MQL in milling processes.

3.3 Effectiveness of MQL in grinding operations

The grinding operation is a vital part of the manufacturing industry since it is the final process for workpieces that require high surface quality and dimensional accuracy. In addition, the need for eco-friendly production alongside ever-increasing disposal costs is one of the most remarkable challenges faced by this industry [70]. For these reasons, MQL has been a chance for grinding operations and has been used with success on several different grinding processes. For instance, Silva et al. [71] used the MQL practice on ABNT 4340 steel by using an aluminum oxide wheel. They compared MQL performance with traditional method. Various tests were performed to find out the optimum lubricant and airflow rate. Dry and MQL machining is considered a better option than the traditional machining. Moreover, a special nozzle is required to vary the fluid application as well. The eco-friendliness of this process was improved by applying a minimal quantity of biodegradable oil. The efficiency of the MQL technique was related to the surface finish of the machined workpiece. The MQL allows better outcomes associated with superior lubricity. It permits the reduction of frictional forces. A proper lubricant with superior properties prolongs the surface integrity characteristics. Tawakoli et al. [72] explored the role of MQL over the forces and surface characteristics. Many fluids were used for conducting the experiments, while comparisons were made against the dry cutting conditions. Here, three different types of grinding wheels were engaged in this process. It provides excellent results when the SH integrated with the MQL technique. Liao et al. [73] analyzed the effect of nanoparticle enriched fluid for both MQL and flood conditions during grinding of titanium grade 5 alloy. In addition, the water-miscible cutting fluid was applied to get relative comparisons. The morphology of the cut surface and wheel loading were kept under the observation. The application of nanoparticles in the system allows noticeable reduction in the roughness associated to lower applied loading on the grinding wheel. It is also found that the nanoparticles produce a rolling effect. Hence, it can reduce the thermal conductivity of the cutting fluid which definitely leads to some improvement on the machining performance. Obviously, the use of the MQL approach can improve the measured machining outputs and environment features.

Sadeghi et al. [74] carried out some comparative studies for the detection of the ability of different coolants. The comparisons were made between synthetic esters, mineral, and vegetable oils. The results prove the utility of the MQL approach when comparing to dry as well as flood cooling techniques. Qu et al. [75] performed grinding tests using nanoparticle-based fluids. The carbon nanosized particles were mixed using an ultrasonic vibrator. The main goal was to explore the potential employment of carbon nanoparticles into the pure-cutting fluid. The experiments were performed on carbon fiber-reinforced ceramic matrix material which is very difficult to cut. The experimental finding showed that nanocutting fluid enhanced by carbon nanopowders can permit to decrease the surface roughness and forces as well as the heat-induced surface damage. Kalita et al. [76] reported important observations while using nanoparticle enriched lubricants in combination with the mist cooling technique. The Molybdenum disulfide (MoS_2) nanoparticles were used for this purpose. Their size was less than 50 nm. The grinding was carried out on cast iron and EN 24 steel by applying nanomist. It was observed that the nanoparticle-based technique enables much better results as compared to the other techniques. The results were improved considerably by increasing nanoparticle concentration. In addition, soybean and paraffin based-nanofluid exhibited superior results for EN 24 steel and cast iron, respectively. Setti et al. [77] done experimental studies in turning of titanium (grade 5) alloy assisted by the nanoparticle enriched fluid using the MQL strategy. The experimental design was built with the assistance of Taguchi's arrays to better control the surface quality and forces. The Al_2O_3 nanoparticle was mixed with water and the results were compared to the traditional techniques. Consequently, the rolling effect developed by the nanoparticles may cause a ball-bearing process. It may enable a reduction in the frictional forces, which inevitably entail a lower cutting force. Moreover, it was reported that surface roughness decreases with higher concentration of nanoparticles. Oliveira et al. [78] used a vitrified CBN wheel under MQL in the grinding operation on AISI 4340 steel. Additionally, the air stream concentrated was released on the cutting zone in order to remove away the chips from the cutting area and to eliminate the cutting fluid. The outcomes of the study were the work material roundness error, surface roughness, wheel wear, and acoustic emission. The results obtained were found positive when using this technique. However, the MQL not only improves the process of economic performance but also permits to reduce the usage of coolants. Balan et al. [79] conducted experiments on Inconel-751 to enhance grinding operation performance. It was concluded that the grinding forces, temperatures and roughness may be reduced when using the MQL technique. Moreover, the crest flattening phenomenon was not noticed with the usage of MQL. Setti et al. [80] examined the potential of Al_2O_3 nanofluid into MQL conditions in order to enhance the grinding operation of titanium (grade 5) alloy. The outcomes were validated against the existing techniques. Zhang et al. [81] performed comparative research among different types of lubrication oils such as rapeseed oil, castor oil as base fluids. The comparisons were made against liquid paraffin considering both cooling and lubrication properties. The grinding of steel was initiated by using the MoS_2 nanoparticles. Later, the relative comparisons of these cooling regimes were conducted. The grinding forces were measured and compared for different fluid viscosities. In addition, the surface roughness evolution was also considered (refer Figs. 5 and 6). It reveals that the palm oil achieved the best lubrication in conjunction with nanofluid jets that are associated with the carboxyl groups identified in the palm oil. Setti et al. [82] performed research using nanofluids as main cutting fluids, while alumina and copper oxide nanoparticles were added in various portions by volume. Water was considered as base fluid during grinding of titanium (grade 5) alloy. The process was initiated in the presence of a mist cooling technique. A surface profilemeter was used to detect the surface properties of the machined surfaces as well as their integrity (i.e., details presented for surface roughness in Fig. 7). It was concluded that the use of alumina nanoparticles with various proportions into base fluid could play a leading role. It may drive the frictional forces as well as the surface roughness data. On the other hand, Fernandes et al. [9] done an assessment for MQL and conventional cooling and they reported that conventional cooling was more useful than MQL since a thermally induced harm was not seen in workpieces. In addition, they claimed that clogging problem in the grinding wheel surface during MQL occurred. In grinding of alumina with diamond grinding wheel, Lopes et al. [83] reported that the best surface quality was achieved by using the traditional cooling, and then MQL. In recent years, Rodriguez et al. [84] noticed that flood cooling was better than traditional MQL application in terms of most quality indicators. In grinding processes, although the MQL environment offers better results of surface quality and friction coefficient, temperature, and force as compared to dry cutting, it has lagged behind conventional cooling, especially in grinding of some materials such as hardened alloys. In addition, in recent years, nanocutting fluids prepared by adding solid nanoparticles to the base cutting fluid into MQL have emerged as a sustainable alternative to conventional cooling, in particular as it helps for evacuating the heat from the machining region. The in-depth literature related to the grinding process has been introduced in the Appendix Table 8.

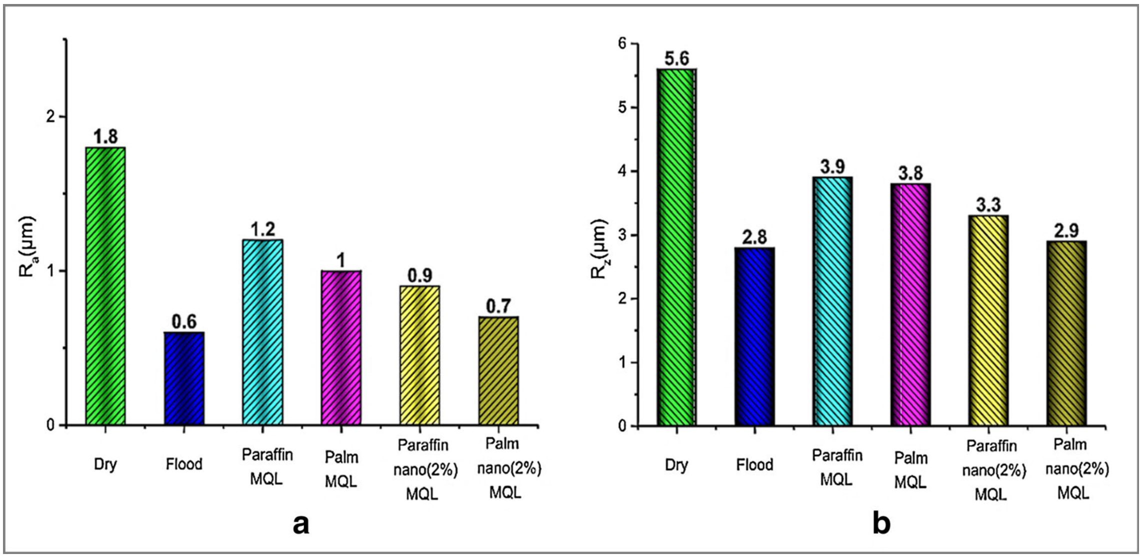

Fig. 5 Surface roughness under various operating conditions [81]

3.4 Effectiveness of MQL in drilling operations

Drilling is considered as the most used machining process in various sorts of industrial applications. The hole quality, tool wear, delamination of workpiece, and surface roughness are the relevant machining indices affected by the various machining parameters and conditions such as dry, MQL, flood, etc. Therefore, in this section, most work reported on drilling operation under MQL conditions was presented. For instance, Heinemann et al. [91] investigated the role of mist lubrication that helps to enhance the life of a drill tool. The primary issue affecting the process efficiency is related to the external supply of fluid. It was proved that the fluid supply and MQL type could have a tremendous effect on the drill tool life. When the drilling was conducted under dry conditions, the absence of any cutting liquid led to friction growth that generates higher local cutting temperatures. As a result, the tool life was reduced considerably. The TiAlN- and TiN-coated drill may bring beneficial features (i.e., advanced hot hardness, oxidation equality and lower heat conductivity). These features can help to save the drill from any wear and tear. The uncoated drill should not be used for drilling of deep boreholes in dry conditions because this will tend to wear out very quickly. Subsequently, it is assumed that the MQL technique with a coolant having less viscosity and better heat capacity produces considerably longer life.

