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Review Article

A review of nanofluid lubrication as a cutting fluid in machining operations

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ABSTRACT

As the demand for higher machining efficiency and tool life continues to grow, researchers and engineers are exploring innovative solutions to enhance the performance of cutting fluids. Nanofluid lubrication, a cutting-edge approach in the field of machining, involves the dispersion of nanoparticles in conventional lubricants to improve their thermal and tribological properties. This paper provides a comprehensive review of the current state of nanofluid lubrication as a cutting fluid in machining operations. The review encompasses an in-depth analysis of the synthesis methods, types of nanoparticles employed, and the effects of nanofluid lubrication on cutting forces, tool wear, surface finish, and overall machining performance. Furthermore, the challenges and opportunities associated with the implementation of nanofluid lubrication in various machining processes are discussed. By synthesizing existing knowledge and highlighting recent advancements, this review aims to contribute to a deeper understanding of the potential benefits and limitations of nanofluid lubrication, paving the way for future research and practical applications in the realm of precision machining.

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INTRODUCTION

Manufacturing is coming out as an essential support in the country's economic widening. In India, the manufacturing sector plays an important role in an evolving nation like India which fully relies on manufacturing for progress and development as it affects the GDP of the country [1-2]. Various sub-sectors contour vast manufacturing that is responsible for the Indian economy including alloy, automotive, natural & man-made rubber, petroleum distillates, food crops, chemicals, electrical machinery and medicine have contributed to this growth. According to economics, Manufacturing is nothing it is just a way of converting raw materials into a finished and semi-finished product by adding some value to the raw material. In the same manner, by technical aspect, manufacturing is the application of physical and chemical processes to alter the geometry, properties and appearance of starting material to make the parts or product [3-4]. In today's technology, the Indian manufacturing sector is undeviating working ahead of more computerized and process-oriented manufacturing, which will enhance the efficiency and productivity of a manufacturing unit [5-6].

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Additive manufacturing, often referred to as 3D printing, stands as a transformative force in the landscape of Industry 4.0, reshaping traditional manufacturing paradigms. This innovative technology enables the creation of complex geometries with unprecedented precision and customization, fostering agility and flexibility in production processes. In the era of Industry 4.0, where interconnectedness and data-driven decision-making reign supreme, additive manufacturing catalyzes on-demand manufacturing, reducing lead times and minimizing waste. Its integration with digital design tools and automation systems streamlines production workflows, empowering businesses to swiftly adapt to dynamic market demands. Furthermore, additive manufacturing facilitates decentralized manufacturing, enabling localized production and reducing reliance on centralized factories. As Industry 4.0 continues to unfold, additive manufacturing will undoubtedly play a pivotal role in driving innovation, efficiency, and sustainability across various sectors, heralding a new era of manufacturing excellence [7-8]. In the era of Industry 4.0, unconventional manufacturing techniques such as water jetting and robotic techniques are emerging as crucial components of advanced production processes. Water jetting, with its ability to cut a wide range of materials with high precision and minimal heat-affected zones, exemplifies the adaptability and efficiency demanded by Industry 4.0. Its non-contact nature allows for intricate designs and the ability to cut various materials, from metals to composites, meeting the demands of diverse industries [9-10]. Moreover, robotic techniques, including robotic arms and automated systems, are revolutionizing manufacturing by enhancing speed, accuracy, and flexibility in production lines. These robots can perform tasks ranging from assembly to inspection with unparalleled consistency and efficiency, while their connectivity and data-sharing capabilities align perfectly with the interconnected nature of Industry 4.0 [11]. By integrating unconventional manufacturing methods like water jetting and robotic techniques into their operations, businesses can unlock new levels of productivity, agility, and customization, driving forward the transformative potential of Industry 4.0 [12].

Nanotechnology is the application of science that involves the developing and controlling of matter in the range of nanometre size i.e., 1-100 nm for various --applications and this technology certifies the fact that small things can cause big changes [13-14]. As technology becomes more advanced the attentiveness towards eco-friendly manufacturing along with higher performances also increases. Much research has been done or going on worldwide over the last 20 years on the practical utilisation of nano-particles in the machining and material processing as preservatives in cool-ants/lubricants/cutting fluids. On considering the evolution of 'nanotechnology' the approach of nanofluid lubrication has evolved [15-16].

Here the word lubrication describes the process of reduction of friction between these two mating surfaces on rolling against each other. Nano-lubrication contains the nanoparticle's preservative layer between the surfaces that are in mutual contact with each other which increases the efficiency and performance. On considering the above points Nano-lubrication process is used in the Metal Cutting machining process. Nano-lubrication is a process of productive cooling and lubrication of the cutting zone (metal working zone) at the time of any machining process by entailing nanofluid used as a cutting fluid. Metal cutting is the process that entails the removal of extra material from a workpiece in the pattern of a chip by employing a wedge-shaped tool. This process keeps the focus on various considerations such as the durability of the tool, probity of the work surface, quantity of material detached, amount of heat generation at the contact of a workpiece with a tool and particular energy expenditure, these are the things which relates with an impact on the class of manufacturing [17-20].

As we know, metal cutting is a high-speed machining process that elevates the temperature at the interface of the tool and workpiece. This elevated temperature at the metalworking cutting zone is caused due to high friction at the chip-tool and tool-work interface that leads to a failure of the cutting tool. To overcome this issue, cutting fluid is utilised at the region of the cutting zone which gradually decreases the friction and hence temperature as well as the removal of chips from the machining zone [21-22]. It has been seen that on utilisation of cutting fluid at the time of machining enhances the life of the tool, obtains a good surface finish and decreases the cutting force to be applied on the workpiece. Along with the use of cutting fluid, there is a negative effect of cutting fluid. It generates environmental and ecological complications as well as cutting fluid disposal, cutting fluid cost, laying of cutting fluid over the machine, etc [23-24]. From this point of view, many researchers [24-26] execute metal cutting by utilising disparate techniques and give a direction in the way of the utilisation of cutting fluids during machining. When nano-lubrication was not introduced in earlier days, many industries utilise an ordinary jet coolant method which makes use of a spray of cutting fluid in the process of metal cutting. This method leads to many problems like cost increment, microscopic pollution, reduced accessibility in the machining area, environmental threats, etc. Figure 1 displays the total costs that are associated with the manufacturing unit. From this, we see that around 17% of the total cost is related to the cost of coolant used at the time of metal cutting operation. It is generally higher than the cost of the tool. Now, the producer aims the aim of reducing costs and decides to reduce the total production cost of producing products as day-by-day competition has increased among the producers. This facility will not allow the company to go into loss [27-29].

