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Review

The Recent Advancements in Minimum Quantity Lubrication (MQL) and Its Application in Mechanical Machining—A State-of-the-Art Review

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Abstract

The move toward environmentally friendly methods in the global manufacturing sector has led to the use of minimum quantity lubrication (MQL) as an eco-friendly alternative to traditional flood cooling. However, the natural limits of MQL in high-performance settings have led to the use of nanotechnology, which has resulted in the creation of nanofluids, engineered colloidal suspensions that significantly improve the thermophysical and tribological properties of base fluids. This paper gives a complete overview of the latest developments in nanofluid technology for use in machining. It starts with the basics of MQL and the rules for making, describing, and keeping nanofluids stable. The review examines the application and effectiveness of single and hybrid nanofluids in various machining processes. It goes into detail about how they improve tool life, surface integrity, and overall efficiency. It also examines the benefits of integrating nanofluid-assisted MQL (NMQL) with more advanced and hybrid systems, including cryogenic cooling (cryo-NMQL), ultrasonic atomization, electrostatic–magnetic assistance, and multi-nozzle delivery systems. The paper also gives a critical look at the main problems that these technologies face, such as the long-term stability of nanoparticle suspensions, their environmental and economic viability as measured by life cycle assessment (LCA), and the important issues of safety, toxicology, and disposal. This review gives a full picture of the current state and future potential of nanofluid-assisted sustainable manufacturing by pointing out important research gaps, like the need for real-time LCA data, cost-effective scalability, and the use of artificial intelligence (AI) to improve processes, and by outlining future research directions.

Keywords: nanofluids; NMQL; LCA

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1. Introduction

As industries work more and harder to become "green," they are moving away from traditional, resource-intensive methods and toward more sustainable and efficient ones. One of the main goals of this change has been to cut down on or get rid of traditional cutting fluids. Even though they work well, they are quite bad for the environment and workers' health. This change in thinking made way for MQL, a revolutionary method that sends a slight mist of oil and air straight to the cutting surface, reducing fluid use by a vast amount.

MQL works on the idea that "more is not always better." It has effectively encouraged cleaner output and lower operating costs, which is a big step toward sustainable machining.

However, that was not the end of the changes in manufacturing. Different ways of improving manufacturing other than MQL have been explored by researchers in recent times [1,2]. Standard MQL has limitations in high-heat situations and when machining superalloys that are difficult to cut, necessitating a new level of innovation. This was made possible by nanotechnology, which led to the creation of "nanofluids." They are manufactured colloidal suspensions of nanosized particles (such as oxides, carbides, or carbon nanotubes) in a base fluid. The primary objective of nanofluids is to enhance the thermophysical properties of the base fluid at a fundamental level, thereby increasing its thermal conductivity and lubricating capabilities beyond those of conventional liquids.

The synergy between these two technologies created NMQL, a method that combines the lean delivery of MQL with the superior performance of nanofluids. This combination has worked very well, making heat dissipation easier and lowering friction at the tool–workpiece contact more effectively than either technique could do on its own. The field has kept moving forward, combining NMQL with other cutting-edge methods to push the limits of performance. Cryo-MQL is one of these hybrid systems. It combines nanofluid lubrication with the freezing effect of liquid nitrogen or carbon dioxide. Other advanced delivery methods include ultrasonic atomization, electrostatic charging, and multi-nozzle or through-tool application systems. These new ideas provide customized solutions that enhance tool life, surface integrity, and overall process efficiency.

Despite these promising developments, there are still problems that need to be solved before nanofluid-based systems can be widely used. A significant problem with nanoparticle suspensions is that, by clumping together, they can lose their improved qualities. Also, these technologies need to be thoroughly tested for their environmental and economic feasibility through extensive LCAs, which must take into consideration the energy-intensive manufacture of nanoparticles. The most significant thing is that the toxicity, safety, and correct disposal of nanomaterials raise serious problems. To mitigate these risks to human health and the environment, a robust regulatory framework and safety measures are necessary.

This review provides a thorough examination of this field, covering all the changes and developments that are happening quickly. It starts with the basics of MQL and nanofluids and then goes into how to use single and hybrid nanofluids in different machining operations. The research examines the application of nanofluids in conjunction with cryogenic cooling and other advanced lubrication systems, providing detailed insights into the performance gains they offer. It also discusses the associated problems, including its environmental impact, cost, and safety. This paper aims to give a complete picture of the current state and future potential of nanofluid technology in sustainable manufacturing by pointing out essential research gaps and suggesting future directions, such as the need for real-time LCA data and the use of artificial intelligence to improve processes.

2. Research Scope and Objectives

This review article looks at the growing topic of nanofluid technology in the context of sustainable manufacturing in a thorough and detailed way. This study covers the basic ideas of MQL and the creation, description, and stability of nanofluids. It systematically examines the use and performance of both single and hybrid nanofluids in various machining processes, focusing on their impact on tool life, surface integrity, and process efficiency.

A significant portion of this review is on how to combine NMQL with advanced and hybrid systems. This includes a thorough look at cryo-NMQL and other new ways to give lubrication, like electrostatic, magnetic, and ultrasonic-assisted lubrication.

The scope goes beyond performance research to include a critical look at the technology's wider effects. This consists of a complete LCA of the environmental and economic viability, as well as an essential consideration of the toxicity, safety, and disposal problems that come with nanomaterials. Lastly, the article talks about the gaps in present research and suggests future approaches. It investigates how artificial intelligence could be used to improve processes and the urgent need for strong regulatory standards. The review is limited to published academic and industrial research. Its goal is to provide a comprehensive and forward-looking overview of the current state of nanofluid-assisted machining. Figure 1 shows the framework of this research.

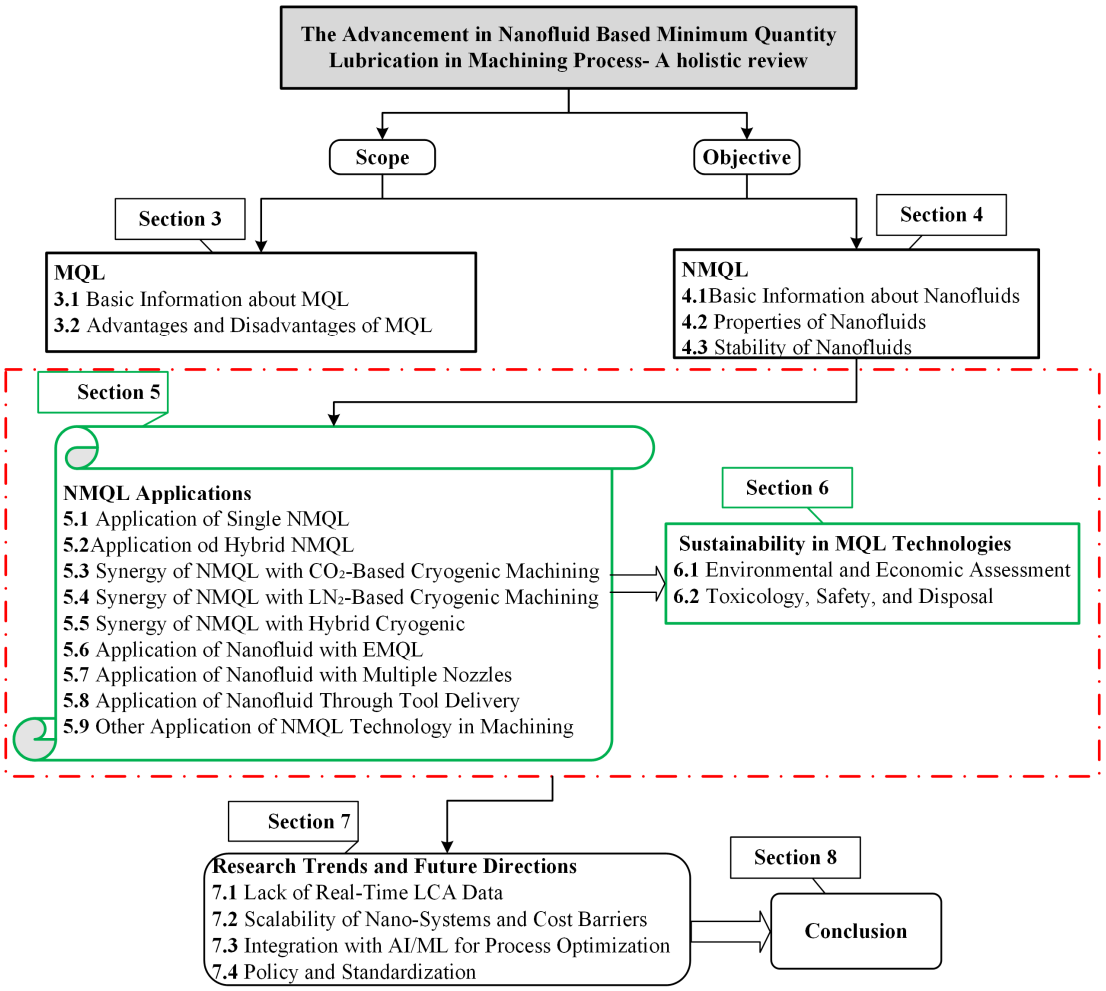


Figure 1. Research framework of the study.

3. Minimum Quantity Lubrication

Recently, "green manufacturing" has become a big concern for many metal-processing industries. This concern can be solved by implementing MQL. This section will describe the basics of MQL machining. The components, types, and advantages of the MQL technology will be discussed.