Bhowmick et al. [92] done a research to analyze the impact of flood and MQL under drilling of AM60 Magnesium alloy. They made comparative studies among flood and MQL. The output parameters namely thrust force and average torque during a drilling operation were considered. The H_2O -MQL distilled water and FA-MQL based fluid (fatty acid) were used

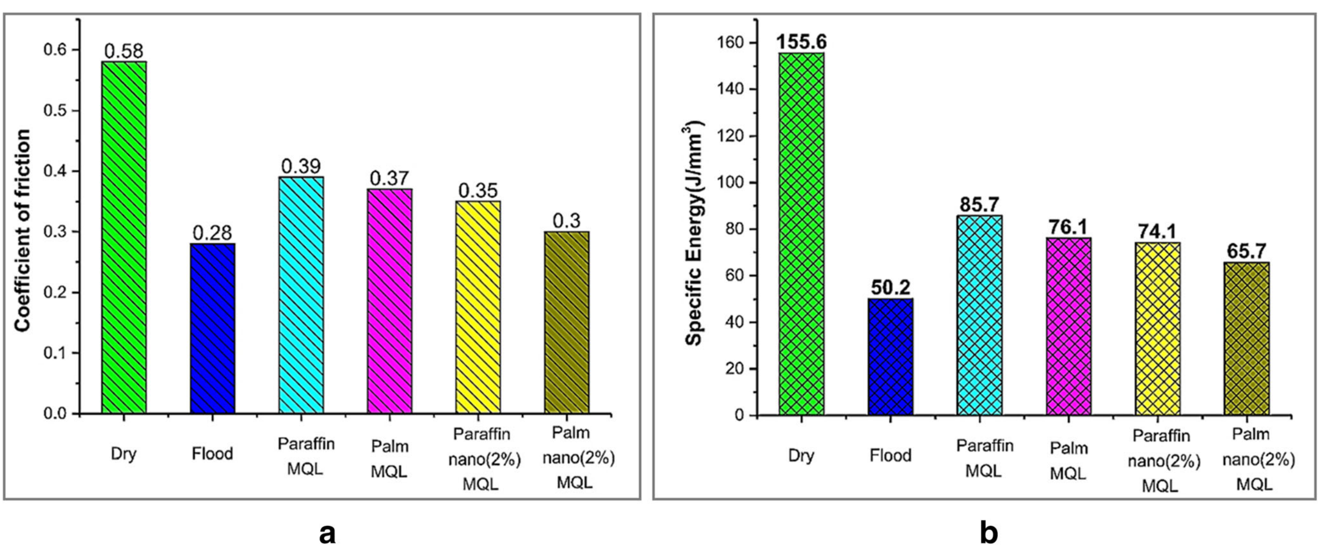

Fig. 6 **a** Coefficient of friction. **b** Specific grinding energy for the nanoparticle jet MQL grinding experiment with four types of base oil [81]

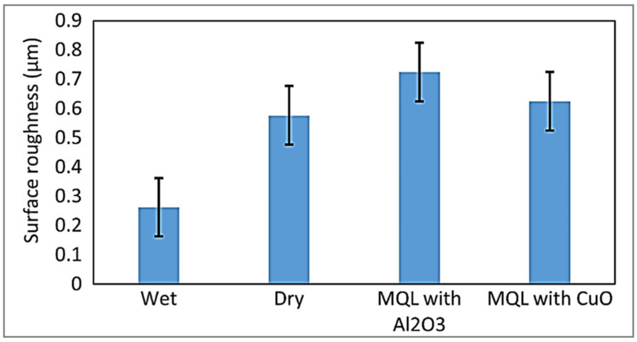

Fig. 7 Variation in average surface roughness values under different environments (error bars represents a standard error in data) [82]

as coolants. The flow rate was kept constant (10 ml/h); then, the results obtained were compared against mineral oils. The outcomes proved a reduction of adhesion amount of magnesium over the tool and only a small amount of built-up edge was noticed. This significant reduction led to much-lowered values of thrust forces and torque. The maximum temperature reached on the workpiece while using MQL technique was found much lower with respect to a typical process. Furthermore, it can provide uniform torque with much stable behavior during the drilling. It presented an improvement in the hole quality. Rahim and Sasahara [93] studied the effects of different type lubricants by applying the MQL technique while drilling the titanium (grade 5) alloy. Synthetic ester-based oil and palm oil were engaged during experiments. It reveals a much shorter tool life in dry drilling caused by the detrimental chipping. The palm-based oil efficiency was demonstrated by the fact that a reduction in thrust force as well as in the cutting temperatures was achieved. It was shown that the oil forms a protective coating around the workpiece at cutting zone. In another study performed by Rahim and Sasahara [94], comparative studies between the palm-based oil and synthetic esters were conducted. The test was made while drilling Inconel 718 alloy (see details of parameters process in Fig. 8). Apart from improving machining outputs, palm oil can aid in improving the microhardness of the workpiece. Kuram et al. [95] explored the efficiencies of different green fluids when drilling several materials. The experiments were designed using the Taguchi L9 arrays combined with the regression analysis. The comparisons with sunflower oil in crude and refined forms were made to detect the best machining performance. The spindle speed variations, depth, and feed rate were conducted to obtain the relative effects on the drilling force, which later enable better hole quality. Biermann et al. [96] studied the distribution of heat while machining aluminum alloy (EN AC-46000). Carbide drills were used for the experimentation together with a single lip procedure. The solid carbide drills promote favorable working conditions. It allows a higher efficiency, which leads to profitable manufacturing. Besides, the use of MQL approach may further enhances the process in terms of cost and environmental effectiveness (making it eco-friendly).

Chatha et al. [97] studied the working efficiency using different lubricating/cooling methodologies including both conventional and nonconventional ones. The use of nanoparticles was proposed to elucidate their effectiveness. The role of input parameters vs measured outputs such as the roughness,

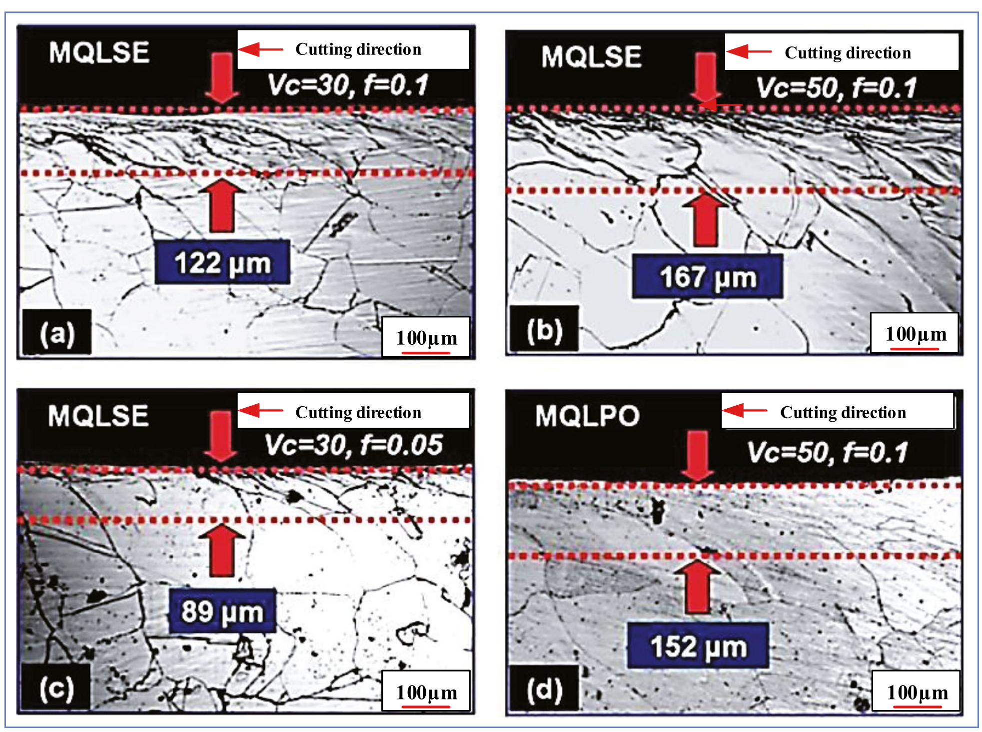

Fig. 8 Plastic deformation layer variations under different cooling regimes [94]

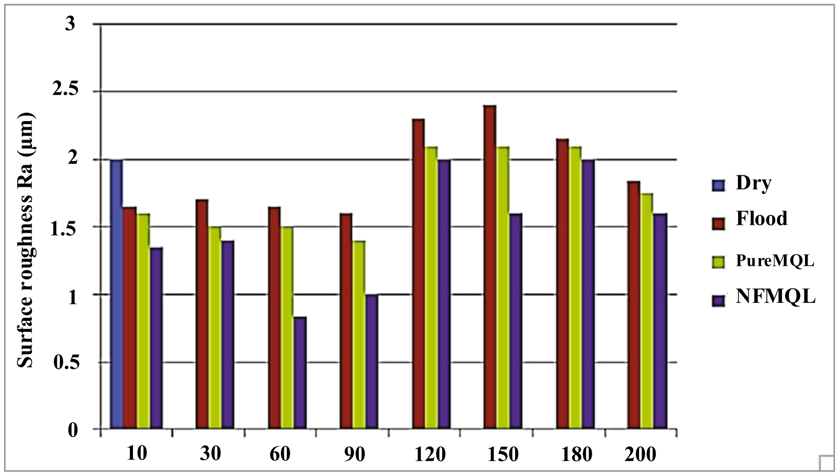

Fig. 9 The average surface roughness (Ra) under dry, flood, pure MQL and nanofluid MQL drilling at spindle speed of 30 m/min [97]

tool wear, and forces were highlighted. HSS drills were used to machine aluminum 6063 alloy. The flow rate used in the MQL process was maintained at 200 ml/h with a compressed air flowing at a pressure of 70 psi. The nanoparticles were mixed with base fluid (made of soya bean oil) to use into MQL system. The employment of such advanced cooling strategies improved the tool life by increasing the number of holes drilled. Moreover, the burr formation was also reduced using MQL technique along with the improvement in the hole quality as seen in Fig. 9. In summary, the success of the drilling operation is significantly impacted by the machining environment. Dry cutting is not strongly recommended for drilling. In addition, the MQL application as an option to dry environment is critical, since it does not cause environmental concerns and brings machining performance close to conventional cooling in a drilling operation. The Appendix Table 9 presents the survey details of MQL drilling process.

