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Research Article

Current research aspects in minimum quantity lubrication for turning operations: Cutting fluid as mono and hybrid nanofluid

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ABSTRACT

The simplest machining method for eliminating undesired material from a workpiece using a single point cutting tool is turning. Appropriate cooling and lubrication save production lead time, machining costs, and environmental impacts controlled by cutting fluids. The impact of cooling cum lubrication techniques, such as minimum quantity lubrication with typical cutting fluids, minimum quantity lubrication with nanofluids, and minimum quantity lubrication with hybrid nanofluids, on turning performance metrics were thoroughly reviewed. The effect of these cooling solutions on results, such as cutting temperature, cutting force, surface roughness, tool wear, and chip morphology, has been extensively reviewed and addressed in the literature. Moreover, the nanoparticle types, size, concentration, base fluid types, and lubrication for nanofluid and hybrid nanofluids with minimum quantity lubrication have been considered during the study. The review of the relevant literature indicates that outcomes are significant. The impact of these cooling solutions on cutting temperature, cutting force, surface roughness, tool wear, and chip morphology has been thoroughly examined and addressed in the literature. The review of relevant literature indicates that outcomes are significantly improved when minimum quantity lubrication with nanofluids and hybrid nanofluids is contrasted with alternative cooling techniques. It is possible to reduce substantially pressures, cutting temperatures, surface roughness, and tool wear. Different kinds of nanoparticles, particle size, concentration, and nozzle inclination angle are the most critical factors in optimizing heat transfer rate and minimizing tool wear. Aluminium oxide (Al_2O_3) is the most commonly used nanoparticle in minimum quantity lubrication applications involving nanofluids and hybrid applications because it forms a coating between the workpiece and cutting tool contact, reducing friction. Additionally, the coefficient of friction significantly slowed. In addition, the minimum quantity lubrication with nanofluids also improves the colour and shape of the chip's morphology.

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INTRODUCTION

During each machining operation, heat is generated at the point of contact between the cutting tool and the workpiece, drastically lowering the tool›s service life and production rate. It increases cutting temperature and surface quality (roughness), and these are both undesirable in a production machining environment. The most straightforward and most popular cutting technique for removing unwanted material from a workpiece is turning, which is done with a conventional single-point cutting tool. It involves several machining processes, such as milling, grinding, and drilling. Cutting fluids are crucial for their ability to cool the interface between the cutting tool and the workpiece, remove chips, and lubricate. Dry or wet/flooded cooling methods are used, although dry cooling creates more heat than flooded cooling due to more friction. Using a blend of compressed air and standard cutting fluids, minimum quantity lubricant reduces the amount of coolant used compared to flood cooling [1].

Minimum Quantity Lubrication

The traditional coolant application system for turning operations is a flood-type system. The workpiece-cutting tool interface zone involves a substantial amount of cutting fluid jet; therefore, it is not economical, safe, or ecologically friendly. In addition, the accessibility of cutting fluid within the cutting zone is a concern. The flood cooling constraints could be circumvented by replacing the cutting fluid with wet machining or dry machining [2]. A novel, economical, and practical approach to minimum quantity lubrication machining technology is created to eliminate the issues above, produced using conventional cutting fluid in the metal industry [3]. The alternative strategy of mist lubrication, where an air and cutting fluid mixture is supplied to the cutting zone and has greater accessibility due to the high pressure, has proven to be a superior option based on the availability of coolant system applications [4]. The nozzle was employed to mix the lubricant/coolant with oil, generally known as an aerosol. To achieve better cooling results, spray the aerosol in the cutting zone at high pressure [5].

Minimum quantity lubrication combines compressed air and the minor oil in thin drops, generating a spray on the workpiece-tool cutting zone [6]. The oil flow rate in these systems is in the lower range, which is in contrast to the type of lubrication and cooling systems that are typically used. A typical lubricating system with a minimum quantity, as shown in Figure 1, consists of a pump, a fluid reservoir, an air-oil mixing unit, a compressor, and a nozzle, in addition to pipelines that connect all of the components. [7].

Minimum quantity lubrication cooling/lubrication systems are classified into two types: external and internal [1]. In Figure 2, It is illustrated here that a schematic diagram of the two ways that were discussed earlier is shown. The external minimum quantity lubrication method involves spraying an aerosol through an external nozzle. This method is being investigated by a number of researchers for its potential to improve turning operation. The atomization process generates aerosol, transforming the air and liquid mixture into mist or spray.

Several researchers have reported on the internal minimum quantity lubrication system, which uses aerosol supplied through an internal passage [9], [10]. There are two techniques to prepare aerosol: (i) external and (ii) internal. The aerosol was prepared externally and fed through internal channels in the cutting tool, referred to as external. The internal atomizer in a spindle mixes a mixture first, and secondly, it is supplied via an internal channel in the cutting tool, referred to as internal. The common machining processes mainly used by minimum quantity lubrication are turning, drilling, milling, grinding, and electro-discharge machining (EDM).

Nano Cutting Fluids

The heat is generated during the machining process due to friction in between cutting tool and workpiece. This heat

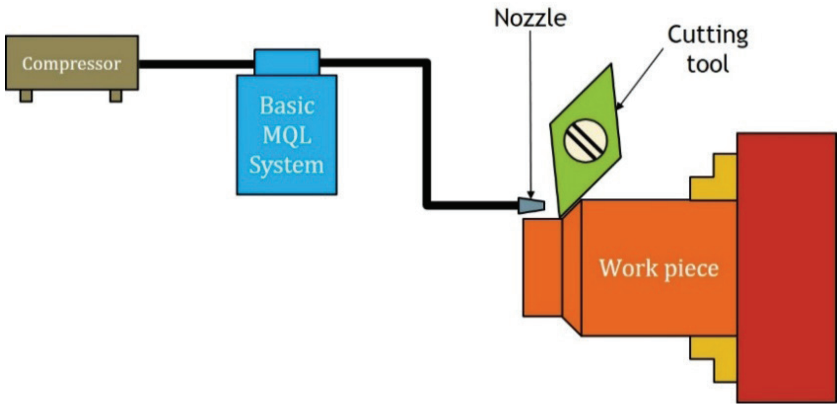

Figure 1. Typical arrangement of turning operation with a minimum quantity lubrication system.

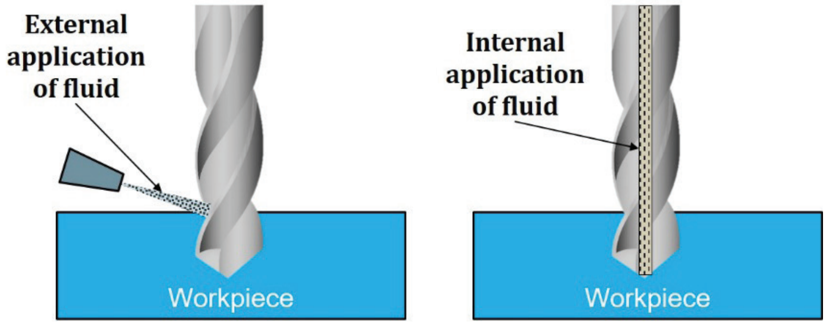

Figure 2. (a) External minimum quantity lubrication and (b) Internal minimum quantity lubrication cooling/lubrication technique [From Okokpujie et al. [8], with permission from from Elsevier.]

is undesirable as it retards cutting tool life and workpiece surface quality. Conventional cutting fluids with cooling and lubrication properties can reduce both heat and friction. Liquids separate surfaces by generating a layer, which reduces frictional resistance, and cooling capability assits to control the heat generation of the cutting tool, chip, and workpiece [11]. However, the application and disposal of these materials have detrimental consequences on personal health and the environment [12]. Nanofluid is a mixture of metal and non-metal nanoparticles (< 100 nm) in usually used cutting fluids [13]. The various shapes, such as cylindrical and spherical nanoparticles are produced from the pure metals (Au, Ag, Fe, Cu), metal oxides (Al_2O_3, CuO, Fe_2O_3, Fe_3O_4, MgO, SiO_2, TiO_2, ZnO), carbides (SiC, TiC), nitrides (AlN, SiN), and various kinds of carbon (graphite, diamond, single or multi-wall carbon nanotubes (MWCNT)) are combined with varying concentrations of base fluids: water, cutting oil, and vegetable oil [14].

Hybrid Nano-Cutting Fluids

Heat transfer between the workpiece-cutting tool interface affects cutting temperature, tool wear, and, consequently, tool life. Mono nanofluids are single-component nanofluids that have been examined for their enormous potential to retard machining output parameters. In addition, growth in nanofluid-based cutting fluids has been hampered by the enhanced demand for more excellent heat transfer capabilities of nanofluids. The creation of hybrid nanolfluids are achieved by combining several nanoparticles in varying proportions with a base fluid. Recent breakthroughs in nanotechnology employ hybrid nanofluids to resolve nanoparticle thermal conductivity and stability concerns [15].

The arrangement of information in the article is sequenced by (i) begins with an introduction, then moves on (ii) to separate headings discussing minimum quantity lubrication plus conventional cutting fluids (CFsMQL), minimum quantity lubrication plus nano cutting fluids (NFsMQL), and (iii) minimum quantity lubrication plus hybrid nano cutting fluids, and (iv) the impacts of various machining input parameters on cutting forces, cutting temperature, chip morphology, and surface roughness. It concludes by discussing the impacts of main input turning parameters on cutting temperatures, cutting forces, and surface roughness.

Nanofluids are a relatively recent practice that enhances machining efficiency and productivity. Varied types of nanofluids have a broad scope of applications in different kinds of machining operations to cool down and lubricate the heat-affected zone in machining. Numerous researchers have carried out experimental work & analysis on the application of different kinds of nano-fluids as a main cutting fluid in lathe, milling, and grinding processes using dry, wet, or minimum quantity lubrication methods and with different tool material, workpiece material, and machining parameters.