3.1. Basic Information About MQL

Prof. I.S. Jawahir proposed the concept of minimum quantity lubrication at the University of Kentucky in the 1990s. At that time, researchers used this technology with machining

with "spray cooling." However, later, with the passage of time, different industries and research institutes called it different synonyms. Most researchers referred to it as MQL. However, some research institutes also refer to it as "near-dry machining" or "NDM," "small quantity lubrication" or "SQL," "minute quantity lubrication," "minimal quantity lubrication," and "micro-lubrication". The working principle of all terminologies is the same; MQL is an alternative sustainable approach to the use of conventional cutting fluids in metal removal processes. Consumption of metalworking fluids (MWFs) has been drastically reduced after MQL implementation in machine shops. Researchers claimed that MQL has the capability to consume 10,000 times less fluid than conventional machining [3,4].

MQL works on the basic principle that "more is not always better." So, it replaces a huge amount of oils, water, and coolants in the workshop and promotes cleaner production. The MQL system is easy to use; the oil and air mixture is delivered to the workpiece–tool interface. Many researchers have designed their own MQL systems according to their requirements. However, the MQL system is also commercially available; Unist (Grand Rapids, MI, USA), DropsA (Macomb, MI, USA), Bechem (Hagen, Germany), MAFA-Sebald Produktions-GmbH (Breckerfeld, Germany), Apache Aerospace (Mukilteo, WA, USA), HES Lubemec (Gloucester, UK), Lubrication Scientifics(Irvine, CA, USA), and Vogel Lubrication (Senftenberg, Germany) are some well-known manufacturers of the MQL system.

3.2. Advantages and Disadvantages of MQL

MQL machining is replacing wet machining as a cost-effective and ecologically beneficial alternative. By employing an aerosol at the process point via a nozzle output instead of flooding the work area, MQL systems save coolant expenses significantly. Therefore, the procedure uses much less coolant. Better system efficiency, longer tool life, and less downtime for cleaning and maintenance boost profits. Most manufacturers still link sustainability with increased prices. When we break down the "wet" production system investment and operation costs, it becomes obvious how much these traditional systems cost. Coolant supply, filtration, and mist-collecting equipment costs rise with transfer, recycling, and pressurization. Operating "wet" equipment increases lifespan costs in energy consumption, chemical maintenance, water make-up, disposal of wasted cutting fluids, and beginning the waste/recovery cycle again by refilling fluids. Considering the wider environment, MQL systems accommodate the greenest of machining requirements. With a substantial reduction in excess oil and white-water usage, the green, eco-friendly solution is used entirely at the rate at which it is dispensed, almost eliminating the need to dispose of excess waste lubricant. For example, Coolube's® 100% natural, non-toxic, renewable plant oil composition is suitable for environmentally conscious enterprises. Coolube® is petroleum-free, chlorine-free, silicone-free, and VOC-free. Although biodegradable, Coolube® has a lengthy shelf life. MQL also offers longer tool life, better surface polish, and less maintenance compared to dry machining. The MQL flow penetrates the cutting zone and it acts in three different ways, that is, cooling the tool and workpiece, lubricating, and removing the chips [5]. Tool longevity increased by up to 300 percent and reduced maintenance time for switching and replacing tools save expenses. Race et al. [6] demonstrated that MQL can improve surface integrity and reduce tool wear when cutting carbon steel. Similarly, Sun et al. [7] noted that it enhanced the overall cutting performance during high-speed machining of the GH4099 superalloy. The mechanism for these improvements was explored by Tasdelen et al. [8], who determined that MQL reduces the tool–chip contact length, leading to a more effective cooling and lubrication effect. Furthermore, studies on difficult-to-machine materials like Ti-6Al-4V have reinforced these findings. Park et al. [9] concluded that MQL milling lowered cutting forces and improved tool wear when compared to traditional wet and dry methods. In a similar vein, An et al. [10] found that, while both MQL and cryogenic

cooling reduced cutting temperatures in high-speed milling of Ti-6Al-4V, the cooling effect provided by MQL was particularly significant. MQL improves engineering productivity while protecting the workplace and environment. MQL systems are seen as cost-effective and eco-friendly lubrication solutions for many applications, gaining industry interest. Engineering procedures are simplified, accurate, and environmentally friendly, utilizing technology that eliminates health and safety issues associated with flood lubrication systems. Engineers may accomplish far better tool life and maintenance with an MQL system than with dry machining, especially in high-pressure environments. MQL systems, like Keencut, reduce labor hours for cleaning and maintenance. For any engineering workplace, the devices provide clean, efficient, self-sufficient lubrication. Manufacturers and suppliers must comprehend client needs at the grassroots level. MQL solutions match market demand and provide customers with a variety of genuine advantages that improve their daily operations. Manufacturers using MQL make workers safer, with short- and long-term benefits. Operators, experienced tradespeople, and engineers are no longer exposed to "wet" machining toxins, germs, and fungus. The oil used for MQL is usually vegetable or ester-based, which is safer. Because no used cutting fluids must be disposed of according to strict laws, the environment is cleaner and production is less seen as "dirty." On the other hand, the disposal of oil and other waste has serious environmental consequences. Environmental mitigation is mandated by law, but enforcement is complex, costly, and problematic.

Though very few, MQL systems also have some disadvantages. Chip evacuation in MQL is inferior to wet machining. MQL is still unsuitable for deep-hole drilling, energy-intensive grinding, honing, small-hole drilling, and hard-to-machine materials like titanium and nickel-based alloys. MQL still creates a thin mist that is harder to filter. MQL deployment may involve machine tool and processing method adjustments.

To overcome the limitations of traditional MQL around the year 2000, researchers developed an advanced approach known as nanofluid-based MQL. By adding nanoparticles into the base oil, this innovative technique improves the conventional MQL fluid. The resulting nanofluid overcomes the performance gaps of standard MQL systems by possessing superior thermal conductivity and improved tribological properties.

4. Nanofluid-Based MQL

Nanofluids are defined as a highly stable mixture of metallic or non-metallic nanoparticles with an aqueous or non-aqueous base fluid to enhance the thermal properties of the base fluid. Lubrication mechanisms of nanofluid improve surface properties and reduce surface energy primarily through two strategies: fluid-film formation and boundary film adsorption. In hydrodynamic lubrication, the relative motion of surfaces generates a pressurized fluid film that physically separates the asperities, virtually eliminating wear and minimizing friction by shearing the lubricant rather than the solid surfaces. When a full film cannot be sustained, boundary lubrication takes over, where additives in the lubricant like nanoparticles adsorb onto the surfaces. This adsorption process is thermodynamically driven by a significant reduction in the high surface energy of the solid, creating a stable, low-shear-strength molecular layer. This sacrificial film prevents direct metal-to-metal contact, adhesion, and scuffing, which leads to reduced friction, minimized wear, and enhanced operational stability. This section will describe the fundamentals of nanofluids, different methods of preparation of nanofluids, criteria to evaluate the stability of nanofluids, and the necessity and importance of nanofluids.

4.1. Basic Information About Nanofluids

As defined before, nanofluids are a customized mixture of nanoparticles and base fluids; the thermal and physical properties of the mixtures change according to the area of application. Before fabricating the nanofluid, it is vital to study the individual properties of the base fluid and nanoparticles. Suppose the nanoparticles used to fabricate the nanofluid do not enhance the properties of the nanofluid as compared to the base fluid. In that case, such a nanofluid is useless in most applications. So, the basic principle of fabricating a nanofluid must fulfill the rule, i.e., combining two different things to an enhanced effect which should be greater than the sum of the two individuals. Nanofluids can be made by mixing nanoparticles of different families, such as carbides (TiC), oxides (Al_2O_3, CuO), semiconductors (SiC), nitrides (ALN, SiN), metals (Au, Ag, Cu), graphene, and carbon nanotubes. Each of the nanofillers has its own distinct benefits. Oxide-based nanofillers, such as aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), and zinc oxide (ZnO), are known for their high thermal conductivity and hardness, which enable them to act as effective heat sinks and mild abrasives that polish the workpiece surface. Carbide-based nanofillers, notably silicon carbide (SiC), are extremely hard and provide exceptional anti-wear and anti-friction properties, helping to extend tool life and improve surface quality. Nitrides, such as hexagonal boron nitride (hBN) and titanium nitride (TiN), are a class of ceramic nanofillers recognized for their outstanding thermal stability, hardness, and lubricity, which are crucial for high-temperature machining applications. Metal nanofillers, including silver (Ag) and copper (Cu), are excellent heat conductors, significantly enhancing the cooling capabilities of the nanofluid which helps in dissipating the heat from the cutting zone [11]. Finally, carbon-based nanofillers, a category that includes graphene and carbon nanotubes (CNTs), are among the most effective for MQL systems due to their superior self-lubricating properties [12], which minimize friction and wear, and their high thermal conductivity, which efficiently dissipates heat, leading to lower cutting forces and a better surface finish [13]. Also, mixing carbon-based nanoparticles into base dielectric fluid yields a notable reduction in surface crack density [14]. In addition, some non-metallic and other recently developed materials are also the best candidates for nanofluids according to the desired application. Similarly, the most commonly used base fluids in machining applications are water (H_2O) and ethylene glycol. However, some vegetable oils such as sunflower oil and blasar cutting oils have also been used by many researchers. In the past, micro-sized particles were used; however, later, to get enhanced properties, novel technology based on nanoparticles evolved. At the end of the 20th century, Choi started work on the classification and fabrication of new nanoparticle-based fluids and gave them the name "nanofluid" [15]. Different methods can make nanofluids, and there are different criteria to evaluate the performance of nanofluids. Recently, nanofluids have been used by many scientists in industrial and metal-processing applications to promote sustainability. In the machining process, nanofluids are applied with a customized or commercially available MQL system. The application of nanofluid in the machining process is a cost-effective, green, clean, and efficient method. In short, nanofluids are gaining fame in many applications as they produce better performance than normal heat transfer fluids (HTFs). Nanofluids are used in electronics, microdevices, chillers, refrigerators, machining, engines, oscillating pipes, heat exchangers, fuel cells, and many medical applications. Lastly, nanofluids can be classified into two major types, i.e., single and hybrid nanofluids. Nanofluid preparation is a complicated process. Figure 2 shows the preparation process for nanofluids.