4 MQL upgradations with nanofluids and application techniques

The increase of heat dissipation is a crucial necessity during the cutting processes. It could present useful outcomes regarding the energy consumption, tool lifespan, and manufacturing capacities. The known ways to increase the heat distributing for numerous industrial functions has been concentrated on the heat exchanging zone modification. Yet, there are still concerns about its thermal capability. As a result, there is a huge need to improve the cutting characteristics. Scholars all over the globe have proposed numerous procedures. The technologies such as MQL or cryogenic cooling are highly friendly in respect to environment. Although the dry machining can be exercised for total stoppage of cutting fluids usage, it shows poor machining characteristics [98]. Kamata and Obikawa [99] investigated another conscious technology known as mist cooling. It has the advantage of high penetration due to the use of compressed air along with the usage of argon gas. Further, the cryogenic aplications are believed as efficient way for improving the heat distributing and machinability characteristics [100].

Generally, nanofluid enables the formation of a new fluid. It can be done by addition of particles having size lesser than 100 nm to a basis liquid. They have the role to improve certain properties [101]. These additives can be divided into several categories such as metallic, non-metallic, ceramic based, carbon based etc. [102]. Several benefits of nanofluids among various practices are listed as following [103]:

- High rate of heat transfer as a result of a higher specific surface area.
- Highly stable when dispersed.
- Energy savings spent in condensing pure-fluid because nanofluids may extend the required heat carrying features.
- Low contact angle and heat carrying features of a surface are controlled by the modifying the concentrations of nanoparticles.

Illustrations of various practices that use the nanofluid method to expand its substantial features including thermal, rheological, and stability are obtained through various literature survey [104]. This section is mainly focused to present a comprehensive literature survey of publications, which are related to the issues such as preparation, characterization, stability, thermal and rheological properties, improvements in machining quality characteristics, and challenges of nanocutting fluids.

4.1 Techniques of nanocutting fluid preparation

In order to achieve the optimum thermal properties, two major parameters, namely, durability and stability, need to be considered. Achieving lower sedimentation velocity of nanoadditives is an essential requirement to ensure the nanofluid's stability. The sedimentation velocity can vary proportionally with the square of nanoadditive radius according to the Stokes law given in Eq. (1):

$$V_s = \frac{2R^2}{9\mu_m}\left(\rho_p - \rho_m\right) g \quad (1)$$

where v_s is the velocity of sedimentation, R represents the average radius of nanoadditives, μ is the viscosity of the base fluid viscosity, ρ_p is the density of nanoadditives, and ρ_m is the density of base fluid. However, using a lower particle radius leads to a decrease in the sedimentation velocity, while the surface energy of the nanoadditives is increased which can result in nanoadditive aggregation. Thus, selecting an optimal value of the nanoadditive size and performing homogeneous dispersion are highly important to avoid both higher sedimentation velocity and occurrence of nanoadditives aggregation [105, 106].

There are two main techniques for nanofluid preparation: two-step and single-step. The two-step technique means manufacturing and dispersion, while the single-step technique depends on making both of them concurrently. In regard to the two-step technique, this is more suitable during dispersion of oxide particles and carbon nanotubes. It shows great potential results for metal-nanoparticles. Even, this technique includes two steps to disperse the nanoadditives into the base fluid; it is simpler when comparing to other technique. Yet, several problems such as nanoadditive agglomeration are noted. Some specific methods are used to resolve the previously mentioned problem using ultrasound, and/or high shear approaches. The two-step technique can fit more volume concentration values which is in turn of 20% [107, 108]. In terms of the single-step technique, drying, storage, and transportation of nanoadditives are included. Hence, a stable and durable nanofluid can be achieved as nanoadditive agglomeration and sedimentation may be avoided. However, the higher efficiency observed on the single-step technique, in terms of nanofluids' stability and durability, cannot fit well when the applications of large volume concentration are required [109]. Nanoadditive suspension and depressiveness greatly influence the characteristics of the fluid. Such dispersions can be achieved using an ultrasonic machine following by mixing. By using a magnetic stirrer, the complete dispersion of nanoadditives can be achieved. Furthermore, the processing time for each previous step depends on the percentage of nanoparticles [110]. The nanoadditive concentration (% weight) into the base cutting fluid is calculated using the Eq. (2):

$$\%\text{of weight concentration} = \frac{\text{nanoadditive weight}}{\text{nanoadditive weight} + \text{the base fluid weight}} x100 \quad (2)$$

Another alternative technique for dispersal of nanopowder into the basis liquid is nanoadditive synthesis using chemical precipitation or organic reduction [111].

4.2 Characterization of nanocutting fluids stability

The nanocutting fluids resulted from the suspension of nanoadditives into the base cutting fluid are characterized by parameters such as nanoadditive types, base fluid, additional additives and scale. During the nanofluid manufacturing process, the fluid composition design is made by taking into account the required thermal, tribo-chemical, physical, and rheological properties. Here, it is compulsory to achieve the resultant nanofluid accordingly to the functional requirements of each nanofluid type. Due to the major issue of clogging, there is a need to ensure the presence of repulsive forces between these nanoparticles in order to increase their dispersion time [112]. Two principles have been studied for establishing a high suspension quality for the nanoadditives into the base oil, namely, diffusion and zeta potential. The first principle is the diffusion, which ensures that the nanoparticles remain evenly suspended in the solution. The second principle is mainly focused on obtaining a better zeta potential value, which offers a repulsive force among the nanoadditives [113].

There are three main methods that offer a high suspension/stability performance in order to avoid the nanoadditive agglomeration, clogging, and sedimentation. The three main methods are as follows:

- Surfactant: The use of surfactants to stabilize nanoparticles dispersed in nanofluid is one of the first preferred ways. In such a situation, the surfactant not only improves the stability of the nanofluid but also has an incentive on hydrate formation [114]. Thus, the suspension of nanoadditives into the base fluid can be improved; however, the selection of optimal amount of surfactant is an important factor because it can affect the resultant electrostatic repulsion. Another limitation of this technique is the difficulty in applications associated with higher temperature as the repulsive forces can be damaged [115]. Here, various examples of surfactant have been used such as; sodium dodecyl sulfate, dodecyl trimethylammonium bromide, and polyvinylpyrrolidone [116].
- pH control: The nanofluid pH can control the stability and may improve the thermal conductivity that are related to the electro-kinetic properties. Using a simple chemical treatment technique is possible to obtain conversion for the nanoadditive shape, which results in higher surface discharge density, electric repulsion force, and zeta potential value. Thus, agglomeration, clogging, and sedimentation effects can be decreased, and high suspension quality of the resultant nanofluid can be accomplished [117, 118]. It has been noted that during the dispersion of Al_2O_3 nanoparticles into water, the base fluid agglomeration size is decreased at pH level of 1.7. However, an increase of agglomeration size has been noticed at a pH level of

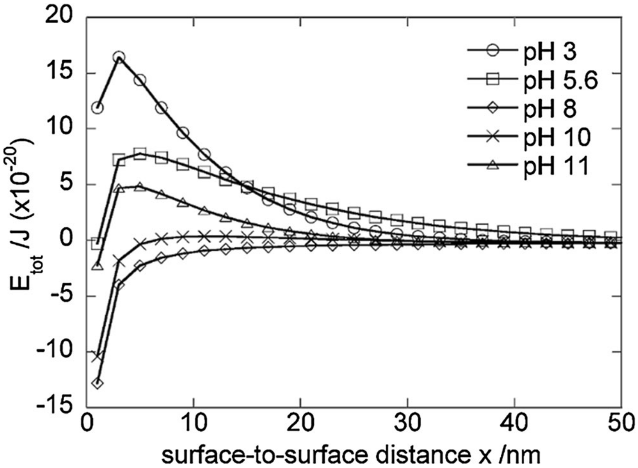

Fig. 10 The inter-particle distance versus the total nanoparticles energies at different PHs [118]

7.66 [119]. Furthermore, another study provided the effects of pH on the Vander Waals attraction and electrostatic repulsion energies (total energy) at different inter-particle distance using metal oxide nanoparticles. Moreover, it can be observed that the total energy is inversely proportional to the pH values at lower levels of inter-particle distance; however, no significant effect of pH can be observed at higher levels of interparticle distance as shown in Fig. 10 [118].

- Ultrasonic vibrations: This technique aims to break down the agglomerations among nanoadditives. It reveals promising results in term of process stability. Nevertheless, optimizing the processing time is required because it lead to a fast clogging and sedimentation of nanoadditives [120]. The ultrasonic disruptor is the most popular apparatus used for ultrasonic vibration to disperse the nanoadditives into the base fluid. The applied mechanisms during the ultrasonic vibration include three stages to ensure fully process stability and decreasing the clogging and agglomeration size [121].

It was mentioned [122] that several instrumentation techniques such as the sediment photography capturing, UV–Vis spectrophotometer, TEM, SEM, and scattering of light are employed to assess the nanofluid suspension performance. However, the zeta potential analysis is the most popular techniques to check the process stability. Table 4 shows the suspension stability at different zeta potential levels [123].

Table 4 The suspension stability at different zeta potential levels [123]

Z potential absolute value	Stability status
0	No stability at all
14	Very less stability
28	Medium stability
42	Fair stability with possible settling
56	Good stability

4.3 The thermal and rheological nanocutting fluid properties

It was previously observed that thermal conductivity evolved when different nanopowder types, sizes, and volume fraction percentages were inserted (details shown in Appendix Table 10). Various analytical models have been performed to express the nanofluid thermal conductivity. The Maxwell equation [137] shown in Eq. (3) can predict the thermal conductivity depending on the base fluid's thermal conductivity (K_m), the nanoadditive thermal conductivity (K_p), and the nanoadditive volume fraction (υ_p), while the resultant thermal conductivity is (K_e).

$$K_e = K_m + 3\,\upsilon_p \frac{K_p - K_m}{2\,K_m + K_p - \upsilon_p (K_p - K_m)} K_m \quad (3)$$

Another modified model has been obtained for calculating the nanofluid thermal conductivity as shown in Eq. (4) [137]:

$$\frac{K_e}{K_m} = \frac{K_p + 2K_m - 2\upsilon_p\,(K_m - K_p)}{K_p + 2K_m + 2\upsilon_p\,(K_m - K_p)} + \frac{\rho_p \upsilon_p Cp}{2\,K_m} \sqrt{\frac{K_p\,T}{3\pi R \eta}} \quad (4)$$

where ρ_p, C_p, T, η, and R are the nanoadditive density, nanoadditive specific heat, temperature, viscosity, and nanoadditive radius.