There are only a handful of studies that have been published in the academic literature that discuss the impact of various hybrid nanofluids, particularly the combination of Al_2O_3, Cu, CuO, ZnO, TiO_2, CNT, and MWCNT as a cutting fluid application in turning operations. For the purpose of utilizing the various cutting fluid combinations, it is necessary to make use of effective parameters such as surface roughness, cutting temperature, and cutting force as minimum quantity lubrication. An investigation into the similarities and differences between a number of cutting fluids, including conventional fluid, nanofluid, and hybrid nanofluid, has been carried out. Workpiece material, cutting tool material, and cutting fluids are all variables that are taken into consideration as effective parameters in this review process. Tabular representations have been used to summarize the most important findings. This article presents a statistical analysis and critique of the work, as well as future scope, economy, sensitivity analysis, and constraints. Additionally, the paper describes their shortcomings.

LITERATURE RELATED TO WORKING MEDIUM

MQL with Conventional Cutting Fluids

Dhar et al. [16] experimentally investigated that minimum quantity lubrication was turning retard cutting temperature, surface roughness and tool wear in contrast to the dry & wet cooling environment in turning AISI-4340 steel. Scanning Electron Microscopy) SEM views of the cutting tool showed retardation in the notch growth and wore on the cutting edge. Dhar et al. [17] experimentally studied the impact of minimum quantity lubrication in machining AISI-1040 steel. The retardation in cutting temperature, good form, the colour of steel chips, and improvement in dimensional accuracy was obtained.

Bruni et al. [18] studied the impacts of wet, minimum quantity lubrication, and dry environments in turning AISI 420B stainless steel with both usual and inserts by wiper technology in turning machines equipped with a bed made of cast iron and polymer concrete. They conclude that the cooling environment does not impact tool wear. Dhar et al. [19,20] studied the operational performance of turning AISI-1040 steel using minimum quantity lubrication to dry lubricant. With the application of minimum quantity lubrication, results revealed that retardation of 5-15% in cutting force, enhancement in surface finish, and accuracy of dimensional parameter due to less flank wear and sizeable retardation in cutting temperature.

Davim et al. [20] experimentally turned commercial brass on CNC to compare the minimum quantity lubrication and wet lubricant system. They concluded that both lubricant systems had less variation in cutting power. The lowest cutting force at a rate of 200 m/min, surface roughness enhanced with an enhancement in feed rate and retardation with lubricant. Khan et al. [21] experimentally analyzed the effects of minimum quantity lubrication by vegetable oil on AISI 9310 alloy steel turning. In contrast to wet machining, they revealed a 10% variation in the temperature of the chip-tool interface, and the rear surfaces of chips generated with minimum quantity lubrication machining were better and smoother. Additionally, minimum quantity lubrication machining has been proven to prolong tool life and defer tool wear significantly.

Hwang et al.[22] studied minimum quantity lubrication and wet machining of AISI 1045 steel with an experimental plan designed by fractional factorial design, i.e., selection of significant factor with MINITAB, and central composite structure, i.e., finding of optimal level with Response Surface Methodology (RSM). It was found that experimental equations suggested by RSM validated cutting force in both lubricant machining but not for surface roughness. Leppert [23] studied the impacts of dry and minimum quantity lubrication cutting over conventional emulsion cooling in turning, while AISI 1045 steel was utilized as workpiece material. They concluded that a rise in cutting force in the absence or retardation of cutting fluid happened at a low feed rate. Significant results were obtained regarding surface roughness, surface topography, profile bearing ratio, and waviness with minimum quantity lubrication machining. Also, feed rate has a considerable influence on output machining parameters.

Che Haron et al. [24] studied the impacts of machining parameters on the surface entirety of Inconel 718. The RSM design of the experiment for a combination of surface roughness, microstructure, surface topography, and microhardness utilized the box-Behnken method. The surface roughness value found ranged from 0.4 to 2.9 meters. According to the ANOVA analysis, feed rate significantly impacted surface roughness. Leppert [25] experimentally looked into the impact of lubrication and cooling modes on the tool›s surface texture, cutting force, and topography of AISI 316L steel. Turning tests were performed in a variety of conditions, including dry (D), minimum quantity lubrication, and emulsion (E). The overall maximum (force F = 458 N) when the cutting interface zone was cooled in (E) lubrication scenario and the least (force F = 312 N) with (D), and minimum quantity lubrication had no significant effect on cutting force. In addition, it had been shown that minimum quantity lubrication at low value of machine feed rates and the employed cutting speeds led to retardation in surface roughness range from 1.34 to 1.50 μm in contrast to dry machining range from 1.54 to 1.82 μm and emulsion range from 1.68 to 2.26 μm. Analysis of surface topography using SEM images has also demonstrated a positive impact of the minimum quantity lubrication approach on conditions of surface quality.

Lohar [26] investigated the effects of wet and dry turning machining over minimum quantity lubrication when using the CBL tool to turn hardened alloy steel AISI 4340. When employing minimum quantity lubrication instead of dry and wet machining, Taguchi›s design and analysis of response factors led to a reduction of 40% in cutting force, a reduction of 36% in cutting temperature, and an improvement of 30% in surface finish. Hadad et al. [27] examined experimentally how machining forces, temperature, and surface roughness are affected by minimum quantity lubrication, nozzle position, and cutting parameters when turning AISI 4140 steel alloy. It is founded on results that nozzle position significantly affects low cutting temperature and retardation of cutting force in minimum quantity lubrication. Also, a temperature model was developed with a heat source and hind sink mechanism for machining plus minimum quantity lubrication, and this model confirmed the validity with experimental results.

Saini et al. [28] investigated how machining parameters affected the cutting forces and tool tip temperature when turning AISI 4340 steel with carbide inserts coated with PVD and CVD. The study was carried out to examine the impact of machine cutting speed, feed rate, and approach angle on temperature changes and the three cutting force components; experiments were devised so that machine cutting speed, feed rate, and approach angle were adjusted to four levels. In contrast, the depth of the cut remains constant. In terms of cutting force and temperature, PVD-coated carbide inserts outperformed CVD-coated carbide inserts. Agrawal et al. [29] experimentally evaluated the effects of aloe vera oil and servo cut s oil in machining M2 steel. Results were obtained after using Taguchi's design method as a design of experiments strategy, and it was found that surface roughness was retard by a value of 6.7%, and tool wear was retard by a value of 0.14% with aloe vera oil compared to conventional oil. Gordana et al. [30] compared previous literature on the impact of minimum quantity lubrication in turning carbon steel C45E with higher feed and cutting speed. Comparing minimum quantity lubrication to standard lubrication, the cutting force, tool wear, and surface roughness were typically found to be more favourable with minimum quantity lubrication lubrication, which was also cost-effective and environmentally benign.

Liu et al. [31] presented a more flexible Coupling Response Surface Methodology (CRSM) under minimum quantity lubrication conditions in machining very hard material titanium alloy with input factors like cutting speed, feed rate, and depth of cut. The Taguchi experimental design was employed with output parameters like machine processing efficiency, machine cutting force, and surface quality. Using ANOVA, the analysis found that feed rate was the primary factor affecting cutting force and surface quality. Additionally, it showed that these parameters had the minimum values at the least depth of cut, the least feed rate, and the highest cutting speed. New developed CRSM method found close agreement with the performed experimental value.

Masoudi et al. [32], experimentally in the machining of AISI 1050 steel, studied the impact of nozzle position (at a flank face, rake face, and both faces) with minimum quantity lubrication and studied hardness of workpiece, machining conditions, and types of tool each with four levels. It is predicated on improved cutting force reduction, rake face surface roughness, and optimal nozzle and tool wear rate reductions that are markedly accelerated by increased workpiece hardness. Sivaiah et al. [33] performed turning of Inconel 718 material, a hybrid textured tool (circular pitting holes) with minimum quantity lubrication declined cutting temperature, tool flank wear, and surface finish roughness by 36%, 59%, and 46%, respectively, contrasted to an untextured tool with minimum quantity lubrication environment.

Sivaiah et al. [34] investigated the cooling strategies for minimum quantity lubrication + textured tool and minimum quantity lubrication + untextured tool when turning AISI 52100 steel. They found the retardation in surface roughness, flank wear, and cutting junction temperature to be 42%, 40%, and 25%, respectively.

Singh et al. [35] investigated the effect of cutting parameters on the performance of turning Hastelloy C-276 in a vegetable oil minimum quantity lubrication environment using a CNMG120408 insert. With the developed RSM-based Central Composite Design (CCD) model, the optimal cutting temperature, surface roughness, and chip retardation coefficient were discovered in this setting as the optimal parameters.

Bhadoria et al. [36] studied the impact of the minimum quantity lubrication environment with ceramic insert in turning EN31 steel. The minimum quantity lubrication + ceramic insert condition helped produce the most petite surface roughness and lower flank wear. In addition, they demonstrated that high-speed cutting and feeding are feasible, enhancing production without sacrificing surface quality.

Sivaiah et al. [37] studied improved performance in machining AISI 304 steel with a circular micro pit textured tungsten carbide tool with minimum quantity lubrication. A new weighted gray relation analysis model was proposed for best-fit parameters. This cooling environment led to a 54 % decrease in surface roughness, a 7% decrease in tool wear, and a 27% enhancement in material removal rate.

It has been stated that a comparative analysis of the research works linked with minimum quantity lubrication using conventional cutting fluid has been carried out. This study was based on the material of the workpiece, the material of the cutting tool, the different types of cutting fluids, the mode of lubrication, and critical observations in Table 1.