Cutting fluids have several uses in the metal cutting procedure, such as creating a lubricating oil coating, releasing heat, clearing chips, optimizing the cutting circumstances, and eventually raising the calibre of the finished product [30]. MQL has a lot of possibilities for cutting operations and is a consistent cutting lubricating technique [31]. Compared with conventional flood cutting, MQL can provide a superior lubricating effect since it uses just under ten percent of the flooding cut inventory of cutting fluid [32]. The MQL instrument is easy to use and has a simple design that allows it to be placed close to the cutting machine instrument [33]. Nevertheless, some cutting fluids that have low heat transfer capacity are unable to fulfil the cooling needs associated with the cutting procedure when the quantity of lubricant is lowered. When compressed air and low-transfer-efficiency lubricants are used together, they can only remove a limited amount of heat from the machining region, falling short of the intended cooling effectiveness [34].

This review delineates a vision of synthesizing existing knowledge to comprehensively evaluate the potential of nanofluid lubrication in machining processes. Its purpose is to consolidate and critically analyze the body of research surrounding nanofluid lubricants in machining, aiming to discern trends, identify gaps, and propose future directions for scientific inquiry. From a scientific perspective, the manuscript endeavours to elucidate the underlying mechanisms governing the efficacy of nanofluid lubrication in improving machining performance, including aspects such as friction reduction, heat dissipation, and surface quality enhancement. By synthesizing empirical findings and theoretical insights, the aim is to provide a holistic perspective that informs further experimentation and innovation in the field, ultimately advancing the understanding and application of nanofluid lubricants in machining operations.

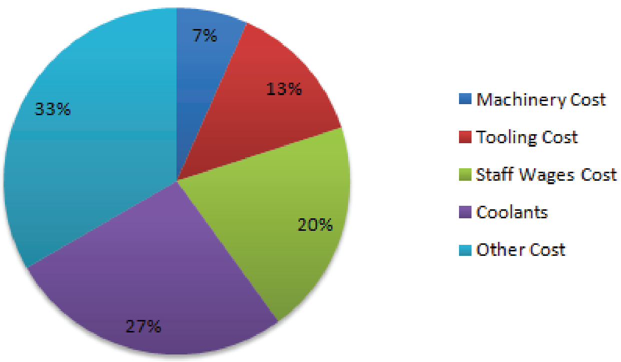

Figure 1. Different costs associated with the product at the manufacturing firm.

Features of Nano-Lubricant

Nano-lubricants offer a plethora of features that revolutionize traditional lubrication mechanisms. Firstly, their diminutive size allows for penetration into microscopic crevices, ensuring enhanced surface coverage and reduced frictional resistance. This leads to smoother operation and prolonged machinery lifespan [35]. Additionally, nano-lubricants exhibit remarkable thermal stability and oxidative resistance, mitigating wear and tear even under extreme operating conditions. Their tailored chemical compositions enable compatibility with diverse materials, minimizing adverse reactions and deposition. Furthermore, these lubricants possess superb load-bearing capabilities, maintaining optimal performance under heavy loads. Overall, the multifaceted features of nano-lubricants herald a new era in lubrication technology, promising unparalleled efficiency and durability across various industrial applications [36]. A lot of research has been done by researchers in the field of nano-lubricant properties that will be well represented in Table 1.

Table 1. Comparison of different nano-lubricants

Ref No.	Nanolubricant	Concentration	Features	Remarks
Hisham et al. [40]	CNC-CuO	0.1% to 0.9% with added SAE Oil	Stability	The wear rates were 33.5% higher. Overall, the engine oil's thermophysical characteristics and performance were enhanced by the 0.5% concentration of CNC-CuO particles.
Zawawi et al. [41]	TiO_2/SiO_2 polyol-ester	0.01 to 0.1%	Stability	Utilizing 0.03% TiO_2-SiO2 nanolubricant is advised to attain the best results.
Al-Janabi et al. [45]	MWCNT	0.1%	Thermal conductivity	When comparing the nanolubricant to regular oil, a 2%–7% improvement is seen.
Kole and Dey [48]	CuO	0.005% to 0.025%.	Viscosity	An increase in viscosity of over three times
Xie et al. [49]	MgO, TiO_2, ZnO, Al_2O_3, SiO_2	0.5% to 5%	Viscosity	MgO–EG nanofluid was shown to have the best characteristics

Stability

The stability of nano-lubricants is a critical aspect that determines their efficacy in various applications. Nanofluid, suspensions of nanoparticles in a base fluid, tends to suffer from particle agglomeration and sedimentation over time, compromising their performance. To enhance stability, several strategies are employed which are shown in Figure 2.

Surface modification of nanoparticles with suitable surfactants or stabilizers can prevent agglomeration by creating a repulsive force between particles, thereby maintaining dispersion stability [37]. Ultrasonication and mechanical agitation techniques are also utilized to break up agglomerates and promote uniform dispersion. Additionally, controlling the pH and ionic strength of the nanofluid environment can influence particle stability [38]. Furthermore, the selection of an appropriate base fluid with compatible properties is crucial for maintaining stability over prolonged periods [39]. By employing these methods, the stability of nanofluids can be greatly enhanced, ensuring consistent performance in various industrial and engineering applications.

Figure 2. Ways to improve stability of nanofluids.

Hisham et al. [40] enhanced the stability of CNC-CuO nanolubricant for a sustainable environment by utilizing it in internal combustion engines. Zeta potential studies were used to evaluate the stability of the entire system. Additionally, fluid lubrication was used in conditions characterized by rapid acceleration and low load, while boundary lubrication was used in situations characterized by low acceleration and high load to calculate the friction coefficient as well as the wear rate. A range of nanoparticle concentrations varied from 0.1% to 0.9 % were investigated in conjunction with SAE 40 oil. The zeta potential measurements showed that the stability of the nanolubricant rose from 0.1% to 0.5% concentration before declining at 0.9% concentration. In terms of tribological effectiveness, the CNC-CuO nano lubricants showed appreciable drops in the coefficient of friction. In blended lubrication, the friction coefficient decreased between 33% and 44%, while in boundary lubrication, it decreased between 48% and 50%.