On the other hand, the use of the hot-wire technique was employed to estimate the values of the thermal conductivity, and it is called transient line heat source method [138]. In addition, the nanofluids have shown promising results to enhance the heat transfer coefficient. The investigation of the cooling capabilities of nanofluids when grinding operation of Ti-6Al-4V alloys (nanofluid heat transfer coefficient/base fluid heat transfer coefficient) for different nanoadditives types and volume fractions was made by Ibrahim et al. [139]. Furthermore, two analytical models have been developed to predict another heat transfer indicator, which is the specific heat. The analytical model that is based on the nanoparticle volume fraction has been shown in the Eq. (5) [140].

$$C = C_{bf}\left(1 - \upsilon_p\right) + \upsilon_p C_p \quad (5)$$

where C_{bf} is the base fluid's specific heat, and C is the nanofluid specific heat.

Another effective property in terms of nanofluid dynamics is the viscosity, because it is an important factor for the heat transfer [141]. Furthermore, the nanofluids rheological behavior can be obtained through investigating its effects. Several analytical models have been implemented to calculate the

Table 5 The analytical models of the nanofluids for viscosity [116]

Model	The effective nanofluid viscosity ratio	Application
Einstein	$1 + \eta\, \upsilon p$	At no nanoadditives interactions and υ_p is less than 1%
Batchelor	$1 + \eta\, \upsilon_p + (\eta\, \upsilon_p)^2$	Brownian motion and interactions of nanoadditives
Ward	$1 + \eta\, \upsilon_p + (\eta\, \upsilon_p)^2 + (\eta\, \upsilon_p)^3$	υ_p is greater than 35%

effective nanofluid viscosity ratio (i.e., nanofluid viscosity/ base fluid viscosity) as shown in Table 5. These models vary depending on the nanoadditive volume fraction and the dynamics of their interactions. The nanofluid rheological behavior has been classified into four main sections [142]:

- Nanofluids with volume fraction less than 0.1% and their viscosity is associated with the Einstein model (without shear thinning);
- Nanofluids with volume fraction between 0.1 till 5% (no obvious shear thinning);
- Nanofluids with volume fraction between 5 till 10% (observed shear thinning);
- Nanofluids with volume fraction greater than 10% (nanoadditives interpenetration).

4.4 Improvements of machining quality characteristics

Recently, many researches have focused on the use of multiwalled carbon nanotube (MWCNT) in combination with the base fluid because of its excellent impact to machining process [8]. In addition to improving the thermal conductivity, the nanoparticles also help to lessen the friction between the workpiece and tool surfaces. The lubrication improvement leads in a better dimensional accuracy and superior surface texture quality [143]. Other studies have been confirmed that the increase in the nanoparticle concentration in conjunction to a smaller particle size allows improvements in the thermal conduction of the cutting fluid [144]. The MQL as single process and in combination with nanoparticle fluids and MWCNT were applied to machine a chromium-based carbon alloy (AISI D2). It was noticed that only conventional MQL technique offers inferior results compared to the combined method [145]. In another promising work, Sharma et al. [146] extended the effects of the abovementioned system in the turning of AISI 304 alloy. It was concluded that the combined methodology offered better surface finish, coefficient of friction, cutting force, as well as tool life due to an improvement of thermal conductivity. Singh et al. [147] performed research analysis while machining titanium grade 3 alloy. The comparisons were made between dry medium, traditional oils, and a specially created MQL fluid enriched with nanoparticles. The surface texture was greatly improved, and a longer cutting tool life was achieved. Setti et al. [82] has concentrated their study to control the friction behavior in the grinding processes. It helps to evaluate the work piece surface and abrasive particle interactions that affect the output parameters. The nanoparticle was added into the base fluid within various concentrations. The titanium grade 5 was used as workpiece material, while the grinding forces, chip formation, morphology, etc. were considered as outputs. It was concluded that application of MQL along with the nanofluid leads to an improvement in the quality of the workpiece. Zhang et al. [81] made observations while grinding of 45 steel with the assistance of nanoparticle enriched solutions. Various lubrications strategies have been employed (i.e., flood, MQL, and dry cutting). It has been observed that the lubrication property can be improved through the use of high nanocutting fluid viscosity. Therefore, the heat transfer performance can be enhanced as well. On the other hand, the optimal mass concentration for MoS_2 nanoparticles into the base cutting fluid was 6 wt%. Sen et al. [148] performed milling experiments on Inconel-690 alloy using MQL mist cooling system. The investigations results were compared with other lubrication techniques (i.e., dry, MQL with palm oil, nanosized silica at various proportions from 0.5 to 1 vol% dispersed in palm oil). The nanocutting fluid-based method mixed with 1 vol% silica has shown promising results. It can reduce the tool wear, surface roughness and resultant cutting force due to its cooling and lubricating effects, which lead to a decrease on the cutting zone temperature. Yildirim et al. [110] carried out turning experiments on Inconel-625 alloy under hexagonal boron nitrite (hBN) mixed nanofluid-MQL in different volume fractions of 0.5% and 1%. They compared findings with other lubrication techniques, i.e., dry and pure-MQL (without any nanoadditives). The 0.5 vol% hBN dispersed nanofluid based MQL method has exhibited better outputs.

The effectiveness of an integrated approach that uses the nanofluid-assisted MQL in the turning, milling, grinding, and drilling processes was successfully demonstrated. The suspended nanoadditives containing diverse sizes are introduced in the base oil allows to boost the heat transfer coefficient. They enable uniformly distribution of heat into the cutting zone. Besides, the prolonged tool life is also linked to the MQL-based nanofluids (NFs). Owing to nanopowders behaving as an intermediate layer between the surfaces in contact is possible to obtain a substantial reduction in frictional coefficient. Hence, superior surface finish, less cutting forces and tool wear are obtained. The key advantages of integrating the nanoadditives with MQL mechanism are summarized as follows [149]:

- A fine mist is achieved by combining the high-pressure air and nanoadditives atomized through MQL nozzle.
- The superior tribological properties (lower friction with better lubrication) is achieved by impinging the nanoadditive-assisted MQL droplets on the cutting insert/chip/workpiece interfacial creating a thin-film layer.
- The multifarious sized nanoparticles enable to increase in the overall nanoadditive concentration. This multifarious sized nanoadditves work as a key role for spacer and penetrated closer to tool-workpiece interface.
- The nanocutting fluid used in conjunction with the high-pressure, on the MQL system, can spread homogeneous on the narrow tool-workpiece interface. It prevents a direct contact of tool with the workpiece surface. The higher number of particles produce thin and a protecting tribo-film on the newly machined surface.

The MQL-NFs helps to improve a bonding mechanism at the tool-workpiece interface. That is why the applied NFs may improve the tool life, surface finish and by restricting the cutting temperature and force. These techniques have demonstrated favorable performance while maintaining an environment for sustainable machining. The conclusion from overall above discussion can be summarized as practicing biodegradable green oils or conventional mineral oils through MQL application are useful in cutting operation leading to decrease in the cutting temperature, tool wear, cutting forces, and surface roughness. It is pertinent to mention that a comparison of MQL with dry and flood conditions was put forward to achieve the machining characteristics. Besides, MQL technique uses a very small quantity (10,000 times less than flood) of lubricant rather than using few liters per second in flood cooling. The MQL approach also encourgaes a green cutting, i.e., eco-benign, environmentally friendly manufacturing, and zero post-process cleaning. The performance of MQL technique can give better results when integrated nanofluid with biodegradable oil. As the following mechanism plays a vigorous role on the nono-lubricant released in mist form: (1) Spherical nanoscale powders have a great tendency to rotate and slip between tool workpiece surfaces. (2) A thin protection film may get develop on the surface of the workpiece and tool due to the ability of nanosized particles to form the friction pairs. (3) The formation of a tribo-film of nanoadditives due to accumulation of particles on the contacted surfaces, leading to mending effect such as lost-mass compensation. (4) The uniform compressive forces beared by the nanosized particles while the compressive stress produced as high contact pressure were reduced significantly [119]. Figure 11 depicts the NF behavior between the two sliding surfaces.

In addition, Hegab and Kishawy [150] investigated the operating mechanism associated with the MQL-nanofluid. Figure 12 presents a schematic of the proposed mechanism. Here, the nanofluids were atomized through MQL employing with a certain percentage of compressed air to form a biodegradable oil assisted fine mist. This fine mist has the capability to enter well into the tool/chip/workpiece interfacial forming a tribo-film layer to limit coefficient of friction and generated cutting heat as well. Therefore, addition of NFs in MQL much enhanced the lubri-cooling functions to sustain the uniform hardness of cutting tool for longer time. Thus, the MQL-nanofluid entails superior performance regarding the tool wear behavior when matched under cutting using pure MQL without any addition of single or hybrid nanoadditives. Additionally, Hegab et al. [151] provided an obvious insight of the abrasive impacts that is generated as result of the application of MQL nanofluid. At high concentration, a high abundance of nanoparticles in the resultant NFs collides with each other. Because, they are impeded due to the work surface asperities, thus producing a high cutting force. Consequently, the nanoadditive induces the wear process,

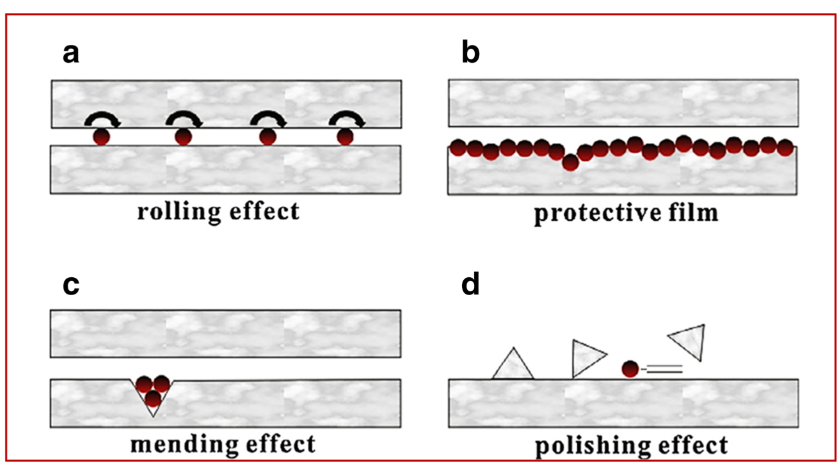

Fig. 11 NFs behavior when sliding between two surfaces: **a** rolling effect of spherical nanoadditives, **b** a nanoprotective film, **c** the mending, **d** the polishing effects [119]