Table 1. Comparative analysis of studies related to minimum quantity lubrication that use traditional cutting fluid

Researchers	Workpiece material	Cutting tool material	Types of cutting Fluids	Lubrication method	Findings	Year
Dhar et al. [16]	AISI-4340 steel	Carbide SNMM 120408	NM	minimum quantity lubrication, dry, wet	Retard CT, TW, and SR. Shown retardation in dimensional deviation.	2006
Dhar et al. [17]	AISI-4340 steel	Carbide SNMM 120408	NM	minimum quantity lubrication, dry, wet	Retard SR and TW. Shown retardation in dimensional deviation.	2006

Table 1. Comparative analysis of studies related to minimum quantity lubrication that use traditional cutting fluid (continued)

Researchers	Workpiece material	Cutting tool material	Types of cutting Fluids	Lubrication method	Findings	Year
Bruni et al. [18]	AISI 420B steel	CVD-coated carbide	Vegetable oil	minimum quantity lubrication, dry, wet	minimum quantity lubrication could not have a significant advantage over dry machining for TW and SR.	2006
Dhar et al. [19]	AISI-1040 steel	Carbide SNMM 120408	Mobil Cut-102	minimum quantity lubrication, dry	Retard CF by 5-15%, and CT. Retardation in SR, TW, and dimensional deviation was obtained.	2007
Davim et al. [20]	Commercial brass (CuZn39Pb3)	K10 inserts CC650 WG	Emulsion oil Microtrend 231L	minimum quantity lubrication, wet	Results showed a slight variation in SR and CP for a given lubrication mode.	2007
Khan et al. [21]	AISI 9310 alloy steel	Uncoated carbide SNMG 120408	Vegetable oil	minimum quantity lubrication, dry, wet	Retard CT by 10%, and CT. Retarded the SR and TW and eliminated built-up edge.	2009
Hwang, and Lee [22]	AISI 1045 steel	CNMG 120404 FG	NM	minimum quantity lubrication, wet	Regarding SR and CF, minimum quantity lubrication has more advantages than wet turning.	2010
Leppert [23]	AISI 1045 steel	MSS 2525–12-EB	Biodegradable vegetable oil	minimum quantity lubrication, dry, emulsion	Improved outcomes for SR and CF. Satisfactory results concerning ST.	2011
Che Haron et al. [24]	Inconel 718	CNMG 12 04 08-QM	NM	minimum quantity lubrication	FR showed a significant effect on SR, as supported by ANOVA.	2011
Leppert [25]	AISI. 316L stainless steel	Carbide SNMG 120408-TF	Accu-Lube LB 8000 oil	minimum quantity lubrication, dry, emulsion	minimum quantity lubrication won't impact CF as much as dry and wet machining. Reduce the SR and build-up edge.	2012
Lohar, and Nanavaty [26]	AISI 4340 steel	CBN TNMA 160404 PB250	Cutting oil	minimum quantity lubrication, dry, wet	Retard CF by 40%, CT by 36%, and SR by 30%.	2013
Hadad, and Sadeghi [27]	AISI 4140 steel	HSS tool steel	Ester oil (RS 1642)	minimum quantity lubrication, dry, wet	Retard CT, CF, and SR. It showed that the minimum quantity lubrication nozzle position has influenced CT and SR.	2013
Gordana et al. [30]	Carbon steel C45E	Carbide SNMG 1204 08 NMX	NM	minimum quantity lubrication, wet	minimum quantity lubrication is an excellent alternative to wet lubrication in CF, TW, and SR. Better results were obtained in machining cost and ecology when minimum quantity lubrication was used.	2013
Liu et al. [31]	Ti-6Al-4V alloy	Coated tungsten carbide	Vegetable oil	minimum quantity lubrication, dry, wet	Shown enhancement in CS and DC leads to the rise in CF. SR was affected mainly due to CS.	2013
Saini et al. [28]	AISI 4340 steel	Coated carbide (PVD and CVD coated)	Soluble cutting oil	minimum quantity lubrication, dry	Compared to CVD-coated inserts, better results were shown in PVD-coated inserts in CF and CT. minimum quantity lubrication improved performance in CVD-coated inserts for CF and PVD-coated inserts for CT.	2014

Table 1. Comparative analysis of studies related to minimum quantity lubrication that use traditional cutting fluid (continued)

Researchers	Workpiece material	Cutting tool material	Types of cutting Fluids	Lubrication method	Findings	Year
Masoudi et al. [32]	AISI 1050 steel	HSS and Tungsten carbide	Ester oil	minimum quantity lubrication, dry, wet	minimum quantity lubrication had significantly retard CF, SR, and TW. minimum quantity lubrication›s nozzle position produced superior outcomes at the rake face as opposed to the flank face.	2017
Agrawal, and Patil [29]	M2 steel	Carbide TNMG	Aloe vera oil, and Servo cut S oil	minimum quantity lubrication.	Lowered SR by 6.7% compared to servo cut S oil cutting fluid, and SR decreased as CS enhanced. TW lowered by 0.14% in aloe vera oil cutting fluid.	2018
Sivaiah et al. [33]	Inconel 718	Tungsten carbide (PVD coated)	Emulsion based flood	minimum quantity lubrication	minimum quantity lubrication with the hybrid textured tool decreased CT, TW, and SR by 36%, 59%, and 46% compared to the untextured device.	2019
Sivaiah et al. [34]	AISI 52100 steel	Tungsten carbide	Emulsion based flood	minimum quantity lubrication, wet	minimum quantity lubrication + textured tool cooling strategy showed retardation in CT, TW, and SR compared to minimum quantity lubrication + untextured tool. minimum quantity lubrication technique uses less fluid consumption than conventional cooling and is more environmentally friendly.	2020
Singh et al. [35]	Hastelloy C-276	CNMG uncoated	Vegetable oil	minimum quantity lubrication, wet, dry	Less CT, SR, and lower chip retardation coefficient were achieved with minimum quantity lubrication. An optimum parameter value was also found from the developed RSM-based CCD model.	2021
Bhadoria, and Bartarya [36]	EN31 steel	Uncoated ceramic insert	Servocut s	minimum quantity lubrication, dry	The most negligible value of SR and lower TW was found in the minimum quantity lubrication environment. minimum quantity lubrication revealed that high speed and feed working without compromising surface quality are indicators of better productivity than dry machining.	2021
Sivaiah et al. [37]	AISI 304	Tungsten carbide coated	Emulsion based flood	minimum quantity lubrication.	A new weighted gray rational model was developed for parameter fitment. Retardation in TW, SR and significant improvement in material removal rate was obtained.	2021

The concise published review articles relate to minimum-quantity lubrication with conventional cutting fluids [4], [5], [38]. The effects of minimum-quantity lubrication, in contrast to dry and flooded cooling methods, in the primary machining processes of turning, drilling, grinding, and milling are the subject of important reviews.

MQL with Nanofluids (MQLNFs)

Krishna et al. [39] investigated experimentally turning AISI 1040 steel using nano boric acid (50 nm) lubricant suspensions in base oils such as SAE-40 and coconut oil. Nanofluid was prepared with different weight propositions at room temperature and mixed with a sonicator for one hour. The impacts of variations in machine cutting temperature, surface roughness, and average tool flank were studied. Rao et al. [40] investigated how cutting tool-workpiece cutting pressures, cutting temperatures, sample surface quality, and tool wear were affected by Carbon Nanotube (CNT) nanofluid when turning AISI 1040 steel. It was found in the results that the above parameters had a good effect, up to 2% CNT inclusion. Vasu et al. [41] investigated experimentally how various conditions—dry, minimum quantity lubrication, and minimum quantity lubrication + Al_2O_3 nanoparticles—affect temperature dissipation, cutting force, tool wear, and surface roughness when turning Inconel 600 alloy. Taguchi method was used for experiments design with input machining parameters and S/N ratios for different environmental conditions, i.e., dry, minimum quantity lubrication, minimum quantity lubrication with 4v% of Al_2O_3 nanoparticles, and minimum quantity lubrication with 6v% of Al_2O_3 nanoparticles.

Khandekar et al. [42] studied the impact of nanofluid as a cutting fluid, prepared by adding 1wt% Al_2O_3 nanoparticles fluid on wear, cutting force, workpiece surface roughness, and chip thickness in turning of AISI 4340. Comparative studies of tools amid dry cutting, conventional cutting fluid, and nanofluid as a cutting fluid were studied. From experimental data, it was found that retardation of 50% and 30% in cutting force retardation in surface roughness by 54.5% and 28.5%, respectively. Amrita et al. [43] studied mist using nanographite (80 nm) when turning AISI 1040 steel with cemented carbide and HSS; soluble oil was tested in lubricating circumstances such as dry, flood, and mist without nanographite. The results showed significant retardation in tool wear and cutting forces with both cutting tools compared to dry and flood lubrication conditions. Furthermore, the findings of the experiment showed that using 0.5 weight per cent nano graphite with soluble oil and both cemented carbide and HSS cutting tools resulted in the least amount of cutting forces and tool wear at a flow rate value of 15 ml/min. Amrita et al. [44] studied the usage of Graphite (80 nm), boric acid (100 nm), and MoS_2 (100 nm) nanoparticles in base fluid as emulsifier oil with minimum quantity lubrication in turning of AISI 1040 steel. The stability of nanofluids containing 0.3 wt % nanoparticles was evaluated, and these cutting fluids were administered at 10 ml/min.

Sayuti et al. [45], examined experimentally how SiO_2 nano lubricants with minimum quantity lubrication affected the AISI 4140 workpiece›s machining. To make sure the SiO_2 particles were uniformly suspended, the mixture was sonified for 48 hours at 240 W, 40 kHz, and 500 W after adding an average of 5–10 nm-sized particles to mineral oil. The experimental design was based on the Taguchi design (L16 orthogonal array). The fuzzy model was trained to determine the association between the output parameters (surface roughness and tool wear) and the input parameters (nano lubrication fraction, air pressure, and nozzle angle). A 60° nozzle tilt, a 2 bar air stream pressure, and a 0.5% weight concentration of nanoparticles in the mineral oil produced the least degree of tool wear. On the other hand, surface quality was improved by a 30° nozzle orientation angle, low air stream pressure, and 0.5 weight per cent nanoparticles in the mineral oil. Shabgard et al. [46] studied the impact of base fluid, a soluble cutting fluid, and CuO nanoparticles on cutting force and surface roughness when turning AISI 4340 steel. For contrasting nanofluid with soluble and dry cutting fluids, tests were conducted. The findings show that adding a 1 wt% fraction of CuO nanoparticle as soluble oil to the base fluid lessens machining cutting force and surface roughness. Furthermore, CuO nanofluid drastically reduces surface quality and machining cutting force by 49% and 24%, respectively. Khalil et al. [47] investigated the impact of Al_2O_3 on tool wear using AISI 10150 mild steel as the workpiece and SDBS + minimum quantity lubrication as the cutting fluid. It is resulted that tool wear got retarded, and enhancement of tool life.