During this preparation process, the nanoparticles are mixed with base fluids and made into nanofluids. The preparation methods include one-step methods and a two-step method. Figure 3 shows a visual representation of one-step methods.

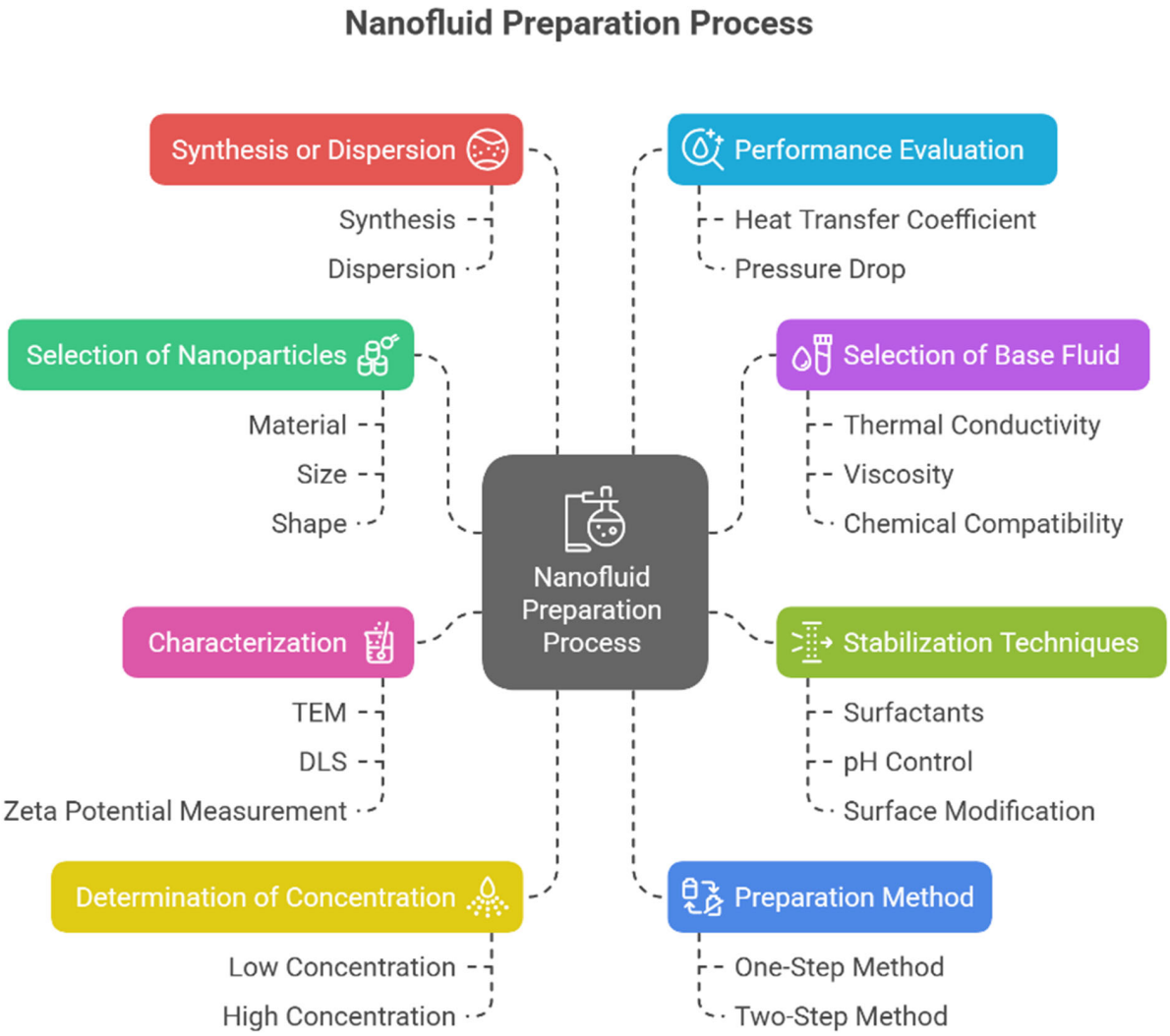


Figure 2. Schematic diagram of nanofluid preparation process.

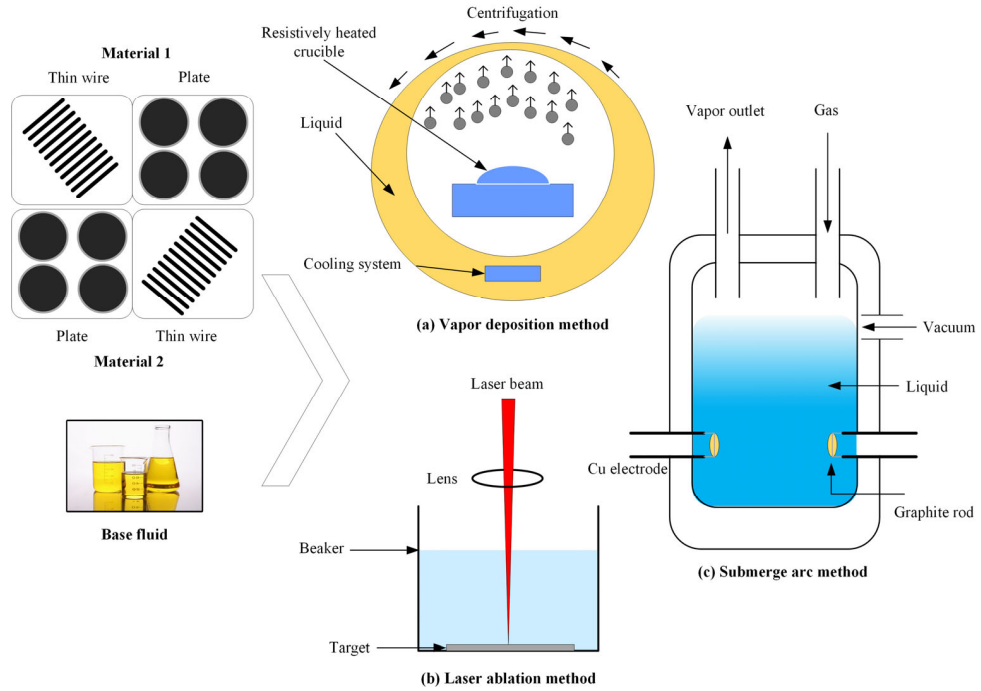


Figure 3. One-step methods of nanofluid preparation.

Figure 4 shows a visual representation of the two-step method.

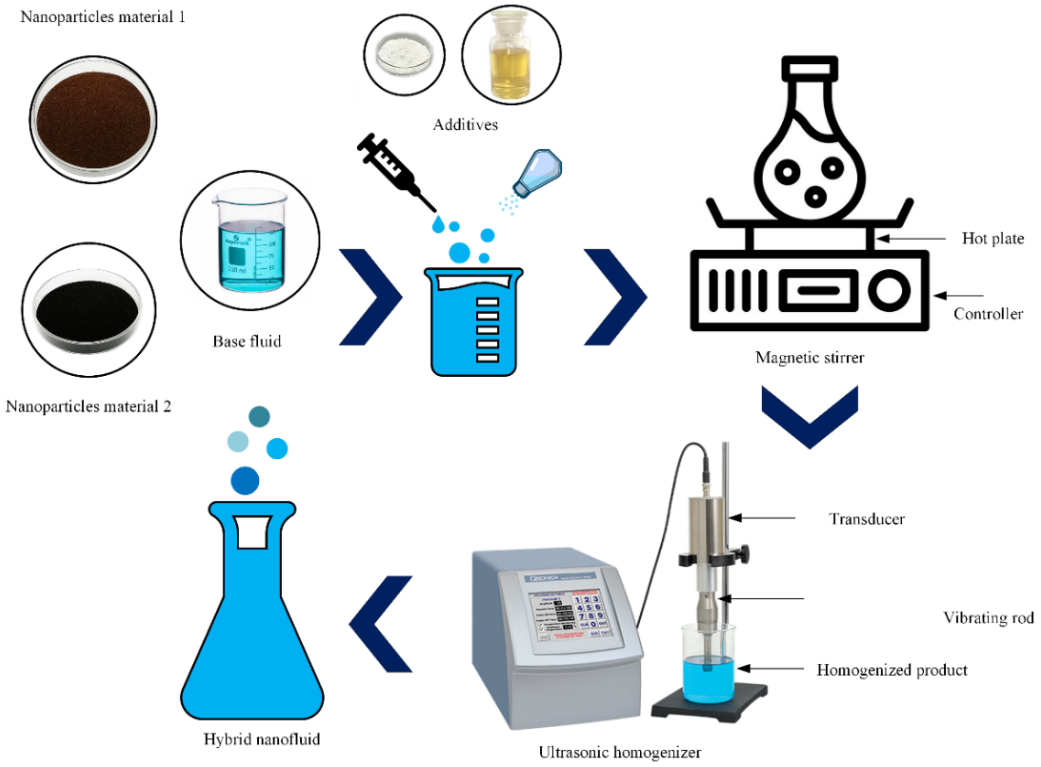


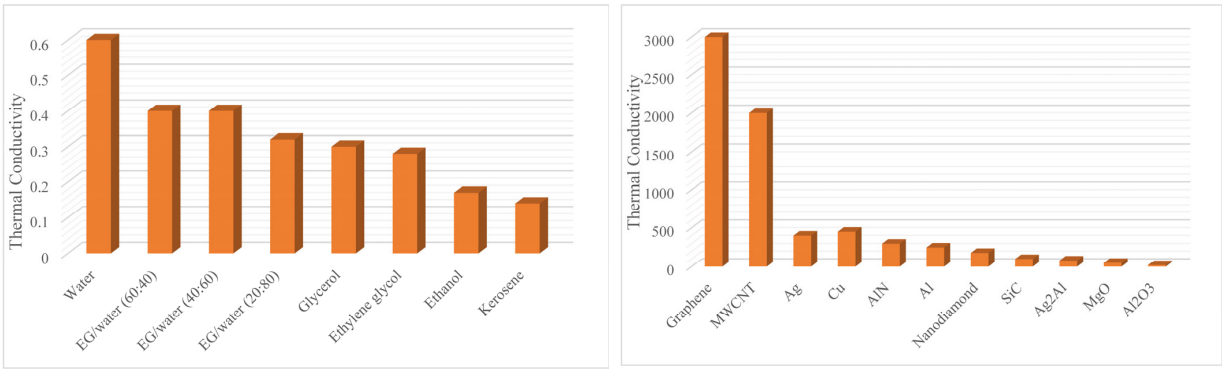
Figure 4. Two-step method of nanofluid preparation.