Zawawi et al. [41] utilized TiO_2/SiO2 polyol-ester nano lubricants to experimentally investigate the electrical compressor air conditioning of automobiles. The volume concentration varied from 0.01% to 1%. The nanolubricant improved the heat absorption by up to 44.2% at a volumetric concentration of 0.03%.

Thermal Conductivity

The thermal conductivity of nano lubricants represents a frontier in material science, offering promising avenues for enhancing heat transfer efficiency in various engineering applications [42]. Nanolubricants, composed of a base lubricant infused with nanoscale particles, exhibit remarkable thermal properties due to their unique structure and composition. These nanoparticles, often metallic or carbon-based, facilitate more effective heat dissipation by promoting phonon scattering and enhancing thermal conduction pathways within the lubricant [43]. Understanding and optimizing the thermal conductivity of nano lubricants hold significant implications for improving the performance and longevity of machinery, reducing energy consumption, and advancing thermal management technologies in various industrial sectors, from automotive

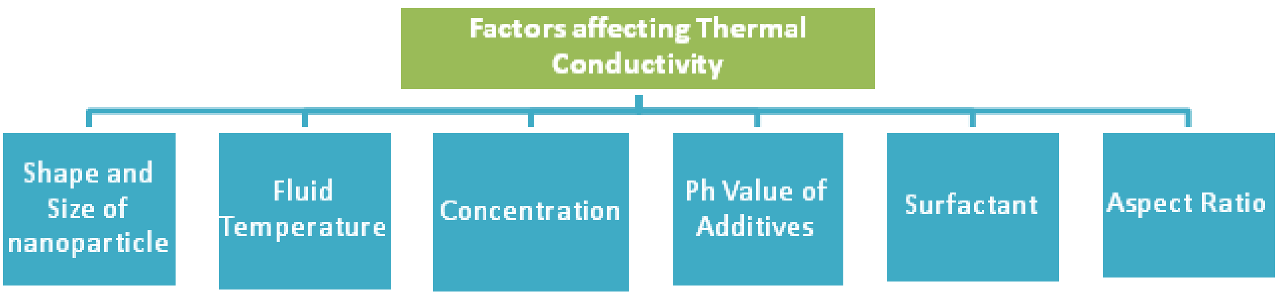

Figure 3. Parameters affecting thermal conductivity of nanofluid.

engines to electronic devices [44]. As researchers delve deeper into the intricacies of nano lubricant formulations and their thermal behaviour, the potential for transformative innovations in heat transfer science continues to expand. The main parameters that affect the thermal conductivity of nanofluid are illustrated in Figure 3.

Al-Janabi et al. [45] used MWCNT nano lubricant with additive surfactants and SL68 oil to check the thermal conductivity enhancement. The conductivity enhancements of a nanolubricant with additional surfactants were determined by measuring thermal conductivity. No discernible increase is seen in thermal conductivity measurement between the various surfactants; nevertheless, a 2% to 7% enhancement is noted when comparing the nano lubricant to simple oil.

Viscosity

Nanolubricants, with their incredibly small particle sizes, exhibit fascinating properties, particularly in terms of viscosity [46]. At the nanoscale, these lubricants boast significantly lower viscosity compared to their conventional counterparts. This attribute stems from the reduced friction between individual nanoparticles and the surfaces they coat. Their diminutive size allows them to penetrate even the tightest spaces within machinery, forming robust protective layers that minimize friction and wear. Consequently, nanolubricants offer enhanced efficiency and longevity to mechanical systems, making them a promising solution for industries seeking to optimize performance and reduce maintenance costs [47].

Kole and Dey [48] used CuO nanoparticles with Hauli 68 gear oil used in automobiles and other machinery. The volume fraction varied from 0.005% to 0.025%. They found that, at a CuO volume fraction of 0.025%, the viscosity of the nanofluids is boosted by around three times compared to the base fluid, and that it dramatically reduces as temperature rises. Xie et al. [49] used five nanoparticles MgO, TiO_2, ZnO, Al_2O_3, and SiO2 with EG base fluid. The concentration was varied from 0.5% to 5%. They found that MgO–EG nanofluid was shown to have the best characteristics of all the investigated nanofluids, having the least amount of viscosity and the greatest thermal conductivity. The incorporation of nanoparticles into MgO–EG nanofluids results in a progressive rise in their thermal conductivity augmentation. The increased value of 40.6% was attained at a volume fraction of 0.05 for MgO nanoparticles. The viscosity of different nanolubricants is represented in Figure 4 [50].

TRIBOLOGICAL FEATURES OF NANO-LUBRICANT

The tribological features of nano lubricants present a captivating realm of study, delving into the intricate dynamics of friction, wear, and lubrication at the nanoscale. These lubricants, infused with nanoparticles, exhibit remarkable abilities to modify surface interactions, reduce friction, and mitigate wear in various mechanical systems [51]. The nanoparticles, due to their minute size, can infiltrate surface asperities, forming a robust boundary or tribofilm layer that effectively separates contacting surfaces and minimizes direct metal-to-metal contact. This phenomenon results in significantly reduced friction coefficients and wear rates, leading to improved efficiency and longevity of machinery. Moreover, nanolubricants demonstrate the potential to enhance load-carrying capacity, damping vibrations, and operate effectively under extreme conditions [52].

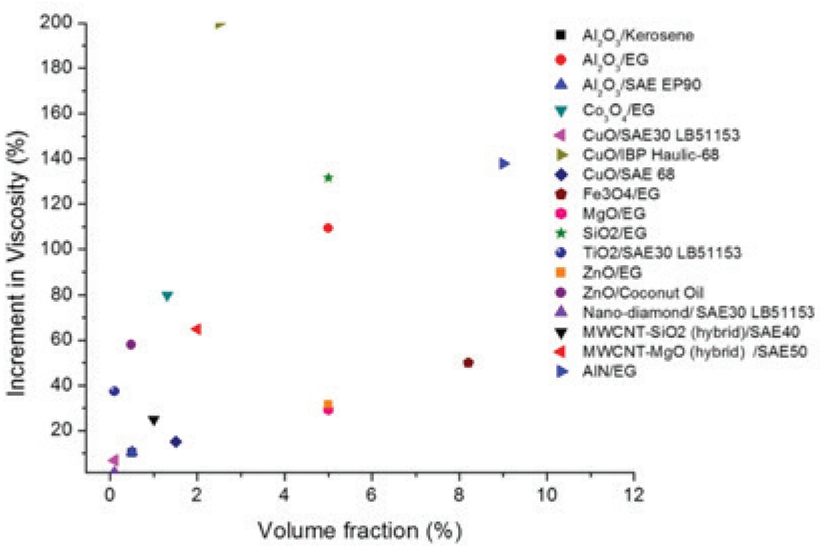

Figure 4. Variation of viscosity as the volume fraction of nanoparticles increases in lubrication From Ghosh et al. [50], with permission from Elsevier.