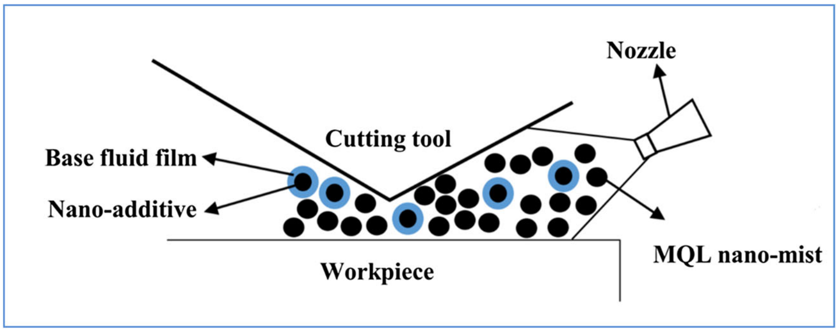

Fig. 12 The nanoadditive assisted MQL mechanism [150]

which is boosted by incrementing the nanoadditives concretion as discussed previously. Subsequently, the resulting flank wear will grow that will affect the surface quality of a final product. It can be seen in Fig. 13 that the high concentration of nanoadditives means more intensive additives in NFs impinging on contact surfaces in the operation region. The direct contact of the cutting tool with the workpiece surface is limited by the layer of nanoadditives, so the resulting friction is reduced because the employed mist become spacer in the cutting zone. Establishing the above understanding, it can be asserted that nanoadditives amount should be attentively chosen to make balance between considerations.

4.5 Nanofluid application challenges

In spite of all favorable characteristic of nanofluids, there are still a few challenges that need to be addressed and resolved when is used the nanotechnology. Some of them are summarized below:

- The main concerns are related to a no sufficient agreement between the results obtained in various studies. Moreover, there is a compulsory need for investigation of properties that drive the lubrication mechanisms [152].
- Long-term stability of nanofluid: It is one of the most important demands needed as the nanoparticles are easily aggregated because of the Van Der Waals interactions. Numerous proposed solutions have been applied and presented (e.g., using surfactant); however, the time period after preparing the nanofluid is a critical factor as the nanoparticles agglomeration can happen [153].
- The challenges of the nanofluids/nanoadditives production (e.g., sedimentation, clustering, agglomeration): An effective recommendation to face these challenges has been obtained through establishing a multi-disciplinary approach, which can lie between the thermal, mechanical, chemical, and materials science aspects [154].
- The high cost of nanofluids [8].
- The nanofluid thermal behavior in turbulent flow cases: There are required to investigate the convective heat transfer and thermal conductivity in the situation of turbulent flows. However, only few studies have obtained promising results for using nanofluids in the turbulent flow cases [155, 156]. The building of a general analytical model that express the flow mechanisms effects is highly required.

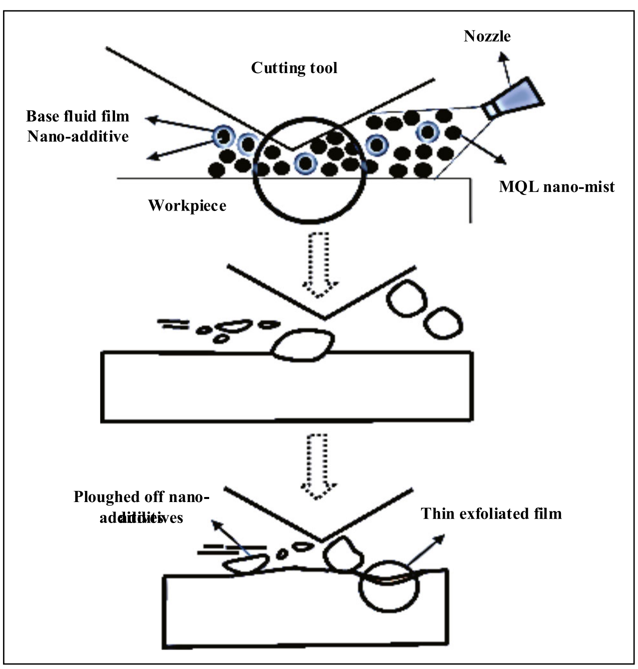

Fig. 13 The effect of nanoparticle concentration in MQL-nanofluid mechanism [151]

5 Miscellaneous MQL upgradations with cold air supply

Although, the nanofluids are being extensively used for upgrading the existing MQL approach, there are yet other techniques being used in combination with the MQL process. The literature is flooded with researches on MQL. Thus, there is need to upgrade the existing process with other advanced techniques. The following section lists and explains the advantages of combining some useful techniques with the MQL process.

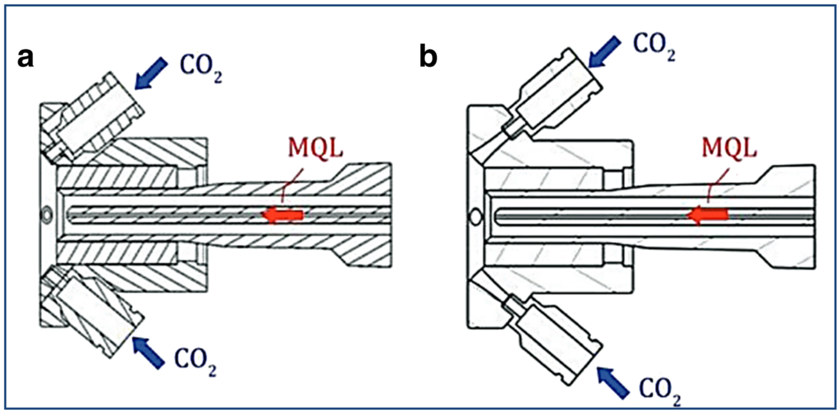

Fig. 14 Cryo-MQL nozzle arrangements [159]

5.1 Cryogenic-MQL combinational applications

Cryogenic-MQL refers to using MQL assisted by cryogenic air. It is believed that the combination of cryogenic air with the MQL leads to a much-improved outcome when compared to the ones obtained without using chilled air. In one of the earlier attempts, He et al. [157] conducted turning experiments to compare MQL with cryogenic assisted MQL process in terms of cutting tool life. The cutting tool used consists of an internal cooling system for passing cryogenic air through in order to assist the cooling process. The data observation from experiments showed that the combining of MQL medium with cryogenic air-cooling might improve the tool life and surface quality. Moreover, it was also noted that the use of compresses cryogenic air also helps to easy break the chip. In another similar study, Chetan et al. [158] performed the turning of Nimonic 90 alloy at variable speeds under different cooling regimes. It was reported that both air-cooling and MQL offer similar results. However, the combined use of the MQL and cryogenic cooling could lead to a substantial advancement.

In a similar attempt, as shown in Fig. 14, Pereira et al. [159] used a unique nozzle system to supply a combined stream of MQL coolant and cryogenic CO_2 into the cutting zone. The experimentation was performed on Inconel 718 alloy. The process was made using fixed cutting parameters, but comparisons were made among several cooling regimes in order to find the best cooling method, which provides longer tool life. It was concluded that although the wet flood cooling offers the highest tool life, the combinational cooling using MQL + CO_2 also could provide a tool life equivalent to 92% of the life provided by the wet cooling. This was accompanied with the minimum use of coolant and much lower cooling cost. In addition, this process is completely environment friendly. In continuation to their previous work, Pereira et al. [160] involved the use of computational fluid dynamics (CFD) techniques to improve the nozzle design that permits to achieve efficient cooling and lubrication while machining aerospace alloys. Some theoretical analyses were compared with the CFD simulations that were corroborated with experimental results. They state that this technique provides a perfect blend between the technical and environmental benefits with much better output parameters. In another work Park et al. [161] compared several cooling techniques, by conducting experiments with different cooling and lubrication regimes. They addressed that cryogenic cooling and MQL exhibited better performance than both dry and wet cutting. However, it was reported that the exposure to liquid nitrogen leads to thermal damage to the cutting insert and the hardening of the workpiece metal in machining, resulting in poor tool life and microbreakage and increasing cutting forces. Zou et al. [162] turned 3Cr2NiMo alloy using a diamond cutting tool. The comparisons were done to compare the combinational effectiveness effect of cryo-MQL cooling. It was reported that the flank wear is reduced by more than 50%. In addition, a perfect finish was obtained in the sample. Thus, it was concluded that the use of cryo-MQL is highly beneficial for the tool life and product quality when machining with a diamond tool. In one of the most recent studies, Shokrani et al. [163] performed a detailed analysis on the effect of cryogenic-MQL combinational effect in order to detect various responses. The evaluation shows that a higher tool life is due to the combinational cooling technique that is superior when is compared to the flood cooling.