4.2. Properties of Nanofluids

Thermal conductivity, viscosity of nanofluids, heat transfer, nanoparticle size, and density are fundamental parameters that influence the properties of the nanoparticles. The thermal properties of the nanofluid include temperature, enthalpy, specific heat, density, and viscosity. Similarly, heat-transfer-related properties include pressure drop, heat capacity, and conductivity. Properties related to the stability of the nanoparticles are pH values, suspension stability, and zeta potential. Some properties of the nanofluids are related to the lubrication capabilities, i.e., extreme pressure, friction coefficient, wear rate, viscosity index, and viscosity rate. It is important to understand that physical properties of the nanofluids are different from those of the host fluid.

4.2.1. Thermal Conductivity

Enhanced thermal conductivity of nanofluids as compared to base fluids makes them an ideal choice for heat transfer applications. Lee et al. [16] prepared Al_2O_3-based nanofluids and observed a 1.44% increase in the thermal conductivity of the nanofluids when compared with base fluid. In another study, Chandrasekar et al. [17] found a maximum increase of 7.52% in the thermal conductivities of Al_2O_3/water when compared with base fluid. A linear relationship between thermal conductivity of concentration percentage and thermal conductivity was found. In the study of Paul et al. [18], it was noted that thermal conductivity of Al-Zn-based nanofluid highly depends upon the particle size, stability of dispersed nanoparticles, temperature, and concentration. With a percentage volume concentration of 0.1, a 16 percent enhancement in the thermal conductivity was observed. Yu et al. [19] prepared kerosene-based Fe_3O_4 nanofluids. The authors observed that increases in the concentration of nanoparticles can increase the thermal conductivity up to 34% which is more than the thermal conductivity of Fe_3O_4 alone. Figure 5 shows the thermal conductivity of nanofluids.



(**a**) (**b**)

Figure 5. (**a**) Thermal conductivity of base fluid; (**b**) Thermal conductivity of nanoparticle.

4.2.2. Viscosity

Viscosity is defined as the tendency of a fluid to restrict its flow; it is a ratio of shear stress to shear rate. Newtonian fluids are defined as those fluids whose viscosity does not change with a change in shear rate. However, in non-Newtonian fluids, viscosity changes as the shear rate changes [20]. Phenomenological hydrodynamic equations were used by Einstein [21] to calculate the effective viscosity of fluid. Chiesa et al. [22] performed experiments to determine the viscosity of Cu nanoparticles. It was noted that Cu-based nanofluid possessed four times more viscosity than the viscosity predicted by the Einstein law of viscosity. Equation (1) shows the law of viscosity.

$$\frac{\mu}{\mu_{df}} = 1 + 2.5\phi \tag{1}$$

where ϕ is volume fraction, μ is the viscosity of the nanoparticles, μ_{df} is the viscosity of the base fluid.

Experimental studies of the dynamic viscosity of stable water-based nanofluids containing ethylene glycol were conducted by Banisharif et al. [23]. Newtonian behavior is seen at all temperatures, excluding lower ranges, in the interval of −20 °C to 20 °C. No substantial increase in viscosity was observed for multi-walled carbon nanotube (MWCNT) nanofluids, which exhibit a reduction in viscosity with increasing nanoparticle concentration, while Cu and Fe_3O_4 nanofluids have a similar trend. Figure 6 shows the viscosity of nanofluids against temperature.

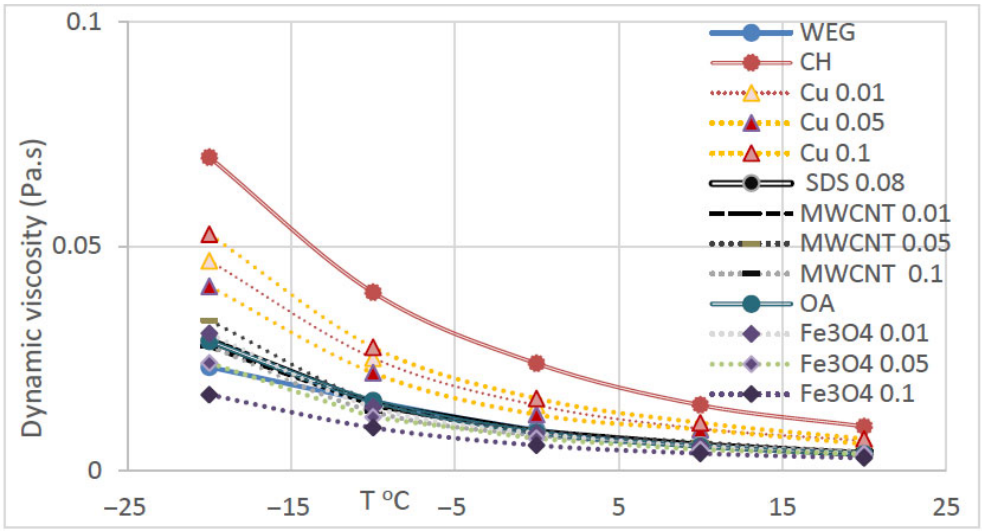


Figure 6. Viscosity of nanofluids [11].

4.2.3. Convective Heat Transfer

For the application of a heat exchanger, it is better to consider the concept of the heat transfer coefficient rather than the thermal conductivity. Heris et al. [24] prepared Al_2O_3 and CuO-based nanofluids and studied the effect of heat transfer during laminar flow. The authors noted the significant increase in the heat transfer (40%); however, just 15% thermal conductivity was enhanced as compared to the base fluid. Putra et al. [25] studied the natural convection of oxide-based nanofluids. The authors noticed during forced convection that natural convective heat transfer deteriorated significantly. This was because convective heat transfer depends upon the particle density.

In summary, nanofluids possess excellent heat transfer capabilities and are suitable for application in many heat exchangers. Recently, theoretical and experimental studies have shown that the heat transfer coefficient of nanofluid is higher than that of the host fluid in both forced and natural convection heat transfer.

4.2.4. Density

Surface tension, specific heat, and density of nanofluids are relatively less studied as compared to other parameters. The density of nanofluids is defined as the volume ratio of nanoparticles to the base fluid. It is a common fact that the densities of solids are usually higher than the densities of liquids, so, in general, the densities of nanofluids are higher than those of base fluids. Before the experimental approach, the density of nanofluids was assessed by the mixing theory; Equation (2) defines the mixing theory.

$$\rho_{nf} = (1 - \phi)\rho_{bf} + \phi\rho_s \quad (2)$$

where ρ_{nf} = density of nanofluid, ρ_{bf} = density of base fluid, ρ_s = density of solid particles, ϕ = volume fraction.

4.2.5. Pressure Drop

Similar to the density of nanofluids, very few studies have been published related to the pressure drop of nanofluids. Furthermore, there is a dire need to formulate the modeling and estimation equations of pressure drop. Peng et al. [26] studied the pressure drop of refrigerant-based nanofluids and found that the mass fraction of nanoparticles has a significant effect on the pressure drop of nanofluids. It was observed that increasing the mass fraction of nanoparticles also increased the pressure drop of the nanofluid. In another study, Xuan et al. [27] conducted experiments to study the pressure drop of TiO_2/water nanofluid for various volumetric concentrations. It was noted from the measurements that the pressure drop of the nanofluid was slightly higher and increased with the increase in the volume concentration. Similarly, Razi et al. [28] measured pressure drops for CuO-base oil nanofluid, Tun-Ping Teng et al. [29] studied pressure drop of TiO_2/water nanofluid, and Suresh et al. [30] measured pressure drop for Al_2O_3–Cu/water hybrid nanofluid.

4.2.6. Specific Heat

Generally, the specific heat of nanofluids is relatively less than that of the same basic fluid, which implies that, for the same increment in temperature, less heat energy is needed for nanofluids compared to the host fluid. Unfortunately, significantly less or no experimental data is available for the specific heat of nanofluids. In the literature, two mathematical models are repeatedly used to find the specific heat of nanofluids. In the first model, the specific heat of the nanofluid can be explained as

$$c_{p,nf} = (1 - \phi)c_{p,bf} + \phi c_{p,s} \quad (3)$$

where the subscripts nf, bf, and s refer to the nanofluid, base fluid, and nanoparticle, respectively.

Equation (3) is easy to understand and use so many researchers have used it in the past to study the specific heat transfer of nanofluids [31–33].

The thermal equilibrium mechanism also helps us to understand the concept of specific heat of nanofluid. From the thermal equilibrium mechanism perspective, the particular heat of nanofluid can be explained as

$$\rho_{nf}c_{p,nf} = (1-\phi)\rho_{bf}c_{p,bf} + \phi\rho_s c_{p,s} \quad (4)$$

Many researchers have also used Equation (4) to find the specific heat. As there is no experimental data available to validate, both equations can be considered accurate and used to determine the response (specific heat) [34–36].