Understanding and harnessing the tribological features of nano lubricants hold promise for advancing the performance and reliability of diverse engineering applications, from automotive engines to manufacturing equipment.

Impact on Coefficient of Friction

The utilization of nano lubricants has emerged as a promising avenue in tribology, significantly altering the coefficient of friction in various applications. By integrating nanoparticles into conventional lubricants, these nanolubricants exhibit remarkable improvements in friction reduction and wear protection [53]. The impact on the coefficient of friction of nano lubricants is profound, as the nanoparticles, typically ranging from a few to hundreds of nanometers in size, alter the lubricant's properties at the molecular level [54]. Through mechanisms such as ball-bearing effect, formation of protective tribofilms, and reduction of surface adhesion, nanolubricants effectively decrease friction between contacting surfaces, leading to enhanced efficiency and longevity in mechanical systems. Moreover, the tailored design and composition of nanoparticles allow for the customization of frictional properties to suit specific applications, presenting a versatile solution in diverse industrial sectors, from automotive and aerospace to manufacturing and biomedical engineering [55]. The parameters that affect the coefficient of friction are shown in Figure 5.

Impact on Wear

Nanolubricants wield a transformative influence on wear characteristics across a spectrum of mechanical applications. Infused with nanoparticles that operate at the molecular scale, these lubricants exhibit a remarkable ability to mitigate wear in sliding and rolling contacts [56,57]. The impact on wear of nanolubricants is profound, stemming from the nanoparticles' multifaceted mechanisms, including the formation of robust tribofilms, reduction of surface adhesion, and inhibition of abrasive wear. By their size and composition, nanoparticles act as active agents, fortifying the lubricant film and shielding contacting surfaces from deleterious mechanical interactions. These results in a substantial reduction in wear rates and surface damage, prolonging the lifespan of mechanical components and enhancing operational reliability [58]. Furthermore, the versatility of nanolubricants allows for tailored formulations, catering to specific wear requirements in diverse industrial sectors, thereby revolutionizing maintenance practices and driving advancements in tribological science [59].

Azmi et al. [60] used SiO_2-TiO_2/PVE nanolubricant to improve tribological features and ultimately the performance of the air-conditioning system. Nanolubricant concentration was varied from 0.01% to 0.1%. They concluded that at 0.005% volume concentration, nano lubricant demonstrated 25% reduced friction and anti-wear behaviour. The application of nanolubricant increased the COP and EER by up to 39.2% and 52.7%, respectively. The wear scarred diameter size is in line with the frictional coefficient's pattern. Conversely, a reduced worn scarred diameter results from a lesser coefficient of friction value.

DIFFERENT TYPES OF MACHINING OPERATIONS USING NANOFLUID UNDER MQL TECHNIQUE

Machining operations utilizing nanofluid under the MQL technique represent a cutting-edge approach in the realm of manufacturing [61]. This innovative method incorporates nanofluids, and suspensions of nanoparticles in base fluids, to enhance machining performance. Various types of machining operations can benefit from this advanced technique, including turning, milling, drilling, and grinding. Nanofluids, owing to their unique properties such as improved lubrication, cooling, and heat dissipation, offer significant advantages over conventional cutting fluids [62]. The MQL technique minimizes the consumption of lubricants while maximizing machining efficiency and tool life, making it an environmentally sustainable and economically viable option for precision machining applications across diverse industries [63]. Figure 6 represents the MQL test setup that is utilized for different machining operations.

Drilling Through MQL Technique

Drilling through the MQL technique is a cutting-edge approach that revolutionizes the conventional drilling process. By utilizing minimal amounts of lubricant, MQL reduces environmental impact while enhancing drilling efficiency and precision [64]. This technique involves

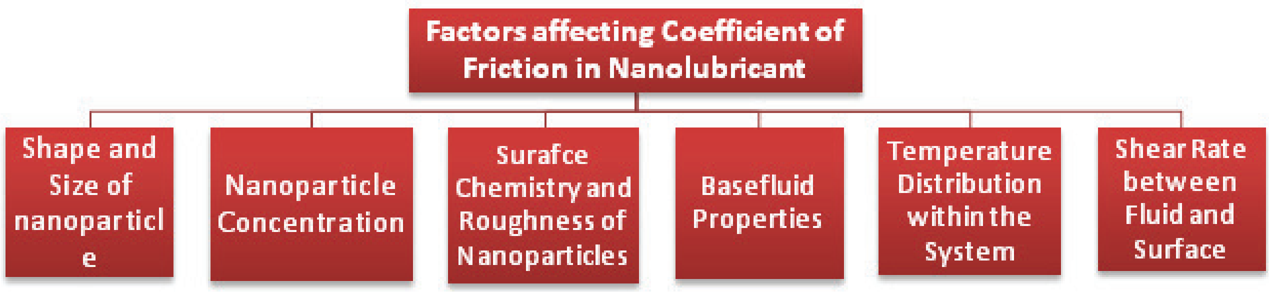

Figure 5. Factors that affect the coefficient of friction in a nano-lubricant.