5.2 Ranque-Hilsch vortex tube (RHVT)–MQL combinational applications

Another source of cold air that can be developed to replace the cryogenic gases is generated with a vortex tube. This device is made of a completely stationary part that only requires compressed air as input. The air outlet with a reduced temperature can be used for the cooling purpose. There is a lot of scope for improvement because it has been used only in very limited situation. We have noticed that the literature volume available on the use of a vortex tube for machining purposes is almost negligible. In one of the earlier attempts, Alsayyed et al. [164] used a vortex tube during milling of brass material. The comparison was made between3 conventional coolants in terms of cutting temperature and surface texture. It was shown that the vortex tube allows reducing the cutting temperature due to its cooling

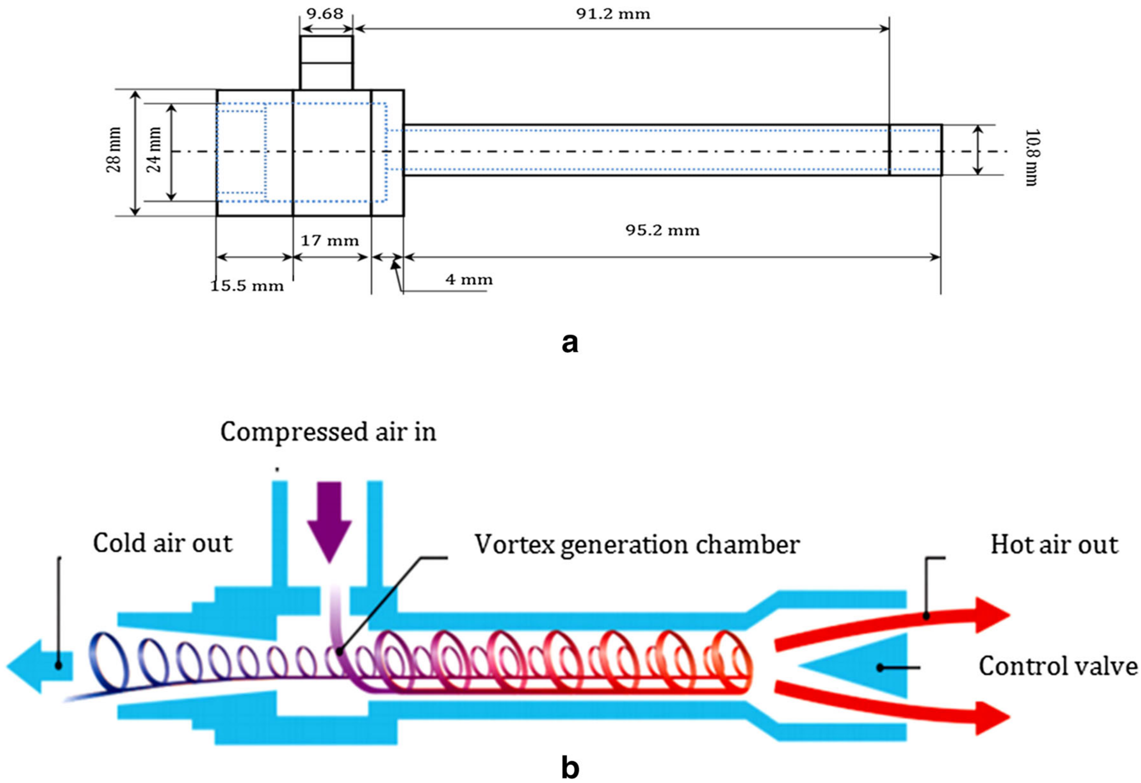

Fig. 15 Construction and working principle of a Ranque-Hilsch vortex tube [167]

effect, but is not able to reduce the roughness. The conventional cooling offers a better surface texture. Lopes et al. [165] explored the grinding of the AISI 4340 alloy using MQL under cold air with vortex tube. They observed that promising results with cutting fluid applied at 0 °C. Another study by Taha et al. [166] compared the use of a vortex tube with ambient air cooling. The experiments were performed while milling of A36 steel workpiece. It was concluded that the vortex tube was only effective at higher speeds due to its cooling effect but failed to give good results at lower speeds due to the absence of its lubricating effect. Gupta et al. [7], in a relatively latest and simple work, compared the cutting temperatures in machining using different tool materials as well as coolants. The RHVT was used as one-coolant competitors. Hence, the cutting temperature was found the highest under dry conditions. In a recently published article, Mia et al. [167] conducted some experimental comparison by combining RHVT with nitrogen gas. The comparisons were made with dry cutting, nitrogen cutting and nitrogen MQL. It was concluded that the inclusion of an RHVT (refer Fig. 15) in the system assisted to improve the machining outcomes. It is clear that the use of the RHVT in conjunction to machining operations can be made with minimum cost additions; however, the results can be improved considerable. Appendix Table 11 presented the work related that combine the applications of MQL with cryogenic gases and RHVT.

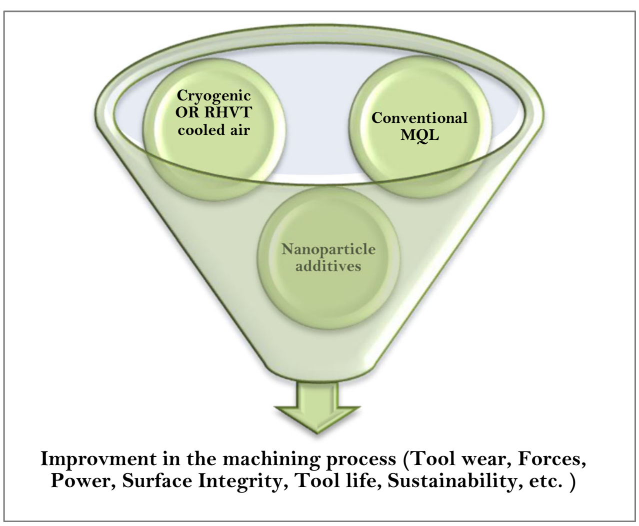

Fig. 16 Graphical representation of the conclusion

6 Conclusions

A robust review was presented associated with the MQL and its use along with different machining operations. This study permits to reduce the gap in the existing literature and proves the success of using advanced methods of lubrication. Figure 16 depicts the key aspects, which enable superior performance for different machining operations (turning, milling, grinding, and drilling). In summary, the main conclusions are drawn as follows:

1. MQL parameters: in numerous researches related to the MQL, the comparisons were simply made with the existing alternatives like dry, flood or cryogenic machining. There is no evident effort where MQL has been upgraded by a particular process and then compared against the classical MQL process. Since 2002, the comparison with dry and flood techniques has been well established and the results was implemented in the most industrial applications.
2. The use of MQL method significantly improves the machinability characteristics such as surface quality, tool life, tool wear, cutting forces, cutting temperature. However, it is obviously the need of further upgrade into the MQL process. Further improvement should be related to the main MQL parameters, i.e., fluid flow rate, compressor pressure, nozzle location, nozzle angle, nozzle number, etc. Such variations and their relative effects may throw light on important results. Moreover, the correct determination of MQL fluid type, MQL operating parameters and cutting parameters depending on each material/cutting tool pair is substantially important for sustainable production.
3. In light of the information collected from the available literature, most of the previous studies stated that the MQL cooling/lubrication method made significant improvements in performance outputs in operations such as turning, grinding, milling and drilling. However, some researchers have identified the negative effects of MQL on the workpiece material and grinding wheels in the grinding process. Therefore, studies on hybrid methods and nanofluid employment have been intensified to make the MQL method more effective. Especially, nanofluid-MQL has contributed significantly to the machining process compared to traditional pure-MQL.
4. There is a quite limited amount of work available for the MQL used for boring process. The boring or internal turning is one of the critical processes used in the manufacturing industry and needs more attention when cutting operation. Thus, the use of MQL strategy within boring process opens new perspective of highly quality manufacturing for critical components.
5. A comprehensive literature survey related to the nanofluid technology has been presented and discussed. The nanocutting fluids have depicted favorable results regarding the base liquid features, but mentioned advances cannot be obvious in the absence of employing a sufficient dispersion method. The improvements are primarily focused on the thermal, tribological, and rheological features. There various works were established for different empirical and analytical models to explore a correlation between the operating parameters and their response parameters. Moreover, the nanocutting fluids have provided favorable findings regarding the machining performance measures (e.g., cutting forces, friction behavior, tool wear, cutting zone temperature). Despite of previous improvements, yet some challenges are on the nanofluid technology usage, such as; long-term dispersion stability of NFs, complexities in turbulent flow cases, higher cost of nanoparticles, and challenges related to production process of nanofluids/nanoadditives.
6. For other possible MQL upgrades, it is worth to investigate further combination with cryogens such as liquid Nitrogen. They may help to improve as well as the results. Moreover, the use of a Ranque-Hilsch vortex tube can also reduce the cutting temperatures significantly. It was noticed that a very limited volume of work is related to the use of vortex tube.
7. In the available literature, it can be said that dry machining is the best way with regard to sustainable and environmental issues. Yet, considering both sustainability and efficiency together, it can be clearly stated that traditional MQL and nanofluid-MQL methods are the best alternative in machining operations.

7 Future directions

The following recommendations can be incorporated in order to upgrade and to obtain sustainable cooling/lubrication processes.

1. Electrostatic MQL (EMQL) and ultrasonic assisted vibration MQL (UAV-MQL) could be implemented in turning, milling, grinding and deep drilling processes since it is reported as the latest trend in upgradation of MQL technique.
2. Ionic liquids with biodegradable base oil (1-butyl-3-methylimidazolium cation as additive to castor oil) assisted MQL can be used to improve the lubricity efficiency during the machining of ultra-hard materials/composites.
3. Particularly in the cutting of difficult-to-machine alloys, the combination of MQL and MQCL can be employed by applying addition of nanosized solid lubricants into vegetable-based cutting fluid. In these combined systems, hybrid nanofluids can be also preferred for effective cooling and lubrication.
4. Some studies demonstrating the benefits of hybrid nanoparticles have been performed recently and they reported that they are very beneficial to increase both the thermal conductivity and lubricity features of base liquid. Therefore, more research can be done on the performance of biodegradable oil-based hybrid nanofluids.
5. To increase the applicability of NFs in machining operations, more investigations are needed to improve the long-term dispersion stability of NFs, wettability, complexities in turbulent flow cases, and challenges related to production process of nanofluids/nanoadditives and to put models of the tribological and heat propagation mechanisms of NFs.