4.3. Stability of Nanofluids

Unsuspended nanoparticles (NPs) promote agglomeration in nanofluids (NFs); hence, a stable nanofluid must have a proper NP suspension. Stabilization keeps NPs apart to prevent agglomeration. Surfactants are most often used to make stable NFs. Surfactants are polymers that reduce liquid surface tension and liquid–liquid and liquid–solid interfacial tension. Surfactants cover NPs to inhibit aggregation by creating steric repulsive forces. Chain–chain interaction of adsorbed surfactant tails creates a steric repulsive force that keeps surfactant-coated NPs apart in the medium. Aqueous polyaniline colloids demonstrate persistent dispersion by electrostatic repulsion in the absence of additives, facilitating environmentally friendly nanofluid processing [37]. The preceding research has examined NF synthesis, stability, thermophysical properties, and heat transport. Figure 7 shows the processes of finding out the stability of nanofluids.

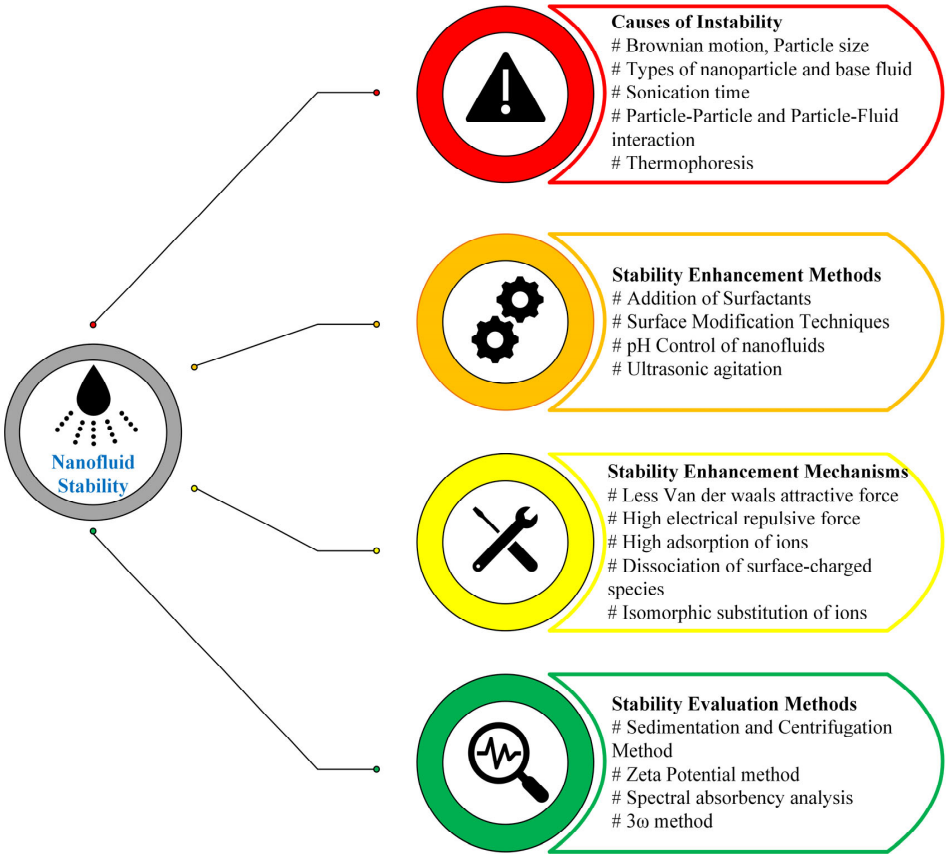


Figure 7. Stability of nanofluid.

4.3.1. Stability Evaluation Methods

The stability of a nanofluid, or the capacity of nanoparticles to stay evenly spread out without clumping together or settling over time, is what makes it worthwhile. If the fluid is not stable, its improved qualities could not work, and it might cause systems to clog and wear out. So, a prudent check of stability is an integral part of developing nanofluids. There are many ways to test the stability of these complicated fluids, and each one gives us a different look at how the suspended nanoparticles act.

Sedimentation and Configuration Method

In the past, researchers have developed many methods to determine and evaluate the stability. Sedimentation is the simplest method to measure the stability of NFs [38,39]. In this method, the stability of NFs is evaluated based on the volume or weight of the sediment. A special apparatus can help to understand the variation in the nanoparticles or size changes in the NPs. A constant size of the NPs or no change in the concentration of NPs indicates a good stability of the NF. Moreover, the stability of NFs can also be judged by photos taken from the bottom side of the test tube. Stability of a graphite suspension was measured by Zhu et al. [40]. A sedimentation balance method was used to determine the weight of the sediments, and the suspension fraction of graphite nanoparticles was also calculated. As mentioned at the start, even though the sedimentation method is simple, the long processing time is the main drawback. To seek alternative ways, researchers developed a new centrifugation method to determine the stability of NFs. Li [37] employed the centrifugation method to study the stability of aqueous polyaniline colloids. It was noted that the excellent stability of the colloids is mainly due to electrostatic repulsive forces—similarly, Singh et al. [41] also used the centrifugation method to evaluate the stability of silver nanofluid.

Zeta Potential Analysis

Zeta potential is defined as the potential difference between the solid surface of the NPs and the host medium (e.g., water). This potential difference is measured between the disperse medium and the layer attached to the outer surface of the nanoparticle, shown in Figure 8. Analysis of zeta potential is fundamental and practical for the assessment of the stability of colloidal dispersions. Higher values of zeta potential indicate an excellent stability of the nanofluids; however, lower values of zeta potential (positive or negative) are associated with a coagulated form of the fluid. Generally, a value of $\pm$25 mV is taken as the reference value, which separates the two charged (low and high) surfaces. The nanofluids and colloids with zeta potential values ranging from 40 to 60 mV are considered as stable NFs; however, the zeta potential value of 60 mV indicates an excellent stability of the NF. Zhu et al. [42] used Derjaguin–Landau–Verwey–Overbeek (DLVO) theory to calculate the zeta potential of alumina/water NF. In another study, the zeta potential of MWCNTs was measured [43]. Kim et al. [44] found the considerable negative zeta potential of Au nanofluid. The authors claimed that the excellent stability of the prepared nanofluid was maintained even after one month. Li et al. [39] also evaluated the dispersion behavior of aqueous copper under different pH values, dispersant types, and concentrations by the method of zeta potential.

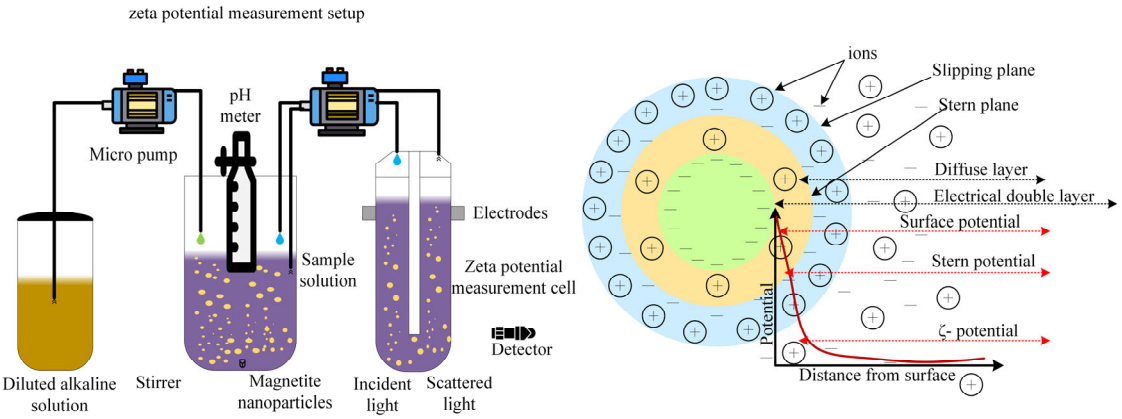


Figure 8. Schematic diagram to understand the Zeta potential.

Spectral Absorbency Analysis

The stability of nanofluids can also be evaluated by analyzing their spectral absorbency. It has been seen that, in most cases, the concentration of NPs has a significant effect on the spectral absorbency analysis. Huang et al. [45] used the traditional sedimentation method to evaluate the spectral absorbency analysis of Al_2O_3 and Cu NFs using a spectrophotometer. In another study, Farahmandjou et al. [46] used a spectrophotometer to investigate the spectral absorbency of FePt nanofluids. Moreover, the absorbency method can also be used to determine the sedimentation kinetics of the nanofluids [42].

Suppose the NPs present in the NF can absorb wavelengths between 190–1100 nm. In that case, UV–vis spectral analysis is a simple and effective technique to determine the stability of the nanofluid. Hwang et al. employed the UV–vis spectrophotometer method to evaluate the stability of NFs. It was noted that the base fluid and the characteristics of the suspended particles affected the stability of the nanofluid [47].