Sharma et al. [48] performed experimentation with the MWCNT's effect on AISI D2 steel spinning at different speeds. MINITAB tests were designed using Taguchi's method. NFminimum quantity lubrication is superior to traditional minimum quantity lubrication in surface quality and cutting junction temperature. Sharma et al. [49] and [50] investigated how minimum quantity lubrication affected the machining of AISI 1040 steel using TiO_2 and Al_2O_3 nanoparticles distributed in a base fluid as a vegetable oil + water emulsion. It resulted that with comparison to dry, mist, and wet machining, nanofluid machining resulted in considerable retardation in surface roughness and tool wear, as well as betterment in chip quality (silver-coloured chips with a curl and segmented morphology). Gupta et al. [51] investigated experimentally the effects of cutting fluid with minimum quantity lubrication on Al_2O_3 (40 nm), MoS_2 (40 nm), and graphite (40 nm) nanoparticles. For Titanium (grade-2) alloy turning, the following factors were selected: machining cutting force, cutting temperature, tool wear, and surface finish. RSM and combined goal functions were utilized to create experiments. Particle Swarm Optimization (PSO) and Bacterial Forging Optimization (BFO) approaches produced superior experimental outcomes, while graphite-based nanofluids were adjusted to decrease output responses.

Paturi et al. [52] demonstrated experimentally the impact of Tungsten disulfide WS_2 as a solid lubricant in turning Inconel 718. Nanofluid for minimum quantity lubrication applications was created by adding nano additives in emulsifier oil at a fraction of 0.05wt%. Multi-liner models were developed and validated using a correlation between cutting parameters. Compared to conventional minimum quantity lubrication machining, nanofluid-based minimum quantity lubrication machining retard surface roughness by an average of 35%. Rapeti et al. [53] applied based fluids such as coconut oil, canola oil, and sesame oil with nano-cutting fluids containing MoS_2 nanoparticles to AISI 1040 steel turning. Experiment design, lubricant, nanoparticle additions, and cutting velocity were optimized using Taguchi's L27 orthogonal array. For statistical analysis, they considered feed rate to be four separate variables, each with three distinct values. In addition, Grey Relational Analysis, which has its roots in the work of Taguchi, was applied to achieve multi-objective optimization. Coconut oil + 0.5% nano MoS_2 improved machining performance at the value of 40 m/min machine cutting speed and a 0.14 mm/rev machine feed rate. A cost estimate of its application further assessed nano-cutting fluids› industrial viability.

Patole et al. [54] experimentally studied the machining parameters optimization in minimum quantity lubrication using nanofluids suspended with MWCNT (15 nm) for turning of AISI 4340 steel workpiece. Experiments involving cutting technique and machining surface roughness are examined using Grey Relational Grade as a response variable. The optimal conditions for the response variable›s value were ascertained by the application of Grey Rational Analysis (GRA). Also, the S/N ratio of GRA yielded excellent results; therefore, the ANOVA findings nearly matched GRA. In addition, a comparison investigation revealed a superior surface roughness in minimum quantity lubrication, including nanoparticles of MWCNT and base fluid ethylene. Singh et al. [55] investigated practically the turning of AISI 304 steel using minimum quantity lubrication and a nanofluid made by mixing Servo Cut base oil with graphene nanoplatelets. RSM was utilized to plan the trials, and testing was done by choosing the orthogonal array L27. ANOVA showed that the concentration of graphene nanoparticles was essential for reducing cutting temperature and surface roughness at higher feed rates and machining cutting speeds.

Joshi et al. [56] experimentally studied the impact of minimum quantity lubrication, dry machining, and minimum quantity lubrication with nanofluid (Al_2O_3 + vegetable oil as base fluid) on the Inconel 600 work material›s surface roughness during a turning operation. They eventually reached the point where a predictive model had been built for it. The results demonstrated that using nanofluid improved the surface quality when compared to machining done under dry machining and minimum quantity lubrication settings. When it came to evaluating surface roughness, Taguchi›s method worked effectively in this investigation. Vishnu et al. [57] experimentally studied a comparison of EN 353 Steel Alloy turning under dry cutting, flooded cutting, and minimum quantity lubrication circumstances. Al_2O_3 nanoparticles were combined with water and stabilizers to produce nanofluids. For the experiment design, the Taguchi method was utilized. Comparisons were made between the dry cutting, flooded cutting, and minimum quantity lubrication conditions; minimum quantity lubrication in machining is a cost-effective, environmentally friendly, and human health-friendly option to complete dry cutting and flood lubricating conditions. It was observed that machining under flooded conditions is superior to dry and minimum quantity lubrication conditions, while the difference between minimum quantity lubrication and flooded conditions is negligible. It was also determined that the impact of lubrication conditions on cutting temperature is more significant than that of tool type, depth of cut, feed rate, and cutting speed.

Pasam et al. [58], experimentally studied developing and testing vegetable oil as a based fluid with micro and nano cutting fluids for turning of AISI 1040 steel in minimum quantity lubrication. Both boric acid (100 nm) and MoS_2 (90 nm) were dispersed in a base fluid as coconut oil. Nanofluids were superior to microfluidics at high cutting rates, but both performed similarly at lower speeds. Furthermore, MoS2 was more effective than boric acid. Ganesan et al. [59] experimentally examined the impacts of nanofluid with copper (50 nm) suspension-based minimum quantity lubrication under dry and wet conditions on H 11 steel turning. Taguchi L18 orthogonal array was used to create experiments, and RSM was utilized to determine the optimal value and mathematical model. Results demonstrated a 66% retardation in tool wear and a 40% retardation in surface roughness. The SEM examination of chip morphology revealed a modest number of notched teeth.

Padmini et al. [60] focused on the performance testing of Molybdenum disulfide-based nanofluids with various nanoparticle inclusions in vegetable oils (coconut, sesame, and canola) as a base fluid for machining AISI 1040 steel in a minimum quantity lubrication environment. Consequently, adding the element of nanoparticles enhances essential nanofluid properties. Cutting temperature, tool wear, cutting force, and surface roughness significantly decreased while 0.5% MoS_2 was blended into coconut, confirming better performance compared to additional lubricating strategies. Sharma et al. [61] studied various concentrations of SiO_2 nanoparticles in vegetable oil and water emulsion base fluid to affect the turning operation of AISI 1040 steel. Dry and minimum quantity lubrication machining procedures were tested in a variety of experiments. It has been demonstrated that dry machining and nanofluid + minimum quantity lubrication reduce cutting force compared to operation in conventional cutting fluids. Furthermore, nanofluid + minimum quantity lubrication retards surface roughness comparable to wet, traditional cutting fluid, and dry machining conditions. Sivalingam et al. [62] improved the machinability of Inconel 718 with a dry and atomized spray cooling environment. In spray cutting fluid was prepared by mixing graphite and molybdenum disulfide in vegetable oil, and experimentation revealed a 17-34% betterment in surface roughness, a decrease in tool wear, an enhancement in tool life, and retardation in machining costs compared to a dry cooling environment.

Das et al. [63] studied how nanofluids like zinc, copper, iron, and aluminium oxide affect turning machining parameters for AISI 4340. Different fluid characteristics were examined. After experiments with minimum quantity lubrication, Al_2O_3 nanofluid was found to have the highest force value, while CuO nanofluid had the lowest force value. After being treated with CuO nanofluid, the flank area saw the least amount of significant wear in tool and the smoothest surface roughness rating. Venkatesan et al. [64] examined the comparative and performance analysis of hard-to-cut material Hastelloy between dry and minimum quantity lubrication cooling conditions with Physical Vapour Deposition (PWD) and Chemical Vapour Deposition (CVD) coated Tools. In coconut oil as a base fluid, amounts of 0.25 wt% and 0.5 wt% of Hexagonal Boren Nitride (hBN) nanoparticles were added for this study. Ramanan et al. [65] designed an experiment to determine the effect of Al_2O_3 nanofluid with minimum quantity lubrication on the turning of Incoloy 800. Results showed that adding 1 % Al_2O_3 improved the wettability of the cutting fluid, decrement in the cutting force, reduced the surface roughness to a negligible value, and slowed the pace at which the tool wore out in the cradle.

Nikouei et al. [66] experimented with the impact of residual stress on turning the Inconel 718 with different nanoparticle sizes, materials, base fluid, and content. It was founded on a result that TiO_2 nanoparticle-induced fluid machining decreased residual stress from 20.03 % to 11.44 %. For the purpose of providing a comprehensive review of the research works associated with minimum quantity lubrication that contains nanofluid, taking into consideration the materials of the workpiece, the materials of the cutting tool, nanoparticles, size, form, base fluid, and the findings that are compacted with Table 2.

Table 2. Comprehensive overview of the works connected to minimum quantity lubrication that contains nanofluid

Researchers	Workpiece material	Cutting tool material	Nanoparticles types and their size (nm)	Types of base Fluid	Findings	Year
Krishna et al. [39]	AISI 1040 steel	Carbide SNMG 120408	Nanoboric acid (50)	SAE-40 oil and coconut oil	Retard CT, TW, and SR with nanofluids. The better performance showed in coconut oil-based lubricant compared to SAE oil-based lubricant.	2010
Rao et al. [40]	AISI 1040 steel	HSS and cemented carbide	CNT (NM)	NM.	Retard CT and TW up to 2% CNT inclusion, and not much change beyond this range.	2011
Vasu, and Reddy [41]	Inconel 600 alloy	Coated carbide CNMG 1 20 408	Al_2O_3 (NM)	Vegetable oil (Coolube 2210)	Shown that FR is the main parameter that influences SR, DC affects CT and FR, and DC influences CF as well TW among all three parameters. It retard SR, CT, CF, and TW by machining under minimum quantity lubrication nanofluid conditions.	2012
Khandekar et al. [42]	AISI 4340 steel	Uncoated cemented carbide	Al_2O_3 (NM)	Servo cut-S	TW retarded while machining with 1v% nanofluid. When using nanofluid, CF and SR are slowed by 50% and 30%, respectively, as compared to dry and traditional fluid machining.	2012
Amrita et al. [43]	AISI 1040 steel	CNMG 120408, and HSS	Graphite (<80)	Soluble oil	Minimum TW and CF with 0.5wt% nano graphite soluble oil for both tools were obtained. The nanofluid application showed improvement in terms of CT, TW, and CF.	2013
Amrita et al. [44]	AISI 1040 steel	CNMG 120408 TTS	Graphite (80), boric acid (100), MoS_2 (100)	Emulsifier oil	For TW, SR, CF, and MoS_2 showed better wear, surface, and force properties, respectively. For CT, boric acid showed better heat dissipation properties.	2014