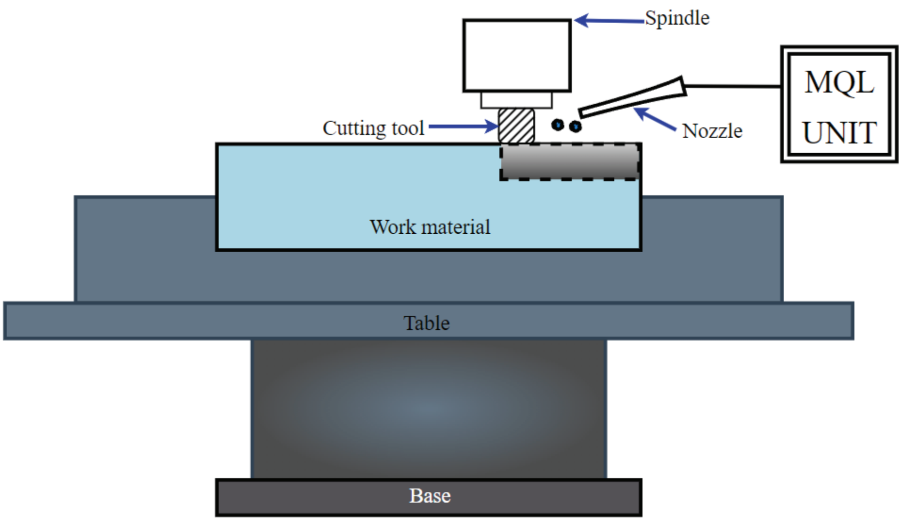

Figure 6. Schematic view of experiment on MQL set-up.

delivering a small, controlled quantity of lubricant directly to the cutting zone, where it effectively reduces friction, heat, and tool wear. MQL drilling offers numerous benefits, including improved surface finish, extended tool life, and reduced energy consumption compared to traditional flood cooling methods [65]. Additionally, MQL minimizes the formation of hazardous machining by-products and eliminates the need for extensive coolant management systems, making it a sustainable and cost-effective solution for various drilling applications in industries ranging from automotive and aerospace to medical device manufacturing [66].

Drilling is a very common machining operation used to make holes in different materials by utilizing a rotating cutting tool well known as a drill bit that is pushed to counter the workpiece to clear away the material and make a hole [67]. Mostly the drill bit is made of steel and carbide and comes in different sizes so that it can make holes of disparate diameters and depths. During the drilling process, the bit tends to rotate at high speed along with the axial load, and force is applied to it. Nano-lubrication is done in the cutting zone. This operation can be done by two different MQL lubrication systems are internally through the tool and externally sprayed on the tool. Whenever the surface

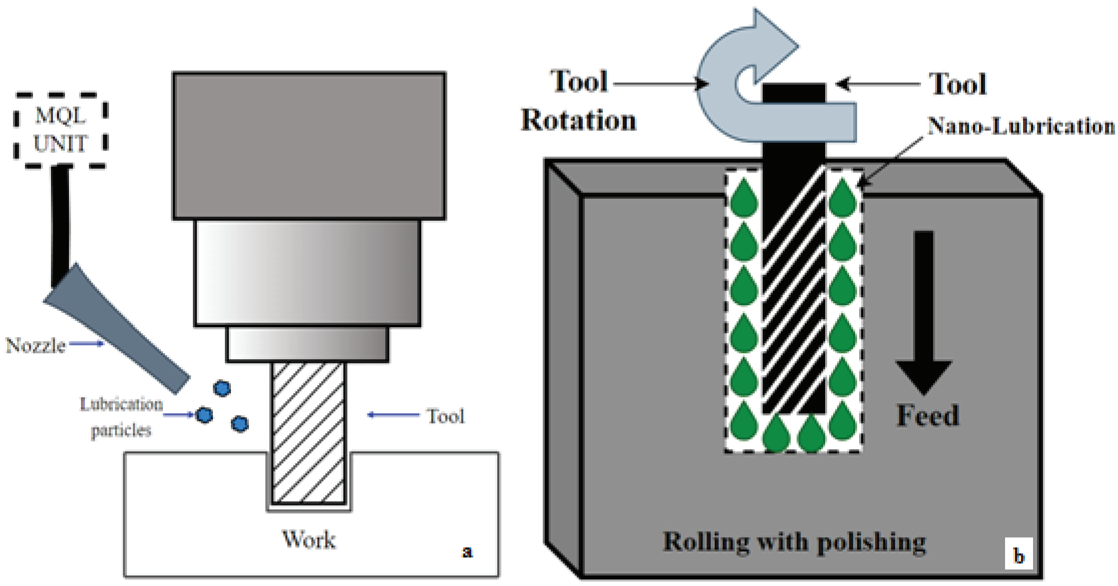

Figure 7. (a) MQL system setup for external lubrication (b) Visualization of MQL between tool-workpiece on performing drilling. Reproduced from Hisham et al. [40] by the authors.

quality of the hole in a drilling operation is compromised then the MQL lubrication can be done externally as illustrated in Figure 7(a) [40]. If you need better surface quality then you can go with the internally applied MQL technique as illustrated in Figure 7(b).

To reduce the cost of the best drilling operation and keep the point of environmental factor in mind palm oil can be used in place of synthetic oil. Jayal et al. [68] evaluated the health effects and performance of machining using cutting fluid in the drilling application of A390.0 aluminium alloy. They proposed the scope for developing a special cutting fluid for drizzling lubrication which has greater latent heat of vaporization. The high aerosol concentration tends to change the atomization properties of cutting fluid during drizzling lubrication. On behalf of this, they suggest developing a cutting fluid whose atom size range lies in the range that does not affect human health. They suggest using a diamond tip tool whenever the drilling of aluminium is performed over 2000 holes.

Khanafer et al. [69] examined the thrust forces, tool wear, and burr growth of a micro-drilling operation utilizing a MQL-nanofluid in contrast to pure MQL and flood cooling. The identical cutting variables, drilling instrument, and machining atmosphere were used for the MQL and the flood cooling in micro-drilling studies utilizing Inconel 718. When utilizing MQL-nanofluid instead of pure MQL and flood coolant, the thrust forces were found to be lowered, according to the findings. It was demonstrated that the unforeseen breakage of the micro drilling tool, the outermost corner destruction, and the flank wear were reduced when micro-drilling Inconel 718 superalloy utilizing MQL-nanofluid. Al_2O_3-containing MQL-nanofluids can enter the drilling domain more effectively, enabling the nanoparticles to produce a ball-bearing impact between their substance and the instrument that may greatly lessen thrust forces and friction.