Non-Colloidal Properties Analysis

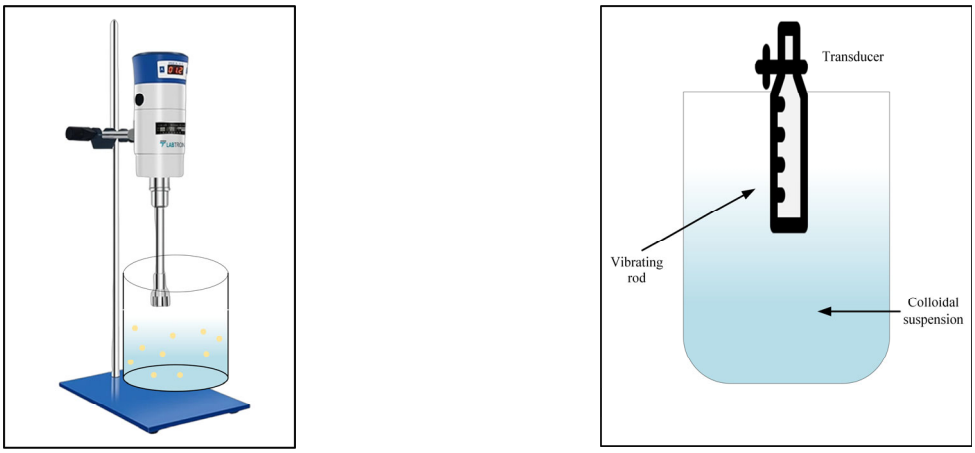
In the previous sections we have talked about the analysis of the stability of nanofluids based on colloidal properties. Nanofluids also have non-colloidal properties such as thermal, chemical, and tribological properties. These properties also have a significant effect on the stability of nanofluids. Thermal properties such as thermal conductivity are measured by the transient hot wear method [48]. The 3 omega method is also used for measuring thermal conductivity [49]. Specific heat capacity is measured using the differential scanning calorimetry method [50]. Chemical properties such as oxidation can also be measured by the differential scanning calorimetry method. The oxidation induction temperature signifies the stability of oxidation. The higher the oxidation induction temperature the better the oxidation stability. The four-ball method is used to measure tribological properties such as coefficient of friction, wear prevention property, and load-carrying capacity of nanofluid [51].

4.3.2. Enhancing Stability of Nanofluids

Generally, it is easy to prepare nanofluids with high-stability characteristics. However, it is a great challenge to keep the stability of the nanofluid for a long time. Researchers have developed different methods to enhance the stability of NFs. Stability enhancement methods can be divided into two main categories. Homogenization and ultrasonic agitation are categorized as physical methods. However, surface modification, pH adjustment, and surfactant addition are classified as chemical methods.

Physical Treatment Methods

A colloidal suspension with good dispersion is a primary demand for stable nanofluids. In the physical treatment method, high energy is required to break clusters of NPs to form a well-dispersed colloidal suspension. The homogenization and ultrasonic agitation methods can achieve this. In the homogenization method, clusters of nanoparticles are broken using high-shear homogenizers, as shown in Figure 9a.



(**a**) (**b**)

Figure 9. (**a**) Schematic illustration of high-shear homogenizers; (**b**) Schematic diagram of ultrasonic probes.

Hwang et al. [52] stabilized NFs using various techniques such as with a high-pressure homogenizer, stirrer, ultrasonic disruptor, and ultrasonic bath to measure the colloid size in NF suspensions. Single-walled carbon nanohorn and titanium oxide nanoparticle-based nanofluids were prepared by Bobbo et al. [53]. The authors used the high-pressure homogenization method to stabilize the nanofluid. Results showed that the applied method was very effective and increased the stability of the nanoparticles in the NFs. Figure 9b shows the commonly used ultrasonication probes for the dispersion of nanoparticles.

Probe sonication is the most straightforward and economical method used to enhance the stability of NPs. Sound energy with a frequency of 20 kHz or more is applied for a specific period. This procedure helps disperse the nanoparticles and enhance the stability [54]. The ultrasonication method highly depends upon the duration of the process, frequency of the energy, and the power used. When the characteristics of the nanofluids change, the optimum conditions of the process also change. Bowers et al. [55] conducted experiments to find the optimum parameters of the ultrasonication method on the stability of multi-walled carbon nanotubes. The best stability of the nanofluid was achieved at a power of 130 W, frequency of 20 kHz, and ultrasonication time of 40 min.

Chemical Treatment Methods

The hydrophilic (oxides) and hydrophobic (CNTs) nature of nanoparticles significantly influence their stability. Separation and dispersion of nanoparticles in NFs can be enhanced with the addition of surfactants. This modifies the surface of the NPs. The addition of surfactants prevents particle aggregation by acting as a bridge between the host fluid and nanoparticles. Various types of surfactants are added to NFs to enhance the stability, and the type of surfactant is chosen after the selection of base fluids. Generally, surfactants are split into two categories, i.e., water soluble and oil soluble. Various kinds of surfactants such as dodecyl trimethyl ammonium bromide (DTAB), sodium dodecyl sulfate (SDS) [47], cetyl trimethyl ammonium bromide (CTAB) [56,57], polyvinyl pyrrolidone (PVP) [56], oleic

acid [16,58], and gum arabic [59,60] have been used by many researchers to enhance the solubility of nanofluids. The effect of SDBS weight fraction on the stability of CuO/water nanofluids is shown in Figure 10.

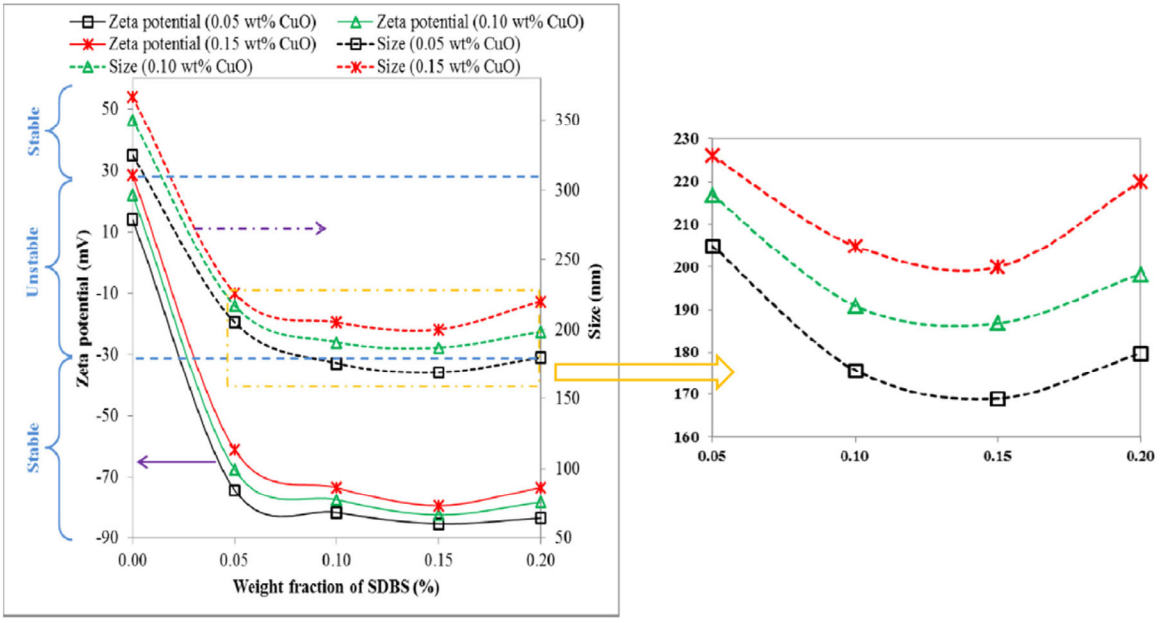


Figure 10. Effect of SDBS weight fraction on the zeta potential and particle size of CuO/water nanofluids (T = 298 K) [61].

Surface functionalization or surface modification is another method to enhance the stability of nanoparticles, in which nanoparticles are processed before adding to the base fluid. The surface of CNTs is modified using an acid treatment process. pH of the nanofluid is also a significant parameter to control, and it significantly affects the stability of the nanofluid. The isoelectric point (IEP) is a point where the zeta potential values and the surface charge of the nanoparticles are zero. To maintain or to improve the stability of the solution, the pH values of the solution must have a big difference from the IEP values. pH values near neutral are considered good because the acidic or alkaline nature of NFs causes corrosion [62].

4.3.3. Stability Mechanism of Hybrid Nanofluids

Enhancement of the stability of hybrid nanofluids is more difficult than that of a single nanofluid. Good dispersion of nanoparticles is a symbol of stability and correspondingly responsible for the increase in thermal conductivity of hybrid NFs. Similar physical and chemical methods are used to enhance the stability of hybrid nanofluids. Suresh et al. [30] measured the zeta potential and pH values of Al_2O_3-Cu/water hybrid nanofluid to evaluate the stability. It was noted that hybrid NF was extremely unstable at the isoelectric point (IEP). This may be due to the weak repulsive forces between the nanoparticles at the IEP. The pH value of Cu/H_2O was 9.6, and that of Al_2O_3/H_2O was found to be 10. However, the pH values of hybrid nanofluid were noted around 6, which shows the good stability of the suspension. The authors also pointed out that the pH of the hybrid nanofluid increases as the concentration of the nanofluid increases, and poor stability was noted at the higher concentration of the nanofluid. Therefore, it is possible to conclude that the concentration of hybrid NPs significantly affects the stability of hybrid NFs—similarly, Jana et al. [63] used the UV–vis–NIR spectrophotometer method to evaluate the stability of CNT-Cu/water and CNT-Au/H_2O hybrid nanofluids.

Kim et al. [64] also used the zeta potential and pH method to evaluate the stability of Ag/Fe nanocomposite fluid. The authors concluded that the addition of NaOH and HNO_3 can control the pH of the nanocomposite fluid. It was also found that, at pH 8, the zeta potential was 0, which shows the poor stability of the suspension. When the pH value was increased to 8, repulsive forces between nanoparticles became stronger and the NF became more stable. In another study, Aravind and Ramprabhu [65] adopted a visible spectrum measurement method to measure the stability of multi-walled carbon nanotubes mixed with graphene oxide dispersed nanofluids. Very excellent results were achieved in terms of the six-month stability of graphene-MWNT-based hybrid NF. Esfe et al. [66] prepared Ag-MgO/water nanofluid and evaluated the stability of the hybrid fluid only based on the pH test. In their experiments, cetyl trimethyl ammonium bromide (CTAB) was used as the surfactant to enhance the stability. Results showed that the nanofluid can stay stable for several days. Using the UV spectrophotometry method, Munkhbayar et al. [67] measured the stability of hybrid NF. In another study, zeta potential was calculated to assess the stability of Fe_2O_3-CNT/H_2O hybrid NF [68].