Table 2. Comprehensive overview of the works connected to minimum quantity lubrication that contains nanofluid (continued)

Researchers	Workpiece material	Cutting tool material	Nanoparticles types and their size (nm)	Types of base Fluid	Findings	Year
Sayuti et al. [45]	AISI 4140 steel	Sandvik DNMG 150608 PM	SiO_2 (5-15)	Mineral oil	Minimum TW and SR with a 0.5%wt SiO_2 concentration and 60º and 30º nozzle orientation angle, respectively, were obtained.	2014
Shabgard et al. [46]	AISI 4340 steel	DNMG 150604-QM	CuO (NM.)	Soluble cutting fluid	CF and SR were retard by 24% and 49% when machining with a cutting fluid containing 1% CuO instead of soluble oil and dry machining.	2014
Khalil et al. [47]	AISI 10150 mild steel	Carbide	Al_2O_3 (NM.)	Soluble cutting oil	Retard TW when turning with Al_2O_3 and Al_2O_3 + surfactant cutting fluid.	2015
Sharma et al. [48]	AISI. D2 steel	Tungsten carbide (CNMG 120408)	MWCNT (NM)	SAE. 20W40 oil	Showed CT could be decreased with the addition of MWCNTs in cutting fluid. Retardation in SR as retardation in CT and less TW was obtained.	2015
Sharma et al. [49]	AISI 1040 steel	Uncoated cemented carbide	TiO_2 (NM)	Vegetable oil-water emulsion	Retard TW up to 58.1% and 35.85%, and CF up to 62.67% and 34.88% with nanofluid machining compared to dry machining and mist machining, respectively. Nano-cutting fluid machining retard average SR by 47.8%, 39.1%, and 25.5% compared to dry, mist, and wet machining and produced silver colour chips with curl and segmented shapes.	2016
Sharma et al. [50]	AISI 1040 steel	Uncoated cemented carbide	Al_2O_3 (45)	Vegetable oil-water emulsion	Retard TW up to 59.1%, 29.2%, and 28.6%, and CF up to 63.9%, 44.9%, and 5.27% with nanofluid cooling, as compared to machining conditions like dry, mist, and wet, respectively. Nano-cutting fluid machining retard average SR by 47.8%, 29.1%, and 25.5% compared to dry, mist, and wet machining and produced silver colour chips with curl and segmented shapes.	2016
Gupta et al. [51]	Titanium (grade-2) Alloy	Cubic boron nitride	Al_2O_3 (40), MoS_2 (40), Graphite (40)	Vegetable oil	PSO and BFO enhance CF, TW, SR, and CT in graphite-based nanofluids. CF, CT, TW, and SR increase with CS and FR and reduce with cutting fluid.	2016
Paturi et al. [52]	Inconel 718	Carbide SNMG 120408	Tungsten disulfide WS_2 (NM)	Emulsifier oil	Optimal machining parameters were obtained using Taguchi design and ANOVA for SR. It retard SR by 35% with WS_2 lubricant-assisted + minimum quantity lubrication machining compared to minimum quantity lubrication machining.	2016

Table 2. Comprehensive overview of the works connected to minimum quantity lubrication that contains nanofluid (continued)

Researchers	Workpiece material	Cutting tool material	Nanoparticles types and their size (nm)	Types of base Fluid	Findings	Year
Rapeti et al. [53]	AISI 1040 steel,	Coated carbide CNMG 120408 NC6110	MoS_2 (NM)	Coconut oil, sesame oil, and canola oil	ANOVA and ANOM showed that coconut oil+0.5% MoS_2 machining retard CF, CT, TW, and SR. Obtained optimum condition at CS of 40 m/min and FR of 0.14 mm/rev for retardation in CF, CT, and TW, and 100 m/min, and CS value of 100 m/min, and FR value of 0.14 mm/rev for minimum SR.	2016
Padmini et al. [60]	AISI 1040 steel	Coated carbide CNMG 120408 NC6110	MoS_2 (NM)	Coconut oil, sesame oil, and canola oil	Enhanced flash, fire points, specific heat, specific density, thermal conductivity, and heat transfer coefficients were obtained as the percentage of nanoparticles increased. Retard CF, CT. TW and SR at coconut oil+0.5% MoS_2 compared to other cooling conditions.	2016
Patole, and Kulkarni [54]	AISI 4340 steel	Tungsten carbide coated CNMT 090308	MWCNT (15)	Ethylene glycol	Obtained optimized machining parameters using grey relational analysis (GRA). minimum quantity lubrication with nanofluid showed retardation in SR and CF from a comparative analysis of all lubrication techniques.	2017
Sharma et al. [61]	AISI 1040 steel	Uncoated cemented carbide	SiO_2 (10)	Vegetable oil-water emulsion	Nano-cutting fluid machining lowered TW by 57.3% and 34.6% compared to dry and mist machining. Nano-cutting fluid machining retarded average SR by 15%, 19.05%, and 40%. It created smooth silver chips with curl and segmented morphologies.	2017
Singh et al. [55]	AISI 304 steel	Uncoated cemented carbide	Graphene nanoplatelets (30–40)	Servo Cut S oil	Higher value concentration of graphene nanoparticles showed that a higher concentration retard CT at a lower CS, FR, and DC. Retards the SR with a higher value concentration of graphene nanoparticles at higher CS, lower FR, and DC.	2018
Joshi et al. [56]	Inconel 600	Uncoated carbide	Al_2O_3 (NM)	Vegetable oil	Nanofluid was performed dry cutting, and minimum quantity lubrication with vegetable oil cutting. Comparing dry and vegetable oil+minimum quantity lubrication machining, nanofluids+minimum quantity lubrication slowed SR. The hybrid fuzzy controller closely matched experimental data.	2018

Table 2. Comprehensive overview of the works connected to minimum quantity lubrication that contains nanofluid (continued)

Researchers	Workpiece material	Cutting tool material	Nanoparticles types and their size (nm)	Types of base Fluid	Findings	Year
Vishnu et al. [57]	EN353 Alloy Steel	CNMG carbide uncoated, CVD, and PVD	Al_2O_3 (NM)	Water	Obtained best and optimal combination for reducing CT at flooded conditions, CS of 1100 rpm, FR of 0.2 mm/rev, DC of 0.5 mm, and PVD coated tool. Shown better machining condition in flooded condition, but a minimal difference in values between minimum quantity lubrication and flooded need.	2018
Pasam et al. [58]	AISI 1040 steel	Tungsten carbide PVD coated	Boric acid (100), and MoS_2 (90)	Coconut oil	Observed nanofluids performed better than micro fluids at higher CS and retard CF, CT, SR, and TW. MoS_2 performed better than boric acid lubricants. However, microfluidics is far more economical and viable than nanofluids.	2018
Ganesan et al. [59]	H11 steel	Carbide	Copper (50)	Ethylene glycol	It decreased SR by 40% with copper nanofluid machining with FR of 0.1 mm/rev and CS of 209 m/min. Retardation in TW by 66% with copper nanofluid machining was obtained. RSM supported the mathematical model, and copper nanofluids+minimum quantity lubrication enhanced cooling, which resulted in a small number of notched tooth chips.	2018
Sivalingam et al. [62]	Inconel 718	Reinforce ceramic insert	Graphite (30-45), and MoS_2 (10-15)	Vegetable oil	Improvement in SR and TL and retardation in TW and machining coast were obtained compared to the dry cooling environment.	2020
Das et al. [63]	AISI 4340	Uncoated cermet	ZnO, CuO, Fe_2O_3, and Al_2O_3 (NM)	Deionized water	In minimum quantity lubrication nanofluid cooling, the higher value of CF was found with Al_2O_3 and the least with CuO. In contrast to the remaining three nanofluids, the least TW was obtained with CuO. The lowest value of SR resulted in CuO nanofluid.	2020
Venkatesan et al. [64]	Hastelloy X	Cemented Carbide CVD and PVD coated	hBN (30-100)	Coconut oil	Weight concentration, 0.25 % of hBN nanofluid with minimum quantity lubrication PVD carbide coated tool showed retardation in SR, CF, and TW compared to minimum quantity lubrication + CVD carbide coating at 0.25 % and dry PVD carbide coating.	2020
Ramanan et al. [65]	Incoloy 800	CNMG PVD coated	Al_2O_3 (20)	Semi-synthetic soluble oil	minimum quantity lubrication with 1% Al_2O_3 nanoparticles improved wettability and the most negligible value of SR. CF and TW were retard compared to dry, flood, and minimum quantity lubrication strategies.	2021
Nikouei et al. [66]	Inconel 718	Carbide coated	TiO_2 (10, 30, 50)	Water	Nanoparticle application got better results in terms of residual stress average from 20.03 to 11.44%	2021

Significant reviews [1], [11], [48], [67], [68] are focused on nanofluid preparation, nanoparticle concentration, nanofluid with minimum quantity lubrication, and performance of output parameters like machining cutting force, cutting temperature, surface roughness, tool wear, and chip morphology in the machining process, namely; turning, milling, grinding, and drilling with an application of nanofluid + minimum quantity lubrication in compared to conventional cutting fluid with minimum quantity lubrication, dry, and wet lubricant system.

MQL with Hybrid Nano Cutting Fluids (MQLHyNFs)

Sharma et al. [69] performed experimentation for analyzing impact of Al_2O_3 (45 nm) and MoS_2 (30 nm) with a fraction of 9:1 to get dispersed hybrid nanofluid in turning operation of AISI 304 steel. Nanoparticle fractions of 0.25, 0.75, and 1.25 v% were employed. Significant retardation in Fx. Fy, Fz, and Ra were 18.08%, 5.73%, 7.35%, and 2.38%, respectively. Singh et al. [70] studied the simulations of the impacts of incorporating graphene nanoplatelets into Al-based nanofluid at fractions of 0.25, 0.75, and 1.25 v% in the construction of a hybrid nanofluid. With an enhancement in nanoparticle concentration, thermal conductivity, viscosity, and wear were all improved. The results of comparing alumina-based nanofluid and base fluid demonstrate that the hybrid has superior wettability. The results showed a decrease in surface roughness by 20.28 %, a reduction in thrust force value by 17.38 %, a decrease in cutting force value by 9.94 %, and a decrease in feed force by 7.25 %.