6. In recent years, although many different nanoparticles have been used in the MQL system, more studies are required on the optimum volume fraction and size of nanoparticles and the time during which NFs can be preserved without losing performance and producing bacteria.
7. In order to achieve better cooling as well as good lubrication, cryogenic cooling plus hybrid NFs-MQL may be considered as it offers promising results up to now for machining of materials that have poor thermal conductivity and high reactivity against tool materials.
8. In order to indicate the relationship between green and sustainable production, well-known models such as life cycle assessment (LCA) can be applied to the above-mentioned cooling/lubrication methods in conventional machining operations. Moreover, various analytical models can be developed for different machining processes to reduce energy, power consumption, and promote economic production.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

Appendix

Table 6 MQL in turning process

Reference (s)	Work/tool material	Cutting parameters	Cutting environment/fluid	Parameters evaluated
Dhar et al. [21]	AISI 1040 steel Uncoated carbide insert.	$V_c = 64,80,110,130$ $f = 0.10, 0.13, 0.16, 0.20$ $a_e = 1.0$	Dry, wet, and MQL Soluble oil as coolant $p = 7$ bar and flow rate = 60 ml/h	Cutting temperature, chip reduction ratio and dimensional deviation.
Sreejith [25]	Aluminum 6061 alloy Diamond coated carbide tool	$V_c = 400$ $f = 0.15$ $a_e = 1.0$	Dry, MQL, flooded coolant Bp-microtrend oil. MQL applied 50 ml/h and 100 ml/h	Tool wear, surface roughness, and cutting force.
Khan et al. [26]	AISI 9310 steel Uncoated carbide TTS	$V_c = 246, 348, 483$ $f = 0.10, 0.13, 0.16, 0.18$ $a_e = 1.0$	Dry, wet, and MQL Food grade vegetable oil $p = 6$ bar	Cutting temperature, chip pattern, tool wear, and surface roughness.
Vasu en Reddy [49]	Inconel 600 alloy Coated carbide	$V_c = 40, 50, 60$ $f = 0.08, 0.12, 0.16$ $a_e = 0.4, 0.8, 1.2$	Dry, wet, and MQL with nanoparticles Al_2O_3 nanoparticles in vegetable oil	Surface roughness, tool-tip interface temperature, cutting force, tool wear, and chip formation.
Amrita et al. [33]	AISI-1040 steel HSS and cemented carbide tool	$V_c = 105$ $f = 0.14$ $a_e = 1$	MQL nanoparticle Nanographite powder (80 nm) size in proportion 0.1, 0.3, and 0.5%, soluble oil used	Cutting force and tool flank wear.
Hadad and Sadeghi, [35]	AISI 1040 steel HSS and cemented carbide	$V_c = 40.7$ $f = 0.14$ $a_e = 1$	Dry, flooded, mist with nanographite Mist with nanographite of 0.1, 0.3, 0.5% weight	Cutting temperature, tool wear and cutting force.
Sharma and Sidhu [38]	AISI D_2 steel Tungsten carbide insert	$V_c = 79, 96, 130$ $f = 0.5, 0.10, 016$ $a_e = 1$	Dry and MQL machining Accu lube 6000 cutting fluid $P = 1$ bar	Cutting temperature, surface finish and microhardness.
Mishra et al. [50]	EN-24 steel CNMG120408 Coated carbide insert	$V_c = 80, 160, 240$ $f = 0.04, 0.08, 0.12$ $a_e = 0.2, 0.3, 0.4$	MQL $p = 5$ bar Flow rate = 50 ml/h	Surface roughness.
Chetan et al. [46]	Nimonic-90 and Ti-6Al-4V PVD coated carbide insert	$V_c = 60, 120$ $f = 0.15, 0.25$ $a_e = 0.5$	Dry and MQL Sunflower oil in water (10:1), nozzle spray at 3 bar	Nose, flank and rake wear, cutting force.
Cetin et al. [51]	AISI 304 l steel Titanium nitride inserts	$V_c = 100$ $f = 0.1$ $a_e = 1$	Vegetable-based cutting liquid MQL and commercial cutting fluid	Surface roughness, Tool wear and turning force.
Mishra et al. [52]	Ti6Al4V Uncoated carbide	$V_c = 90$ $f = 0.1$	MQL and nMQL $p = 4$–7 bar	

Table 6 (continued)

Reference (s)	Work/tool material	Cutting parameters	Cutting environment/fluid	Parameters evaluated
		$a_e = 1$	flow rate = 100–250 ml/h	Main cutting forces, contact length and contact area, coefficient friction, tool wear, chip morphology.
Maheshwera et al. [53]	Inconel 718 alloy Carbide cutting.	$V_c = 60, 80, 100$ $f = 0.1, 0.5, 0.3$ $a_e = 0.05, 0.75, 0.1$	Dry and MQL Tungsten disulfide dispersed 0.5% wt in emulsion oil	Surface roughness, S/N ratio for the result obtained by Taguchi method.
Das et al. [54]	AISI 4340 steel Uncoated cermet insert	$V_c = 80, 100, 120, 140$ $f = 0.05, 0,1, 0,15, 0.2$ $a_e = 0.1, 0.2, 0.3, 0.4$	Water soluble coolant and Al_2O_3-based nanofluid-MQL Flow rate = 150 ml/ $p = 7$ bar	Cutting forces, chip thickness, and tool wear.
Ozbek and Saruhan [23]	AISI D2 steel PVD and CVD coated carbide insert	$V_c = 60, 90, 120$ $f = 0.09$ mm/rev $a_e = 1$	Dry and MQL Flow rate = 150 ml/h $p = 6$ bar	Cutting temperature, surface roughness, vibration, tool wear, and tool life.

*Units of cutting speed, V_c = m/min; feed rate, f = mm/rev; depth of cut, a_e = mm

Table 7 MQL in milling processes

Reference/year	Work/tool material	Cutting parameters	Environment/cutting fluid	Parameters evaluated
Liao and Lin [57]	NAK-80 mold steel Indexable carbide insert	$V_c = 300, 400, 500$ $f = 0.10, 0.15, 020$ Axial depth = 0.3 Radial depth = 5	Dry and MQL Biodegradable ester Flow rate = 10 ml/h $P = 0.45$ mPa	Tool wear and surface roughness
Thamizhmanii and Hasan [58]	Inconel 718 Super hard cobalt tool.	$V_c = 10, 20, 30$ $f = 0.15$ $a_e = 0.40$	MQL vegetable sunflower oil, flow rate = 12.5, 25, 37.5 ml/h	Surface roughness, tool wear.
Thepsonthi et al. [59]	ASSAB DF3 hardened steel Ti-Al-N coated carbide ball end-mill inserts	$V_c = 125, 150, 175$ $f = 0.01, 0.02, 0.03$ $a_e = 0.2$ mm	Pulsed jet MQL, dry, and flooded Pulsing rate = 400 pulse/min, $p = 20$ mPa Flow rate rate = 2 ml/min.	Flank wear, surface texture, cutting zone temperature
Li and Chou [60]	SKD 61 steels Two-flute flat end mills	$V_c = 200, 225, 250$ $f = 0.01, 0.015$ $a_e = 0.03$	Air =25 and 40 l/min $p = 0.5$Mpa flow rate = 1.88, 3.75, and 7.5 ml/h MQL, dry, and near micro-milling.	Tool flank wear, surface roughness.
Silva et al. [61]	Compact graphite cast irons TiN- and TiAlN-coated cemented carbide cutting tools	$V_c = 200$ and 300 $f = 0.1$ and 0.2	Dry and MQL with Vascomil MMS FA 2 fluid Flow rate = 50 ml/h Pressure = 6 bar	Tool life, surface quality, and electric current consumption
Taylor et al. [62]	Tool steel with 53 HRC Coated cemented carbide ball-nose tool	$V_c = 250$ $f = 0.05$ Radial depth = 0.75 Axial depth = 10	MQL and dry Plant oil based cutting fluid	Tool life
Zhang et al. [63]	Inconel 718 Cemented carbide.	$V_c = 55$ $f = 0.1$ Axial depth = 0.5 Radial depth = 1	Dry and MQCL Bescut −173 cutting oil.	Tool wear and cutting temperature.
Wang et al. [66]	Inconel 182, PVD-coated tool inserts.	$V_c = 160$, $f = 0.2$, $a_e = 1$	Dry and MQL Accu-Lube type MQL system, vegetable oil.	Tool wear and microstructures.
Priarone et al. [67]	Titanium aluminides Ti-48Al-2Cr-2Nb Tungsten carbide inserts.	$V_c = 25, 50, 100$ $f = 0.08$ $a_e = 0.3$	Dry, wet and MQL. Aerosol of LB2000 vegetable-based oil, $p = 5.5$ bar	Tool wear and surface roughness
Jang et al. [69]	SM45C structural steel. Two-blade flat-end mill.	$V_c = 1200, 1600, 2300, 3000$ rpm $f = 0.02, 0.03, 0.04$ $a_e = 1.0, 1.5, 2.0$	Dry and MQL machining Vegetable cutting oil, flow rate = 0, 2, 10 ml/min	Various applications for optimization and specific cutting energy.

*Units of cutting speed, V_c = m/min; feed rate, f = mm/rev; depth of cut, a_e = mm