Pal et al. [70] investigated the drilling effectiveness of AISI 321 stainless steel including cutting fluid that utilized vegetable oil under various MQL techniques. In comparison to pure MQL conditions, the experimental results showed that MQL drilling with 1.5 weight percent of graphene nanoparticles significantly decreased the thrust force by 27.4%, torque by 64.9%, surface roughness (33.8%), and friction coefficient by 51.7% at the 30th hole. It also increased the tool's lifespan. In summary, adequate concentrations of graphene nanoparticles in the nanofluid MQL drilling may enhance drilling properties by improving lubrication capability and lubrication surface durability.

Cetin et al. [71] examined the cutting forces and surface characteristics of newly invented nano-silver-added cutting fluids when drilling AISI 304 steel. SEM, XRD, and 3D topography were employed to both visually and analytically assess the drilling surfaces. The experimental findings demonstrated that a vegetable-based cutting fluid with nanosilver added outperforms boron fluid by about 15% when it comes to surface roughness reduction. The surface roughness was positively impacted by a decline in viscosity; However the cutting forces were not significantly changed. The addition of nanosilver to pH values has been seen to increase corrosion resistance and enable secure utilization of cutting fluids concerning worker health.

Turning Through MQL Technique

Turning through the Minimum Quantity Lubrication (MQL) technique revolutionizes machining processes by significantly reducing lubricant usage while enhancing efficiency and sustainability. Unlike traditional flood or spray cooling methods, MQL delivers a precisely controlled amount of lubricant directly to the cutting zone, minimizing waste and environmental impact [72]. This technique utilizes a fine mist or aerosol of lubricant, optimizing its application to the tool-workpiece interface, thus reducing friction, heat generation, and tool wear. MQL not only improves machining performance but also promotes cleaner working environments by eliminating excess coolant runoff. Embracing MQL represents a paradigm shift towards greener manufacturing practices, aligning with the growing emphasis on sustainability in industrial operations [73].

Thakur et al. [74] analysed the machining executions; cutting effort (force), roughness and temperature of cutting at the time of turning performed on EN24 (alloy steel) by utilising the MQL technique with SiC-established nanofluids. The weight % of nanoparticles was varied from 0.5 wt% to 1.5 wt%. Their findings showed that when the weight percentage of NPs rises, so does the thermal conductivity of SiC nanofluids. At 1.5 weight percent of NPs, the maximum thermal conductivity was detected. SiC-based nanofluids exhibit a decreasing specific heat as the weight percentage of NPs increases, with the lowest specific heat seen at 1.5 wt% NPs. Das et al. [75] investigated cutting effectiveness and comparative evaluation towards machinability augmentation during hard turning of HSLA- AISI 4340 steel utilizing four different nanofluid combinations via MQL technology. Al_2O_3, CuO, and Fe_2O_3 were used to generate three sets of nanofluid specimens with rice bran oil, and their varied characteristics were

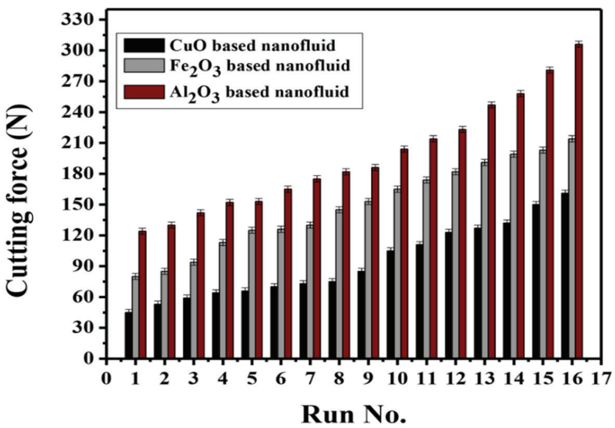

Figure 8. Variation of Cutting force with run number for three different nanofluids [From Das et al. [75], with permission from Elsevier].

examined at a concentration of 0.1%. Figure 8 compares the cutting forces of three nanofluids. Friction reduces when a fluid or lubricating film forms.

There will be less material adhesion when friction drops. Because the cutting edge and the edge's retention with the lubricating film's sharpness have a significant impact on the material's adherence. Thus, aluminium oxide-based coolant was shown to have more material adhesion than copper oxide-based coolant. Thus, more cutting force is encouraged by greater material adhesion. Additionally, the high thermal conductivity of copper-based nanofluid accelerates the rate of heat dissipation, protecting the cutting edge from heat-induced deformation and resulting in a decrease in force magnitude.

Hadad and Sadeghi [76] used the MQL technique to examine the impact of process variables on the turning of AISI 4140 steel alloy. They concluded that MQL machining outperforms dry and traditional machining when cutting fluid is supplied in a flood manner. This is because MQL works to improve chip-tool interaction, preserve cutting-edge precision, and reduce machining temperatures by decreasing cutting forces. The primary cause of the enhanced surface finishes was the utilization of MQL, which reduced corrosion and wear at the tooltip.

Ramanan et al. [77] utilized Al_2O_3 in the MQL system for the face turning of Incoloy 800. They concluded that the major influence on chip thickness is particular cutting. In comparison to ordinary coolant, it was discovered that applying 1% Al_2O_3 nanoparticle to the cutting fluid significantly improved its wettability characteristic. This decreased cutting forces in both directions and prepared the way for a reduction in the specific cutting energy.

Milling through MQL Technique

Milling through the MQL technique represents a paradigm shift in machining methodologies, emphasizing efficiency, sustainability, and cost-effectiveness. Unlike traditional flood coolant methods, MQL delivers a precisely controlled stream of lubricant directly to the cutting zone, significantly reducing fluid consumption while enhancing machining performance [78]. By minimizing coolant usage, MQL mitigates environmental impact and reduces waste disposal challenges, making it an eco-friendly solution. Moreover, MQL improves tool life and surface finish by reducing heat generation and friction during the milling process [79]. Its precision application ensures optimal lubrication exactly where it's needed, maximizing productivity and minimizing downtime. As industries increasingly prioritize sustainability and operational efficiency, MQL emerges as a transformative technique revolutionizing milling operations worldwide [80]. Many investigations are performed to give the best suitable cutting fluid.

Rahmati et al. [81] employed an experimental setup depicted in Figure 9 to perform research using a MoS2-based nanofluid as a lubricant during a milling process on AL6061-T6 alloy. According to their research, 0.5 weight percent of nanoparticles in oil, 4 bars of air pressure, and a 60° nozzle alignment angle yield the highest level of surface roughness. A concentration of 0.5 weight percent of nanoparticles in the mineral oil, a greater air stream pressure of 4 bars, and a 30° nozzle alignment angle are required to attain the minimal cutting temperature.