Sharma et al. [71] checked the impact of hybrid nanofluids made of Al_2O_3 and GnP in turning AISI 304 steel. The development of Hybrid nanofluids was achieved with varying concentrations of 0.25, 0.75, and 1.25 v%. Hybrid nanofluids had the lowest pin wear and friction coefficient per tribological and wettability testing. Results revealed retardation of 5.29% in cutting temperature and 12.29% in tool wear with nanofluids compared to Al-based nanofluid. Jamil et al. [72], experimentally studied the usefulness of cryogenic cooling (CO_2) and minimum quantity lubricationHF in turning tungsten alloys. Al_2O_3 (30 nm) and MWCNT (10-30 nm) are suspended in vegetable oil base fluid for nanofluid preparation. Experiments were designed using Taguchi's L9 orthogonal array with cutting speed, feed rate, and cooling techniques as design variables. It was seen from the results that mean surface roughness was retard by 8.72%, machining cutting force by 11.8%, and tool life enhanced by 23% with hybrid nanofluids in contrast to CO_2 cooling. Although, retardation of 11.2% in cutting temperature was seen with CO_2 cooling compared to hybrid nanofluid-based minimum quantity lubrication.

Yildirim [73] experimentally investigated the effects of cooling conditions, notably dry, minimum quantity lubrication, cryogenic, nanofluids, and combinations of these approaches on the turning of Inconel 625. Al_2O_3 (70 nm) and hBN (70 nm) were incorporated to the nanofluid in various concentration ratios, nonetheless LN2 worked better for cryogenic cooling. Surface roughness, tool wear, and tool-chip junction temperature were the output parameters. The results indicate that employing the 0.5 v% hBN cooling approach in addition to LN2 was the optimum combination for enhanced manufacturing. Thakur et al. [74] studied the results of turning EN 24 steel using various cooling methods, including minimum quantity lubrication, MQLNF, and minimum quantity lubricationHF. Al_2O_3, CuO, and Al-CuO nanoparticles were added to water at a fraction of 0.2, 0.4, and 0.6wt%, respectively, to create nano-fluids and hybrid nano-fluids. Thermal conductivity of hybrid nanofluids was discovered to be greater than that of either mono nanofluid. The experiments showed that using a hybrid nanofluid + minimum quantity lubrication reduced the coefficient of friction, surface roughness, cutting temperature, and tool wear. Thakur et al. [75], experimentally evaluated The impact of turning EN 24 steel from different cooling methods, minimum quantity lubrication, nanofluids + minimum quantity lubrication, and composite nanofluids + minimum quantity lubrication. Water was enriched with 0.5, 1, and 1.5 percentage per cent of Al_2O_3, CuO, and Al-CuO nanoparticles, respectively. After a comparison investigation, the hybrid nanofluids performed better than the nanofluids. Therefore, two nanofluids› parameters were optimized, and RSM created hybrid nanofluids using ANOVA. According to experimental data and multi-response optimization, the hybrid nanofluid with minimum quantity lubrication had the lowest coefficient of friction, which resulted in a notable reduction in cutting force, cutting temperature, and surface roughness.

Gugulothuet al. [76] experimentally studied sedimentation tests and characterization of nanofluids, which were prepared using CNT (30 nm) and MoS_2 (30 nm) nanoparticles in 0.5, 1, 1.5, 2, 2.5, and 3wt% concentration in sesame oil as a base fluid. These nanofluids were used in machining under minimum quantity lubrication to turn AISI 1040 steel with an uncoated carbide tool. Results revealed retardation in coefficient of friction, thrust force, feed force, main cutting force, and surface roughness at 02 wt% of CNT+MoS_2 hybrid cutting nano-fluids compared to dry and conventional cutting fluids. Furthermore, cutting temperature and tool wear was retard at 3wt% of CNT+MoS_2 hybrid cutting nano-fluids in contrast with dry machining and conventional cutting fluid machining. Zaman et al. [77] studied the influence of parameters: cutting speed, feed rate, depth of cut, nanoparticle concentration, tool type on cutting temperatures, and surface roughness in turning of Ti-6Al-4V alloy under hybrid Al_2O_3-MWCNT nanofluid based minimum quantity lubrication. The Box-Behnken method was implemented in the experiment design. Empirical models were established employing RSM. The temperature improved with cutting speed, depth of cut, and feed rate, consistent with estimations and experimental results. Yet, while the particle proportions enhanced, the temperature declined to its lowest possible point and then expanded even more. The most crucial factor regarding roughness was the machine feed rate.

Sandeep Kumar et al. [78] studied the impact of hybrid nanofluids with Cu-Zn with base fluid as a groundnut oil with an application of minimum quantity lubrication in turning operation of Inconel 718 with a cutting tool fitted with Ti coated insert. In experimentation, input machining parameters were applied under conditions like dry, minimum quantity lubrication including vegetable oil, and minimum quantity lubrication including nanofluid. From investigation, it is founded that retardation in cutting temperature and surface roughness in minimum quantity lubrication + nanofluid with comparison to dry and minimum quantity lubrication + vegetable oil colling conditions.

Sandeep Kumar et al. [79] conducted tests using CuO + ZnO (50:50) hybrid nanoparticles in vegetable oil like palm oil and coconut oil as a base fluid for turning of AISI 1018 steel. In experimentation, the performance of hybrid nano cutting fluids was compared with dry machining process and notable retardation in surface roughness; feed was the main indicating parameter compared to the cut and cutting speed depth. Table 3, presents the thorough analysis of the research works concerning least quantity lubrication in conjunction with hybrid nanofluid based on the material of the workpiece, the cutting tool, the types of nanoparticles, the size, the base fluid, the characterization approach, and the most important discovering.

Table 3. Comprehensive review of the research works concerning minimum quantity lubrication in conjunction with hybrid nanofluid

Researchers	Workpiece material	Cutting tool material	Types of nanoparticles and their size (nm)	Types of base fluid	Char. Tech.	Findings	Year
Sharma et al. [69]	AISI 304 steel	Coated carbide	Al_2O_3 + MoS_2 (45, 30)	Vegetable oil	TEM	Hybrid nanofluid machining reduced thermal conductivity. Al-MoS_2 hybrid nanofluid has lower friction and pin wear than alumina. Al-MoS_2 nanofluid machining over Al_2O_3 nanofluid retarded CF and SR.	2017
Singh et al. [70]	AISI 304 steel	Coated carbide	Al_2O_3 + GnP (45, 11-15)	Servo cut oil	TEM	Thermal conductivity got enhanced by utilizing Al-GnP hybrid and alumina nanofluids. Retardation in the coefficient of friction with an enhancement in nanoparticle concentration was achieved. Hybrid nanofluid machining achieved significant retardation in CF and SR.	2017
Sharma et al. [71]	AISI 304 steel	Coated cemented carbide	Al_2O_3 + GnP (NM)	Conventional fluid	TEM, SEM	Retard the coefficient of friction and pin wear with enhanced nanoparticle concentration for both lubricants, but the hybrid lubricant has a lower coefficient of friction. Retardation in TW and CT with hybrid nanofluid over alumina nanofluid was achieved.	2018
Jamil et al. [72]	Ti–6Al–4V alloy	Coated carbide	Al_2O_3 + MWCNT (30, 10-30)	Vegetable oil	NM	Retard SR, CF, and enhanced TL with hybrid nanofluids+minimum quantity lubrication compared to cryogenic cooling. Retard CT with cryogenic cooling compared to hybrid nanofluids+minimum quantity lubrication cooling.	2019

Table 3. Comprehensive review of the research works concerning minimum quantity lubrication in conjunction with hybrid nanofluid

Researchers	Workpiece material	Cutting tool material	Types of nanoparticles and their size (nm)	Types of base fluid	Char. Tech.	Findings	Year
Yildirim [73]	Inconel 625 superalloy	Coated carbide	hBN + Al_2O_3 (70, 70)	Vegetable oil	SEM	Obtained best results with 0.5 v% hBN when all nano additives were compared as having a higher heat coefficient of hBN than Al_2O_3. CT was retard by 26.77 % and 45.58 % compared to dry machining using liquid nitrogen and minimum quantity lubrication, respectively. Retard SR with 0.5 v% hBN + liquid nitrogen method used, and got lowest TW value with 0.5 v% hBN + minimum quantity lubrication + liquid nitrogen method.	2019
Thakur et al. [74]	EN 24 steel	Tungsten carbide CVD coated	Al_2O_3 + CuO (NM.)	Soluble oil	NM.	When compared to CuO and Al2O3 nanofluids, hybrid nanofluids had the lowest friction coefficient. minimum quantity lubrication and other Al-CuO hybrid nanofluids produced the lowest SR value. Reduce CT and TW using Al-CuO hybrid nanofluids and minimum quantity lubrication turning in comparison to alternative cooling conditions.	2019
Thakur et al. [75]	EN 24 steel	Tungsten carbide CVD coated	Al_2O_3 + CuO (30, 50)	Soluble oil	TEM	Found enhanced thermal conductivity with the addition of nanoparticles. They have significantly retard SR and CT with Al-CuO hybrid nanofluids+minimum quantity lubrication. Retardation in CF due to the lowest coefficient of friction with hybrid nanofluids+minimum quantity lubrication was observed.	2019
Sandeep Kumar et al. [78]	Inconel 718 alloy	TiAlN coated	Cu + Zn (NM)	Groundnut oil	TEM, XRD	SR drop from minimum quantity lubrication tool-tip damage and wear. Hybrid nanofluids enhanced cutting fluid wettability and heat transfer.	2020
Sandeep Kumar et al. [79]	AISI 1018 steel	TiAlN coated	CuO + ZnO (NM)	Coconut oil and Palm oil	NM	Shown retardation in SR with hybrid nanofluids in contrast to conventional dry machining. ANOVA results imply that the major impact for SR is FR, followed by DC and CS.	2020

Table 3. Comprehensive review of the research works concerning minimum quantity lubrication in conjunction with hybrid nanofluid

Researchers	Workpiece material	Cutting tool material	Types of nanoparticles and their size (nm)	Types of base fluid	Char. Tech.	Findings	Year
Gugulothu, and Pasam [76]	AISI 1040 steel	CNMG 120408 uncoated carbide	MWCNT + MoS_2 (30, 30)	Sesame oil	NM	Enhanced thermal conductivity, viscosity, and specific heat with increasing particle concentration. CF was retarded by 32%, 27.3%, SR by 28.5%, and 18.3% at 2wt% of hybrid nanofluids compared to dry and conventional. Retards the CT by 43.4% and 28%, respectively. Retardation in TW by 81.3% and 75% at 3 wt% of hybrid nanofluids compared to dry and conventional.	2020
Zaman et al. [77]	Ti–6Al–4V alloy	Uncoated and TiN-coated carbide	Al_2O_3 + MWCNT (50, 8-15)	Cutting oil	NM	Decreased CT with an enhancement of nanoparticle concentration, CS was the main factor for CT. FR was the most influencing factor for SR, and lower SR was produced with lower DC, but SR was enhanced due to tool vibration.	2020

The concise reviews of minimum quantity lubrication with hybrid nanofluids [80], [81] have been carried out by considering the performance of input variables such as thermal conductivity, specific heat, and friction coefficient, and output parameters such as cutting force, cutting temperature, surface roughness, tool wear, and chip morphology in machining processes with an application of hybrid nanofluids have been the subject of extensive reviews.