4.3.4. Future Challenges for the Stability of Hybrid Nanofluids

Excellent stability of both single and hybrid nanofluids is a dire need not only for researchers to prepare good-quality nanofluids but also for practical application in industry. Some physical or chemical methods are used to enhance the stability of nanofluids. However, some challenges have still not been addressed by researchers.

- Regarding the stability of hybrid nanofluids, a suspension of two different types of NP is a big challenge, and more efforts are needed to study the separation mechanism of two different types of nanoparticle.
- A lot of studies preach about the stability analysis of nanofluids before the experimentation. However, the consequences of the transferring nanofluids from the laboratory to the area of application have not been explored yet. What is the effect of distance and transferring medium on the stability of nanofluids?
- Somehow, phenomena of pressure drop during the application of hybrid nanofluids is still a black box. There has still been very little work to understand the effect of different particle sizes and densities of individual nanoparticles on the on the pressure drop and the pumping power.
- Production of nanoparticles is a costly process and it is important to develop new cost-effective methods of producing hybrid nanofluids. Nanofluids are considered and this is the main reason industry is reluctant to use them.
- In machining difficult-to-cut material, temperature is very high in the cutting zone, and application of nanofluids in the high-temperature zone is required. Similarly, application of nanofluids with cryogenics could also be demanded as a special requirement. So, it is very important to understand the stability of hybrid nanofluids in such severe environments.

5. Nanofluid MQL Application in Machining Process

Nanofluids are widely used in machining processes nowadays because of their ability to make machining processes greener and more environmentally friendly. The application of nanofluids, however, is not always similar in every machining process. Nanofluids can be categorized into two distinctive categories based on the properties within the fluid, single nanofluids and hybrid nanofluids. This section talks about the application of both these categories in detail.

5.1. Application of Single NMQL

A single nanofluid is a fluid in which a single nanoparticle is mixed with a base fluid like water, oil, glycol, etc. The materials that are often used to make these nanoparticles are Al_2O_3, SiO_2, CuO_2, or TiO_2. The size of the materials is typically 1–100 nm. Adding the nanoparticles to the base fluid generally enhances the thermal, physical, and tribological properties of the fluid. Jose Jamie et al. [69] performed a comparative study to find out the optimum grinding parameters for creep feed grinding of Ti-6Al-4V using a green silicon carbide wheel, under three different lubrication conditions: flood lubrication with water-soluble synthetic oil, MQL with ester oil, and NMQL, where alumina nanoparticles are homogeneously dispersed in ester oil. The study found that, at infeed levels of 0.635 mm and 1.27 mm, all three lubrication methods performed similarly in terms of surface quality and material removal. However, at a higher infeed of 1.905 mm, conventional MQL failed to provide acceptable surface finish, while NMQL and flood lubrication delivered nearly identical, superior results. The optimal combination was identified as a crossfeed of 0.254 mm, an infeed of 1.27 mm, and a table feed rate of 6.7 m/min, which achieved a material removal rate of 2163 mm^3/min with a surface roughness (Ra) of 0.515 µm. These parameters offer the highest productivity while maintaining industrial surface quality standards. Vardhanapu et al. [70] present a comprehensive investigation into the development and evaluation of green nano-metalworking fluids (nano-MWFs) based on vegetable oils for MQL machining of Nimonic 80A, a hard-to-machine superalloy. The authors formulated 12 nano-MWF combinations using canola, coconut, and sunflower oils mixed with SiO_2 and Al_2O_3 nanoparticles at two concentrations (0.5 wt.%% and 1 wt.%). These were characterized for physio-thermal, tribological, and mist flow properties, and their performance was tested in turning operations under various machining conditions. Surface roughness, cutting temperature, tool wear, and chip morphology were assessed, and machine learning models—linear regression, support vector regression, and artificial neural networks—were employed to predict optimal lubrication conditions. The study found that certain nano-MWFs significantly improved machining outcomes compared to dry, flood, and compressed air cooling, with sunflower-oil-based nanofluids exhibiting superior wettability and lubrication. Figure 11 shows the collective results of temperature found throughout the studies.

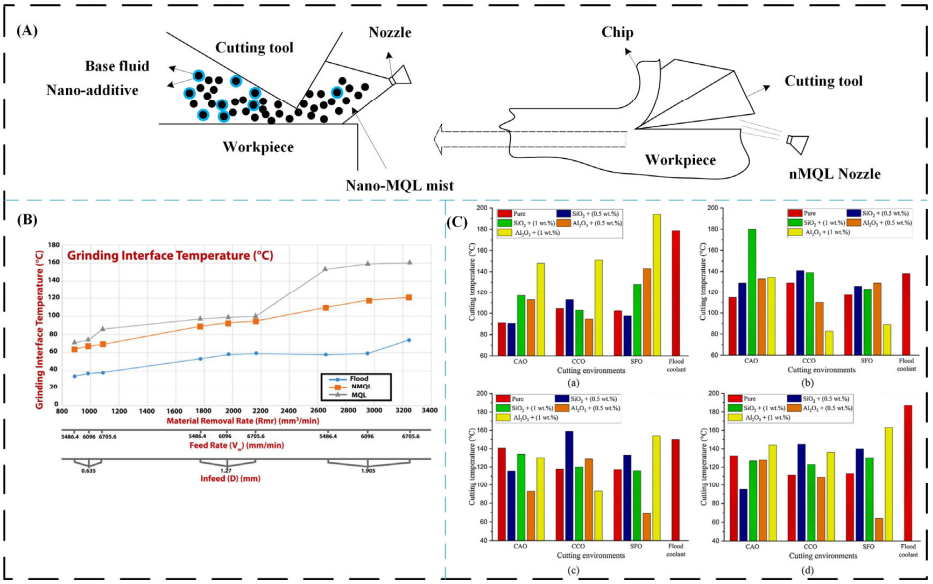


Figure 11. (**A**) NMQL mechanism; (**B**) Grinding interface temperature of Ti-6Al-4V using flood, MQL, and NMQL [69]; (**C**) Cutting temperature vs. cutting environments for (**a**) Parameter setting-1; (**b**) Parameter setting-2; (**c**) Parameter setting-3; (**d**) Parameter setting-4 [70].

Hegab et al. [71] presents an integrated finite element (FE) model for simulating machining processes using MQL with nanoadditives, explicitly focusing on Inconel 718 and Ti-6Al-4V alloys. The model, the first of its kind, addresses the limitations of traditional flood coolants and conventional MQL by incorporating nanofluids to enhance heat transfer and tribological characteristics, which significantly improves MQL performance. The research involved two main phases: developing a 2D axisymmetric computational fluid dynamics (CFD) model to analyze the thermal characteristics of the nanofluid mist, followed by using these results in a Lagrangian-based FE model to simulate cutting forces, temperatures, and residual stresses. Experimental validations showed good agreement between theoretical and simulated heat convection coefficients, and a reduction in cutting forces, temperatures, and residual stresses was observed when using MQL-nano-cutting fluids compared to classical MQL. The study highlights the advantages of nano-cutting fluid technology in reducing friction and thermal softening, ultimately enhancing machinability. Eltaggaz et al. [72] investigate the influence of various coolant strategies on tool life and surface roughness when machining austempered ductile iron (ADI), a material known for its challenging machinability due to its unique microstructure. Dry machining, flood cooling, MQL with vegetable oil, and MQL with a 4% volume of gamma-Al_2O_3 nanofluid are compared in this work. At optimal cutting conditions, MQL with nanofluid shows improvements of 19.4%, 4.1%, and 30.5% compared to MQL, flood, and dry procedures, respectively; the results indicate that MQL greatly increases tool life. Moreover, the nanofluid usually results in better surface roughness because of enhanced heat transmission and lubrication at the tool–workpiece interface brought about by the nanoparticles. The study underlines the need for choosing suitable cooling techniques for raising the machinability of challenging-to-cut materials such as ADI. Further examining the impacts of MWCNTs and Al_2O_3 gamma nanoparticles as nanoadditives in MQL for turning Inconel 718, a difficult aerospace alloy, Hegab et al. [73] intended to address environmental and health issues related to conventional flood cooling by increasing the MQL heat capacity, thereby improving the Inconel 718 machinability. Due mostly to their better cooling and lubricating qualities, the research analyzes tool wear modes and chip morphology and shows that both nanofluids greatly lower flank wear, crater wear, oxidation, and built-up edge generation compared to MQL without nanoadditives. MWCNT nanofluid notably showed greater performance than Al_2O_3 nanofluid, ascribed in part to its higher thermal conductivity and zeta potential values. A more desirable chip shape, such as segmented chips with MWCNTs, suggesting improved chip breakability, resulting from the use of nanoadditives. The study finds generally that MQL with nano-cutting fluids provides an efficient and environmentally friendly method to raise Inconel 718 machining performance. Kishawy el al. [74] present a comprehensive sustainability assessment model for turning Ti-6Al-4V alloy using MQL with nanoadditives, considering surface quality, tool wear, and power consumption, alongside environmental impact, waste management, and operator safety and health. The study employs a sustainability assessment algorithm that integrates machining quality characteristics with various sustainability indicators to determine optimal sustainable design variables. The results show that MQL-nanofluid, particularly with a 2 wt.% concentration of Al_2O_3 nanoparticles, yields better overall sustainability performance compared to classical MQL, balancing improved machining outputs with reduced environmental and safety concerns. By lowering friction and improving heat transfer characteristics, the research emphasizes the possibilities of nano-cutting fluids to achieve more sustainable machining techniques. Figure 12 shows the tool wear results found throughout the studies. Other researchers' findings are shown in Table 1.