Muaz and Choudhury [82] looked into the use of solid lubricant-assisted cutting fluids in the MQL for nano-finishing of AISI 4340 steel utilizing $TiCN/Al_2O_3/TiN$ chemically vapour-coated carbide tungsten inserts during the flat end milling operation. According to their findings, the viscosity of the metal-working fluid was a significant factor in ensuring that the MQL process was properly lubricated. The tiny droplets exiting the MQL nozzle were able to easily penetrate the region being machined because of the fluid's low viscosity. Compared to the flooded lubrication, in which high-viscosity fluids functioned better because a thick and durable lubricating film developed, lower-viscosity fluids were most appropriate for MQL.

Kilincarslan and Cetin [83] conducted a thorough investigation into the tribological characteristics of cutting fluids that contained boric acid and nano-silver during the milling of AA7075-T6 material. The cutting fluid made with BA and nAg in an EG medium reduced surface roughness by 14.59% higher than the nAg and EG combination and by 5.27% higher than the BA and EG combination, based on the results. Furthermore, it was noted that the cutting forces of EG + BA + nAg were 0.846% and 0.115% lower, respectively, than those of EG + nAg and EG + BA.

Şirin and Kivak [84] utilized three different hybrid nanofluids such as hBN-Grpt, hBN-MoS_2, and Grpt-MoS_2 to the MQL milling performance of Inconel X-750

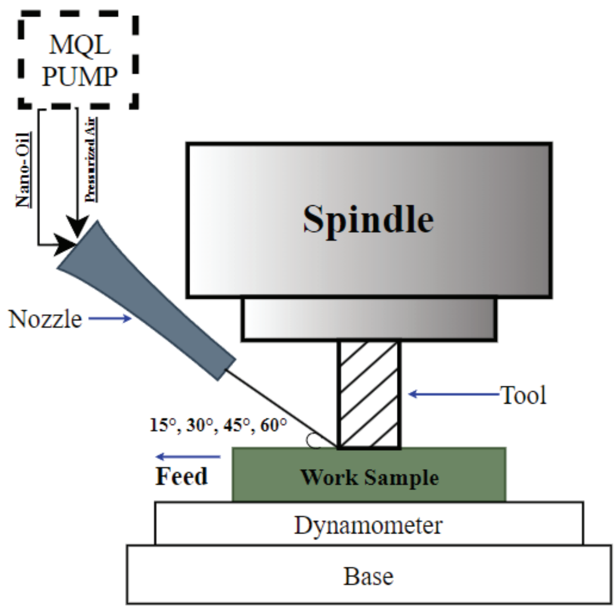

Figure 9. Experimental setup for milling operation. Reproduced from Rahmi et al. [81] by the authors.

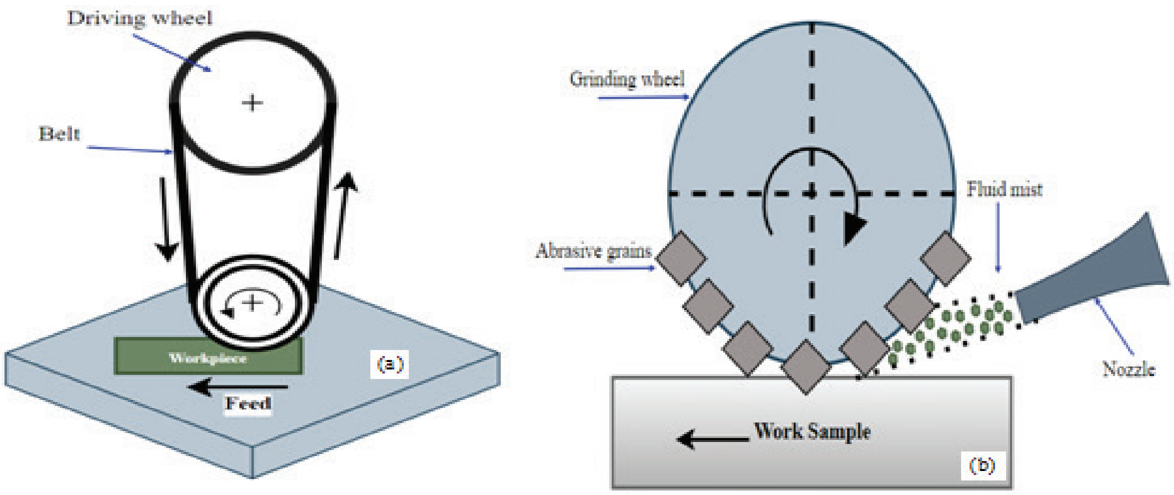

Figure 10. Simplified representations of the workpiece and aggravating in grinding operation (a) Wheel grinding (b) belt grinding. Reproduced from Madarkar et al. [86], Hou et al [87] by the authors.

superalloy. The feed rate during the machining operation was varied from 0.05 to 0.15 mm/rev and cutting speed was varied from 30 to 60 m/m. The studies' findings led to the understanding that the hBN-Grpt hybrid nanofluid functioned better across the board than the hBN-MoS_2 and Grpt-MoS_2 circumstances. In comparison to Grpt-MoS_2 and hBN-MoS_2 nanofluids, correspondingly, hBN-Grpt hybrid nanofluid demonstrated a 36.17% and 6.08% increase in tool life.

Jamil et al. [85] utilized Al_2O_3-MWCNT hybrid nanofluid to enhance the machinability performance for the milling of Ti-6Al-4V through MQL. The results indicate that at a nanofluid volume fraction of 0.24wt% and 120 mL/h of discharge at 0.6 MPa of air pressure, the lowest consequence force, cutting temperature, and roughness of the surface are, respectively, 24.3 N, 148.7 °C, and 0.67 μm.

Grinding Through MQL Technique

Grinding is a machining operation that is used to detach the material from a workpiece by utilizing an aggravating wheel or belt as shown in Figure10(a) [86] and Figure 10(b) [87] which gives a straightforward and accurate surface finish. Whenever a high tolerance is required on the hardened material this operation is utilised in the best manner. In the grinding procedure, the aggravating wheel or belt makes contact with the workpiece and removes small material chips through a mixture of rubbing, cutting and shearing steps. As per the requirement of the surface finish of the workpiece, different grinding machines are utilised such as centerless, surface and cylindrical grinders [88]. This operation has the ability that provide dimensional control and high accuracy on the workpiece. To increase the surface quality many researchers have performed grinding through the MQL technique which some discussed below.