Many investigators have studied the various application of minimum quantity lubrication in the turning process with cutting coolant fluid cum lubricants: conventional cutting fluid, vegetable oil (ester oil, aloe vera oil), soluble cutting oil, and emulsion oil. For enhancing process performance in the turning process by improving behaviour in terms of thermal and frictional parameters [82] and reducing health and environmental issues associated with the utilization of conventional cutting fluid, major researchers have studied nanofluid with minimum quantity lubrication. Within this presentation, a comparative analysis of cutting fluid and nano-additives that are relevant is presented in Table 4.

Table 4. Comparative analysis of cutting fluid and nano-additives

Cutting fluid	Conventional cutting fluid	Vegetable oil	Soluble cutting oil	Emulsion oil	Water
Al_2O_3	[42,50]	[41,51,56]	[47]	-	[57]
Boric Acid	-	[39,58,83]	-	[39,44]	-
Graphite	-	[51]	[43]	[44]	-
SiO_2	-	[61]	[45]	-	-
MWCNT	[40]	[54]	-	[48]	-
CuO	-	-	[46]	-	-
TiO_2	-	[49,51]	-	-	-
MoS_2	-	[53,58,60]	-	[44]	-
Tungsten disulfide WS_2	-	-	-	[52]	-
Copper	-	[59]	-	-	-
Graphene Nanoplatelets	-	-	-	[55]	-

Development in nanoscience demands a higher enhancement in nanofluids' heat transfer properties. A few investigators have used hybrid nanofluids with minimum quantity lubrication in turning metals and alloys. According to the study, hybrid nanofluids with different nanoparticles had been with conventional cutting fluid, vegetable oil, and soluble cutting oil as base fluid. Sharma et al. [69] used Al_2O_3 + MoS_2, Singh et al. [70], and Sharma et al. [71] used Al_2O_3 + GnP, Jamil et al. [72], and Zaman et al. [77] used Al_2O_3 + MWCNT, Yildirim [84] used hBN + Al_2O_3, Thakur et al.[74], and [75] used Al_2O_3 + CuO, Sandeep Kumar et al.[78], and [79] used CuO + ZnO, and Gugulothu, and Pasam [76] used MWCNT + MoS_2.

Apart from cutting fluid applications, the mono and hybrid nanofluid can be implemented for various applications, such as electronic component cooling using heat pipes [85], automobile radiators [86], solar water distillation systems [87], solar collectors [88], and energy storage system [89].

Statistical Analysis

A number of cutting fluids for different machining operations are examined in this review study. Performance characteristics, experimental analysis, preparation process, characterization methodologies, and working fluids are among the various aspects of the review work carried out during the last ten years that are highlighted. The cited works in this study are primarily taken from a conference proceeding, notable Elsevier, Taylor & Francis, and Springer publications.

The total number of works published in various categories in the form of nature of work is shown in Figure 3. More research articles on experimental work across multiple cutting fluids have been published throughout the previous decade. The number of articles that have utilized conventional fluid, nanofluid, and hybrid nanofluid as a cutting fluid with minimum quantity lubrication method between the years 2010 and 2021 is displayed in Figure 4. The conclusion that was reached was that the research trends that involve conventional cutting fluid are decreasing with time; the use of nano-fluid as a cutting fluid was trending in the middle of the decade, and the use of hybrid nano-fluid as a cutting fluid is a trend that is currently occurring.

The number of research works that make use of particular kinds of workpiece material while employing a specific kind of cutting fluid is displayed here in Figure 5. As indicated in the figure, most researchers employed AISI 1040 steel as workpiece material, while hybrid nanofluid was employed as cutting fluid.

Figure 5 shows a particular sort of cutting fluid; the number of articles while utilizing a particular kind of tool

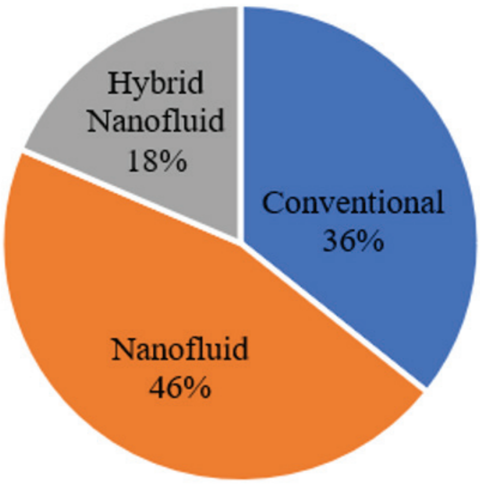

Figure 3. Publications with the nature of work based on cutting fluids.

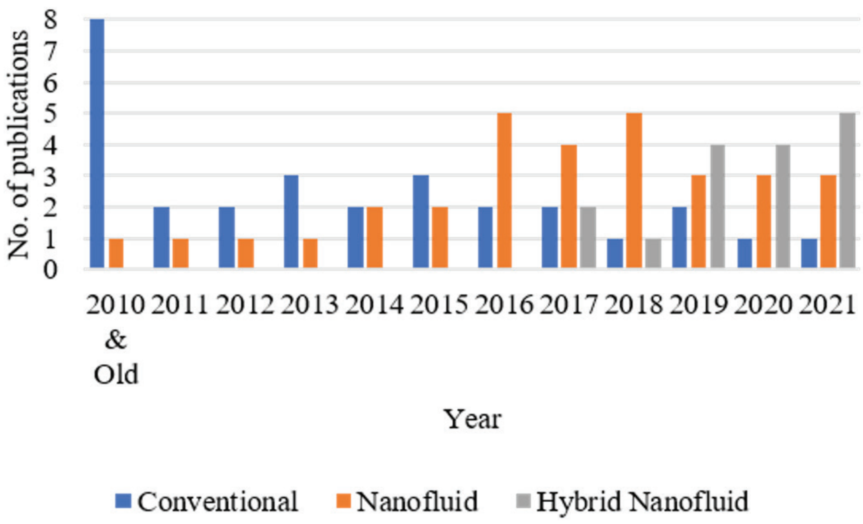

Figure 4. Numbers of publications between 2010 and 2021.

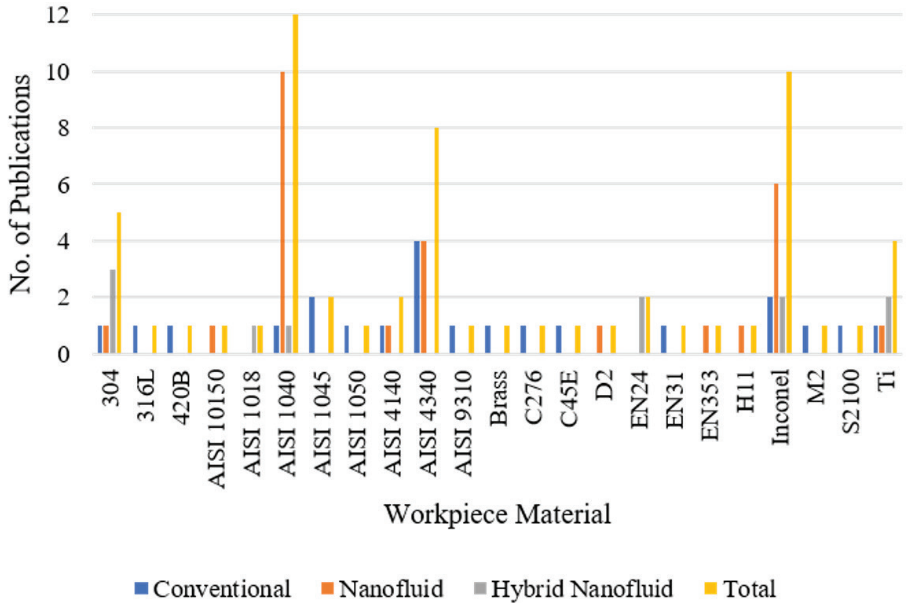

Figure 5. Number of studies and types of workpiece materials.