Table 8 MQL in grinding process

Reference/year	Work/tool material	Cutting parameters	Environment/cutting fluid	Parameters evaluated
Da Silva et al. [71]	ABNT 4340 steel Aluminum oxide grinding wheels	$V_S = 30$ m/s $a = 0.1$	Conventional, MQL, and dry grinding LB-1000 lubricant	Surface integrity.
Tawakoli et al. [72]	100Cr6 vitrified bond wheels	$V_C = 1800$ $a_e = 0.03$ $V_{fi} = 3000$ mm/min	Dry, fluid, air jet, Mql supply Syntilo XPS Castrol in a 5% concentration. Flow rate = 100 ml/h	Grinding force and surface quality.
Liao et al. [73]	Ti-6A14V alloy Diamond wheel grinder	$V_C = 1800$ $W_S = 4.2$ m/s $a_e = 0.01$, 0.015, and 0.02	MQL using a mixture of water and Besol 37 cutting oil	Grinding forces and coefficient of friction "lotus effect" of nanoparticles, surface finish.
Sadeghi et al. [74]	AISI- 4140 steel Aluminum oxide grinding wheels.	$V_C = 1800$ $W_S = 10$, 20, 30, 40 $a_e = 0.005$, 0.010, 0.015	Dry, wet and MQL. Vegetable oil, synthetic oil, Behran cutting oil.	Grinding force and surface quality of ground parts.
Qu et al. [75]	Carbon fiber-reinforced ceramic matrix composites Diamond grinding wheel	Flow rate = 40, 60, 80, 100 ml/h and $p = 3$, 5, 7, 9 bar $V_s = 26$ m/s $V_w = 3$ m/min $a_e = 0.03$	Conventional wet, dry, MQL, NMQL. Carbon nanoparticle-based nanofluid and pure fluid were applied in MQL grinding.	Surface roughness/topography, grinding force, sub-surface damages, and grinding debris.
Kalita et al. [76]	Cast iron and EN24 steel vitreous bonded aluminum oxide (Al2O3) grinding wheel	$V_c = 1800$ $a_e = 0.02$ $WS = 0.06$ and 0.1 m/s	MQL using nanolubricants, pure base oils, base oils containing MoS2 base oils containing MoS2 Paraffin oil Soybean oil. Flow rate = 2.5 ml/min	Friction coefficient of grinding, specific energy and grinding ratio.
Balan et al. [79]	Inconel −751 Resin bond diamond wheel	$V_C = 2826$ $W_s = 0.9$ $a_e = 0.03$	MQL grinding Cimtech D14 MQL oil, flow rate = 60, 80, 100 ml/h p = 2, 4, 6 bar	Grinding force, surface roughness and temperature.
Zhang et al. [81]	Steel 45 K-P36 numerical control Precise grinder	$V_c = 1800$ $V_w = 3000$ m/min $a_e = 0.01$	Dry, flood lubrication, MQl and nanoparticle jet. Base oil Liquid paraffin, Palm oil Rapeseed oil Soybean oil (2 wt.% flow rate = 50 ml/h), nozzle distance =12 mm	Coefficient of friction, normal, tangential and axial force, Ra, specific energy.
Setti et al. [82]	Titanium alloy Ti-Ti-6Al-4V Silicon carbide	$V_C = 1020$ $a_e = 0.005$	Dry, wet and MQL with soluble oil Al_2O_3 and CuO nanofluids and water as a base fluid.	Coefficient of friction, ground surface and chip characteristics and chip formation.
Oliveira et al. [85]	AISI 4340 steel Cubic boron nitrite	$V_w = 0.58$ m/s $a_e = 0.012$, 0.025, 0.037	Flood coolant, MQL, MQL accompanied by wheel cleaning	Wheel cleaning, surface roughness, geometric error, microhardness, acoustic emission.
Bianchi et al. [86, 87]	AISI 4340 steel Aluminum oxide grinding wheel	$Vc = 1800$ $V_f = 0.5$ mm/min $V_w = 0.58$ m/s $a_e = 0.012$, 0.025, 0.037	Conventional technique MQL plus WCJ method and conventional MQL method (non-cleaning wheel cleaning way)	Surface finish, geometrical error, wheel wear at diameter, power, microhardness.
Bianchi et al. [88]	AISI 4340 steel Cubic boron nitrite	$Vc = 1800$ $V_f = 0.5$ mm/min $Ws = 0.58$ m/s	MQL	Surface roughness, roundness deviation, diametrical grinding wheel wear, power.
Lopes et al. [89]	Alumina Diamond wheel	$Vc = 1800$ $V_f = 0.5$ mm/min mm/min $n_w = 204$ rpm	Conventional cooling, only-MQL, MQL plus air jet with angles from 0 degrees to 90 degrees	Grinding wheel wear, power, workpiece quality.
Javaroni et al. [90]	Alumina Diamond wheel	$Vc = 1800$ m/s, $V_f = 0.75$, 1, 1.25 mm/min $a_e = 0.1$	Conventional, MQL	Surface finish, dimensional error, G-ratio, and output acoustic emission

*Units of cutting speed, V_c = m/min; feed rate, f = mm/rev; depth of cut, a_e = mm

Table 9 MQL in drilling process

Reference/year	Work/tool material	Cutting parameters	Environment/cutting fluid	Parameters evaluated
Bhowmick et al. [92]	AM60 magnesium alloy HSS twist drill	V_C = 1000, 1500, 2000, 2500 rpm f = 0.10, 0.15, 0.20 and 0.25	Dry, H2O-MQL, FA-MQL flooded	Torque, thrust force, Surface texture and chip morphology.
Rahim and Sasahara [93]	Titanium (Grade 5) Coated carbide drill (TiAlN)	V_C = 60, 80, 100 f = 0.1 and 0.2 d = 14 mm	Dry and MQL Synthetic ester and palm oil.	Surface roughness, tool life, thrust force, torque and work piece temperature, micro-hardness.
Rahim and Sasahara [94]	Inconel 718 Coated carbide (TiAlN)	Vc = 30, 40, 50 f = 0.05 and 0.1. t = 20 mm d = 14 mm	MQL Synthetic ester and palm oil. Flow rate = 103 ml/h	Microhardness, surface roughness, surface defects and sub-surface deformation.
Kuram et al. [95]	AISI 304 stainless steel HSS-E tool	Spindle speed = 320, 420, 520 rpm f = 0.10, 0.12, 0.14 t = 15, 18, 21 mm	MQL with vegetable-based fluids	Thrust measurement and surface roughness.
Biermann et al. [96]	Aluminum cast alloy EN AC-46000 solid carbide tool	V_C = 140, 200 f = 0.1, 0.3	MQL P = 14 bar	Mechanical load, heat load and simulation of deep hole
Chatha et al. [97]	Aluminum 6063 HSS drills bits	V_C = 30, 53.7 f = 60 mm/min t = 20	Dry, flooded, mist cooling, nanoparticle-enriched mist cooling P = 70 psi	Forces, torque, Ra, coefficient of friction, drill wear.

*Units of cutting speed, V_c = m/min; feed rate, f = mm/rev; depth of cut, a_e = mm

Table 10 Literature summary of the thermal conductivity enhancements for various nanofluids (water-based)

References	Nanoadditive type	Nanoadditive diameter (nm)	Volume fraction %	The percentage of thermal conductivity improvement %
Assael et al. [124]	MWCNT	100	0.6	38
Assael et al. [124]	MWCNT	130	0.6	28
Lee et al. [118]	CuO	36	3.4	12
Lee et al. [118]	CuO	23.6	3.5	12
Lee et al. [118]	CuO	23	9.7	34
Lee et al. [118]	CuO	23	4.5	17
Lee et al. [118]	Al_2O_3	33	4.3	15
Lee et al. [118]	Al_2O_3	38.4	4	10
Murshed et al. [125]	TiO_2	15	5	30
Murshed et al. [125]	Cu	100	7.5	78
Murshed et al. [125]	TiO_2	10	5	33
Murshed et al. [125]	TiO_2	10	0.5	8
Masuda et al. [126]	Al_2O_3	13	4.3	30
Masuda et al. [126]	Al_2O_3	13	4.3	30
Masuda et al. [126]	TiO_2	27	4.3	10.8
Masuda et al. [126]	TiO_2	27	3.25	8.4
Liu et al. [127]	Cu	100	0.1	24
Xuan et al. [128]	Cu	100	2.5	22
Li and Peterson [129]	Al2O3	36	10	22
Patel et al. [130]	Au	10	0.026	21
Patel et al. [130]	Ag	60	0.001	17
Patel et al. [130]	Al_2O_3	36	2	15
Xie et al. [131]	Al_2O_3	68	5	21
Xie et al. [131]	Al_2O_3	60.4	5	20
Xie et al. [131]	Sic	26	4.2	16
Xie et al. [131]	Al_2O_3	60.4	1.8	7
Xie et al. [131]	MWCNT	15	1	7
Yu et al. [132]	CuO	28.6	4	14
Yu et al. [132]	Al_2O_3	38.4	4	9
Jana et al. [133]	Al_2O_3	28	3	12
Kang et al. [134]	Ag	15	0.39	11
Wen and Ding [135]	Al_2O_3	42	1.59	10
Chon et al. [136]	Al_2O_3	11	1	9
Chon et al. [136]	Al_2O_3	47	4	8

Table 11 Combined applications of MQL with cryogenic gases and RHVT

Reference/year	Process/work/tool material	Cutting parameters	Environment/cutting fluid	Parameters evaluated
He et al. [157]	Turning, 304 stainless steel, coated carbide tool	$Vc = 43, 75, 108, 160, 217$ m/min $f = 0.12$ mm/rev $ap = 0.4$ mm	Dry Cryo-air (0.4 MPa, − 20 °C) Cryo-MQL(0.4 MPa, − 20°, 30 ml/h)	Tool life and chip morphology
Chetan et al. [158]	Turning Nimonic90, CNMG120408-THM-F uncoated carbide	$Vc = 40, 60, 80$ m/min $f = 0.1$ mm/rev $ap = 1$ mm	Dry MQL Cryogenic	Flank wear and surface finish
Pereira et al. [159]	Milling Inconel 718 ARAF–Ball nose finishing end mill	$Vc = 120$ m/min $ap = 0.2$ mm	Dry, Wet, CO_2 cryogenic, MQL (Vegetal oil, Flow rate = 100 ml/h), CO2 + MQL(100 ml/h) + CO2 (14 bar, −80 °C	Tool life
Pereira et al. [160]	Milling,Inconel 718 ARAF–ball nose finishing end mill	$Vc = 120$ m/min $ap = 0.2$ mm	Cryo-MQL cooling	Flank wear, tool life
Pereira et al. [160]	Milling Ti-6Al-4V R245-12T3M-KM(H13A) Uncoated carbide insert	$Vc = 47, 76, 100, 120$ mm/rev $f = 0.15$ mm/rev $ap = 2$ mm	Dry, MQL, cryogenic, MQL+ cryogenic	Cutting forces, Tool wear, Chip morphology
Zou et al. [162]	Turning 3Cr2NiMo Diamond tool	$Vc = 40$ m/min $f = 0.01$ mm/rev $ap = 1$ mm	CMQL (Cryo MQL)	Tool wear
Shokrani et al. [163]	End milling Ti-6Al-4V Solid coated carbide	$Vc = 60, 90, 120, 150, 180$ m/min $f = 0.03$ mm/tooth $ap = 1$ mm	Dry MQL Cryogenic MQL + cryogenic	Tool wear, Surface roughness
Taha et al. [166]	Turning A36 steel Tungaloy Tnmg 160,408 tmt 9125 coated carbide	$Vc = 160$ m/min $f = 0.10, 0.18, 0.28$ mm/rev $ae = 1–4$ mm	Dry, RHVT	Temperature Tool wear
Mia at al. [167]	Turning AluminumT6 alloy CNMG120404 WIDIA	$Vc = 160, 320$ m/min $f = 0.05, 0.15$ mm/rev $ae = 2$ mm	AC, NGC, NGMQL, RHVT-NGMQ	Surface roughness Tool wear
Alsayyed et al. [168]	Milling, brass	$Vc = 850$ rpm $ae = 0.5$ mm	Dry, conventional coolant, RHVT	Temperature Surface texture
Gupta et al. [169]	Turning HSS, uncoated carbide	$Vc = 355$ rpm	Water, dry, soluble oils, RHVT	Cutting temperature

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