Yang et al. [89] used carbon nanotube, SiO_2, Fe_2O_3, and hydroxyapatite nanofluids with mass fractions of 2%, 4%, 6%, 8%, and 10%, respectively, to conduct a nanoparticle jet MQC grinding test. They concluded that, within a specific mass fraction span, the cooling impact of nanofluids exhibits an inversely proportional connection with mass proportion; however, outside of this span, the association is proportionate. The critical mass percentages vary across various types of nanoparticles.

Balan et al. [90] have performed MQL grinding of Inconel 751, using oil mist. According to their research, improved grinding efficacy can be achieved under the MQL circumstances if the minimum order oil flow rate is met along with increased pressure. Higher force and roughness are the result of decreased air pressure and flow velocity, even at lower temperatures. The research also shows how important flow rate is in MQL grinding from a quantitative standpoint. A minimal level of surface roughness and grinding force can be obtained in MQL by raising the air and fluid pressure levels.

In the externally performed cylindrical plunge grinding of AISI 4340 steel employing an aluminium oxide grinding wheel, Lopes et al. [91] assessed the standard MQL implementation, MQL with cooled air (MQL+CA) and supported by a wheel cleaning jet (MQL+WCJ), and compared them with the traditional approach with prevalent fluid. The results of the investigations demonstrated that, across all examined factors, the traditional approach yielded the best outcomes. Additionally, MQL+WCJ and MQL+CA performed better than every result from regular MQL, demonstrating the value of these environmentally friendly methods and their industry application. Furthermore, the MQL+WCJ approach outperformed the MQL+CA, yielding nearly identical results when compared to the traditional method.

CONCLUSION

This review provides a comprehensive examination of the utilization of nanofluid lubricants in machining processes from both sectoral and academic viewpoints. Through an in-depth analysis of existing literature, it has been established that nanofluid lubrication offers significant potential to enhance machining efficiency, tool life, and surface quality while mitigating environmental impacts. From an academic perspective, the manuscript contributes to the understanding of the fundamental mechanisms underlying nanofluid behaviour in machining, thereby paving the way for further research and development in this field. Moreover, from a sectoral standpoint, the insights presented in this review can inform industry practitioners about the feasibility and benefits of integrating nanofluid lubrication into their machining operations. By bridging the gap between academia and industry, this manuscript serves as a valuable resource for advancing the adoption of nanofluid lubricants in machining processes, ultimately driving innovation and sustainability in the manufacturing sector. The following conclusions are drawn from this review article:

- Nanofluid lubrication applied through the Minimum Quantity Lubrication (MQL) technique offers enhanced lubrication efficiency compared to traditional cutting fluids, leading to reduced friction and wear during machining operations.
- The utilization of nanofluid lubrication via MQL helps in minimizing the consumption of cutting fluids, thus reducing waste generation and environmental pollution associated with machining processes.
- Nanoparticles dispersed in the lubricant contribute to the formation of a protective boundary layer on cutting tool surfaces, resulting in prolonged tool lifespan and reduced tool replacement frequency.
- Nanofluid lubricants improve surface finish quality by reducing machining-induced defects such as burrs and built-up edge formation, leading to higher precision and smoother surface textures.
- The efficient utilization of nanofluid lubrication through the MQL technique can lead to cost savings by reducing the consumption of expensive cutting fluids and minimizing maintenance requirements for machining equipment.
- The promising benefits demonstrated by nanofluid lubrication through the MQL technique suggest its potential for widespread adoption in industrial machining operations, offering a sustainable and cost-effective alternative to conventional cutting fluids.

Future Recommendation

Some future recommendation of this review article is mentioned below:

- Investigate the effects of different types, sizes, and concentrations of nanoparticles on the performance of nanofluid lubrication in machining operations via MQL. This exploration can help identify the most effective nanoparticle configurations for specific machining processes and materials.
- Conduct comprehensive tribological studies to better understand the mechanisms governing the interaction between nanoparticles and the machining environment. This will aid in elucidating the underlying friction and wear mechanisms and optimizing the lubrication performance of nanofluid MQL systems.
- Evaluate the environmental impact and sustainability aspects of nanofluid lubrication through the MQL technique compared to traditional cutting fluids. This assessment should consider factors such as resource consumption, waste generation, and overall ecological footprint to provide a comprehensive understanding of the environment.
- Explore the potential for integrating nanofluid lubrication with advanced machining techniques such as high-speed machining, hard machining, and multi-axis machining. Optimizing the synergy between nanofluid lubrication and these processes can further enhance machining efficiency, surface quality, and tool life.
- Investigate the scalability and feasibility of implementing nanofluid lubrication through the MQL technique in large-scale industrial machining operations. This research should address practical challenges such as nanoparticle dispersion stability, system reliability, and cost-effectiveness to facilitate the widespread adoption of this technology in manufacturing industries.
- Develop advanced monitoring and control systems capable of real-time assessment and adjustment of nanofluid MQL parameters during machining operations. This will enable adaptive optimization of lubrication conditions based on dynamic changes in cutting conditions, material properties, and tool wear, leading to improved process stability and performance.
- Develop advanced computational models to simulate the behaviour of nanofluid lubricants at the nanoscale and predict their performance in macroscopic machining processes. Integrating computational fluid dynamics (CFD) with molecular dynamics (MD) simulations can provide valuable insights into the underlying mechanisms governing nanofluid behaviour under cutting conditions.

ABBREVIATIONS

BA	Boric acid
CA	Cooled air
COP	Coefficient of performance
EER	Energy efficiency ratio
EG	Ethylene glycol
GDP	Gross domestic product
Grpt	Graphite
HSLA	High strength low alloy
hBN	Hexagonal boron nitride

MQC	Minimum quality cooling
MQL	Minimum quality lubrication
MWCNT	Multi-walled carbon nanotubes
NP_S	Nanoparticles
nAg	Nano-silver
WCJ	Wheel cleaning jet

AUTHORSHIP CONTRIBUTION

All the 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 manuscript.

CONFLICT OF INTEREST

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

ETHICS

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

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