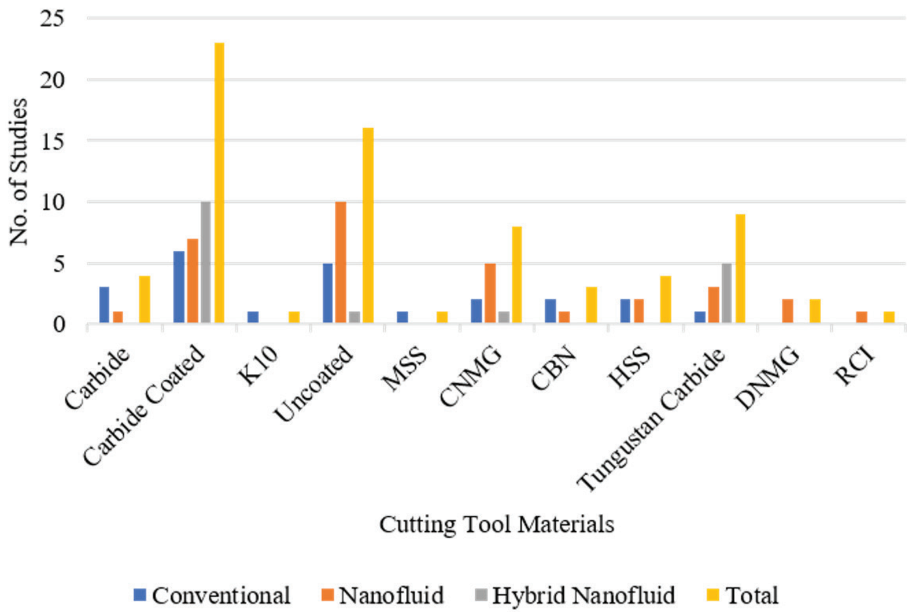

Figure 6. Number of studies with types of tool materials.

material is significant. As can be seen in the picture, an increasing number of researchers have utilized tungsten carbide as a tool material with a carbide coating, while hybrid nanofluid has been used as a cutting fluid.

Figure 6 addresses a variety of studies involving different kinds of tool materials. According to this figure, the majority of researchers used a hybrid nanofluid along with minimum quantity lubrication as a cutting fluid, AISI 1040 steel as a workpiece material, and tungsten carbide as a tool material coated with carbide. Research suggests using a hybrid nanofluid as cutting fluid with AISI 1040 steel as a workpiece material and a tungsten carbide tool coated with carbide for various lathe operations.

Economy and Sustainibility

Aspects in terms of economy and sustainability are incorporated during a critical review of open literature. Significant aspects related to cost and environmental impacts are drawn below:

1. Excellent thermos-physical characteristics lead to a reduction in operational costs. Overall investments got retarded by a cut down in cost [90].
2. Identical heat transport characteristics as conventional working fluids lead to an opportunity to retard the flow while using the minimum quantity lubrication with mono and hybrid nanofluids [90].
3. Conventional cutting fluids are highly hazardous, whereas the minimum quantity lubrication with mono or hybrid nanofluids has a less or null environmental impact in terms of hazard [91].
4. Minimum quantity lubrication, as a cutting fluid, needs less flow than conventional cutting fluid. This leads to less focus on storage, safety, and cleaning of minimum quantity lubrication cutting fluid than conventional ones [92].
5. Minimum quantity lubrication with mono or hybrid nanofluid as a cutting fluid creates a temporary film on the cutting zone interface of the cutting tool and workpiece. It reduces the tool wear and improves the tool life compared to the conventional cutting fluid [93].
6. Minimum quantity lubrication with mono and hybrid nanofluid can reduce wastage and enhance overall productivity in contrast with the conventional cutting fluid [90].
7. Efficiency improvement for heat exchangers, enhancement in compactness, energy recovery, reduction in cutting fluid usage, and improvement in the thermal process are key aspects of nanofluids for practical integration [92,93].

Limitations

After careful consideration of minimum quantity lubrication use along with nanoparticles in the context of performance improvement, a few limiting characteristics have been observed from the part of the literature. The following are the limitations of current work:

1. Utilizing nanofluid for lubrication in minimal quantities increases the initial cost. However, following thorough consideration and a wider range of industrial applications, it is possible to achieve this reduction by producing it in bulk.
2. Nanoparticle size plays a critical influence on jet flow. A greater size might cause the nozzle used in the lowest quantity of lubricating mist to choke. Selecting smaller-sized nanoparticles might lessen the chances of repeated spray nozzle choking.
3. Only a small percentage of nanoparticles possess potentially harmful properties, raising questions about operations› safety. Avoiding the selection of such dangerous particles could resolve safety concerns. Mandatory selection of potentially harmful nanoparticles would result in the implementation of one-of-a-kind and cutting-edge safety measures.
4. Agglomeration is produced, and the stability of the working medium decreases when nanoparticles are added to concentrations greater than 2 wt%. As a result, the utilization of concentrations that are lower than the maximum allowable level will lessen the likelihood of agglomeration and improve the consistency of the working medium.
5. The utilization of surfactant or detergent enhances the stability of the working medium, but it also negatively impacts its thermo-physical properties. It is possible to achieve superior thermo-physical properties of the working medium by avoiding the addition of surfactant or detergent and paying particular attention to stability.

Future Trends

To this point, numerous academics have focused more on nanofluids with minimum quantity lubrication. The below-mentioned points lead to the enhancement of the research in this field:

1. On the other hand, hybrid nanofluids that use a minimum quantity lubrication cooling approach are being investigated to improve turning parameters and boost the efficiency of heat transmission perticularly for turbine blade machining.
2. During the machining (turning) process, the impact that nanofluids with the least quantity of lubrication have on chip shape must be considered. Additionally, hybrid nanofluids with minimum quantity of lubrication should also be considered during gear machining.
3. The purpose of the theoretical and experimental inquiry is to optimize the minimum quantity lubrication operational factors, which include spray distance, flow rate, nozzle distance, air pressure, and nozzle orientation angle, as well as the respective influences that these variables have on turning in micro machining operations.
4. Additional research is still required to optimize the particle size and variable concentration of nanoparticles and their effects on the turning process in terms of tribological parameters, particularly wear and friction during high speed machining on hard-to-machine materials.
5. During turning operations, vibration analysis of a cutting tool should be explored both experimentally and theoretically. This analysis should also investigate the impact that vibration has on cutting parameters during internal boring operations.
6. When using the machining process, it is important to consider the properties of mono and hybrid nanofluids, including their stability, sustainability, and safety in application of profile turning where the operators are very close to machining operations.
7. It was necessary to conduct a thorough analysis of the technological and economic investigations conducted using mono and hybrid nanofluids, respectively, for mass production of a particular job for the machining operation.
8. Predictive and ensemble models, as well as machine learning, can be used to optimize machining parameters such as fluid flow rate or nanoparticle size in Artificial Intelligence and Machine Learning applications.

CONCLUSION

This paper has presented an overview of critical published investigations on applying minimum quantity lubrication with conventional cutting fluid, mono nanofluid, and hybrid nanofluid in turning operation. During the last decade, various experiments shifted the focus of study from traditional juice cutting to nano and hybrid nanofluid due to superior tribological properties that do not affect product quality. A literature survey shows significant improvement in machining parameters with mono and hybrid nanofluid with minimum quantity lubrication. The below-mentioned observations and outcomes are drawn from the following literature:

1. When using minimum quantity lubrication in conjunction with nanofluids and hybrid nanofluids, significant reductions in cutting forces, cutting temperatures, surface roughness, and tool wear can be attained
2. Applying minimum quantity lubrication with nanofluids improves the chip›s morphology in terms of its colour and form.
3. minimum quantity lubrication with hybrid nanofluids significantly improves its machining performance and tribological properties compared to minimum quantity lubrication with nanofluids.
4. The various types of nanoparticles, their particle size, concentration, and the nozzle›s inclination angle each play a crucial role in optimizing heat transfer rate and reducing tool wear.
5. As it tends to develop film between the interface of cutting tool-workpiece and retard friction, Aluminium Oxide (Al_2O_3) is the nanoparticle employed the most in minimum quantity lubrication applications that involve nanofluids and hybrid applications.
6. When comparing minimum quantity lubrication with hybrid nanofluid to minimum quantity lubrication with nanofluid, the coefficient of friction is found to be retarded when there is an enhancement in the nanoparticle concentration in minimum quantity lubrication with hybrid nanofluid.
7. AISI 1040 steel is the most suitable workpiece material for lathe operations when using nanofluid as a cutting fluid.
8. Tungsten carbide-coated tool material is suitable for lathe operation, while hybrid nanofluid + minimum quantity lubrication was used as cutting fluid.
9. The cutting fluid effect on turning parameters has a complex and non-linear research trend. So, it is difficult to predict using a simple mathematical model, simulation, etc.

In addition, theoretical and experimental research is required to comprehend the minimum quantity lubrication employing hybrid nanofluid as a cutting fluid for diverse applications in lathe operations during machining processes.

ABBREVIATIONS

Ag	Silver
Al_2O_3	Aluminum Oxide
AlN	Aluminum Nitride
ANOM	Analysis of Means
ANOVA	Analysis of Variance
Au	Gold
BFO	Bacterial Foraging Optimization
CCD	Central Composite Design
CFsMQL	Conventional Fluids with minimum quantity lubrication
CNT	Carbon Nanotube
CO_2	Cryogenic Cooling
CRSM	Coupling Response Surface Methodology
Cu	Copper
CuO	Copper Oxide
CVD	Chemical Vapour Deposition
EDM	Electro Discharge Machining
Fe	Iron
Fe_2O_3/Fe_3O_4	Iron Oxide
GRA	Gray Rational Analysis
hBN	Hexagon Boron Nitride
LN_2	Liquid Nitrogen
MgO	Magnesium Oxide
MoS_2	Molybdenum Disulfide
MQLNF	minimum quantity lubrication with Nanofluid
MWCNT	Multi-Wall Carbon Nanotube
NFsMQL	Nanofluid with minimum quantity lubrication
NM	Not Mentioned
PSO	Particle Swarm Optimization
PVD	Physical Vapour Deposition
PWD	Physical Vapour Deposition
RSM	Response Surface Methodology
SAE	Society of Automotive Engineers
SDBS	Spectral Database for Organic Compounds
SEM	Scanning Electron Microscopy
SiC	Silicon Carbide
SiN	Silicon Nitride
SiO_2	Silicon Oxide
ST	Surface Topography
TiO_2	Titanium Oxide
WS_2	Tungsten Disulfide
ZnO	Zinc Oxide

Symbol

CF	Cutting Force (N)
CP	Cutting pressure (bar)
CS	Cutting speed (m/min)
CT	Cutting temperature (^oC)
DC	Depth of Cut (mm)
F	Force (N)
FR	Feed Rate (mm/rev)
SR	Surface Roughness (Micron)

TW	Tool Wear (Unitless)
v	Volume Fraction (%)
wt	Weight Fraction (%)

Subscripts

x	Feed
y	Thrust
z	Cutting

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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