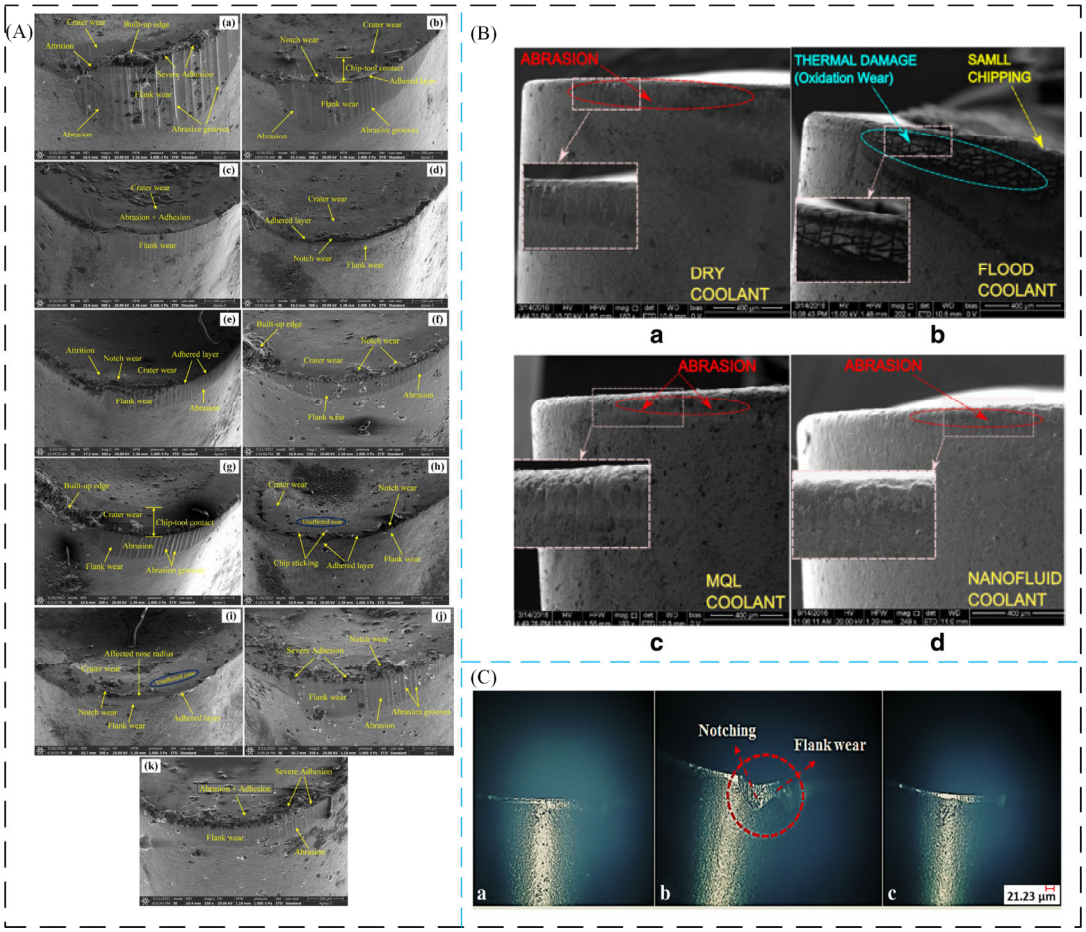


Figure 12. (**A**) SEM images of the tool inserts in (**a**) Dry machining and (**b**) MQL+CAO, (**c**) MQL + (CCO + (1 wt.%) SiO_2), (**d**) MQL + (SFO + (0.5 wt.%) SiO_2), (**e**) MQL + (CAO + (0.5 wt.%) Al_2O_3), (**f**) MQL + (CAO + (0.5 wt.%) SiO_2), (**g**) MQL + (CCO + (0.5 wt.%) Al_2O_3), (**h**) MQL + (CCO + (0.5 wt.%) Al_2O_3), (**i**) MQL + (SFO + (1 wt.%) Al_2O_3), (**j**) MQL + (SFO + (1 wt.%) Al_2O_3), (**k**) MQL + (CCO + (1 wt.%) Al_2O_3) NMQL machining [70]; (**B**) SEM images of inserts after machining at V = 120 m/min and f = 0.3 mm/rev under different coolant strategies (**a**) dry coolant, (**b**) flood coolant, (**c**) MQL coolant, (**d**) nanofluid coolant [72]; (**C**) The observed flank tool wear at cutting speed of 50 m/min and feed rate of 0.3 mm/rev using (**a**) 4 wt.% MWCNT nanofluid; (**b**) no nanoadditives; (**c**) 2 wt.%Al_2O_3 nanofluid [73].

Table 1. Studies on single nanofluids.

Researchers	Nanoparticles	Processing Conditions	Effects
Agunsoye et al. [75]	SiO_2	Turning of aluminum alloy	Nano-cutting fluid significantly reduced cutting force and flank wear, as well as improved surface quality (92.96%, 88.59%, and 93.40%, accordingly).
Tong et al. [76]	Al_2O_3	Milling	At 1.0 vol% concentration and with 20 nm particles, the Al_2O_3–palm oil nanofluid demonstrated optimal heat transfer and lubricating capabilities.
Kumar et al. [77]	Al_2O_3, TiO_2	Turning of AISI D2	The TiO_2 nanofluid tool has 29% less flank wear than Al_2O_3, a 9.7% lower cutting temperature, and 14.3% lower Ra.
Hamid et al. [78]	TiO_2	Rotary drilling	TiO_2-soluble oil nanofluid reduced drilling temperature.
Edelbi et al. [79]	Al_2O_3, ZnO	Milling of Ti-3Al-2.5V	ZnO nanofluids had lower cutting temperature as well as surface roughness than Al_2O_3 nanofluids, by 1% and 2%, accordingly.
Huang et al. [80]	MWCNTs	Milling of AISI P21 and 1050	MWCNTs dramatically lower cutting temperatures and surface roughness improved by 9%.
Zhang et al. [81]	SiC	Turning of 40Cr	NMQL lowers wear by 55.1%, cutting temperature by 41.5%, and surface roughness by 19.2%.

These studies underline the great benefits of using nanoadditives in MQL and nano-MWFs as sustainable alternatives for conventional lubrication methods. Studies on several

difficult-to-cut alloys like Ti-6Al-4V, Inconel 718, Nimonic 80A, and ADI indicate repeatedly that nano-cutting fluids improve essential machining parameters, including tool life, surface quality, material removal rates, and chip formation. The superior heat transmission and tribological properties of nanoparticles, which reduce friction and hence minimize thermal softening and improve lubrication at the tool–workpiece contact, are the major factors driving these improvements. Moreover, the studies underline the environmental and health advantages of these methods; some of them also combine sustainability assessments and machine learning for process parameter optimization, therefore highlighting the change towards more effective and ecologically friendly production.

5.2. Application of Hybrid NMQL

A hybrid nanofluid is created when two or more different types of nanoparticle, particles with diameters typically less than 100 nanometers, are mixed into a conventional base fluid (such as water, oil, or ethylene glycol). The basic idea behind hybrid nanofluids is to use the synergistic benefits of aggregating many nanoparticles. In comparison to both the base fluid alone and conventional nanofluids (which contain only one type of nanoparticle), this can result in improved heat transfer performance and enhanced thermophysical properties, especially thermal conductivity. Many researchers have been working on the implementation of hybrid nanofluids during machining in recent times. Li et al. [82] used graphene and Al_2O_3 nanoadditives in oleic-acid-based nanofluids to examine the efficiency of NMQL for grinding hard-to-cut materials, specifically Ti-6Al-4V titanium alloy and ZrO_2 ceramic. The thermal conductivity, viscosity, and contact angle features of these hybrid nanofluids were studied at different concentrations and ratios. Grinding force, specific grinding energy, temperature, surface quality, wear rate, and friction coefficient were all evaluated when using NMQL. According to the findings, hybrid nanofluids demonstrated better lubrication than dry conditions. For example, a 1 weight percent concentration of nanoadditive decreased specific grinding energies, friction coefficients, and friction test temperature increments by 73.92%, 46.57%, and 65.69%, respectively. Comparing ZrO_2 and Ti-6Al-4V workpieces to dry cutting, the optimal surface quality was attained at two weight percent and three weight percent nanoadditive concentrations, resulting in a 60.53% and 48.66% decrease in surface roughness, respectively. According to the study's findings, the lamellar structure of graphene and the spherical structure of Al_2O_3 work together to produce a synergistic lubrication mechanism that improves cooling and lubrication through a "sandwich layer" effect. The application of GnP-ZrO_2 hybrid NMQL to enhance the machinability of GH4169 nickel-based superalloy, which generally experiences significant tool wear and poor surface quality during cutting, was examined by Ma et al. [83]. After creating GnP-ZrO_2 hybrid NFs, the researchers evaluated their thermophysical characteristics, such as contact angle, thermal conductivity, and dynamic viscosity. Additionally, they performed turning experiments and wear tests on GH4169 in the following conditions: dry, MQL, GnP-NMQL (GNMQL), and GnP-ZrO_2 hybrid NMQL (GZNMQL). The findings demonstrated that the hybrid NFs significantly decreased the coefficient of friction and enhanced thermophysical characteristics. In particular, tool life was increased considerably and machined surface roughness and cutting temperatures were reduced by 53.53% and 54.06%, respectively, under GZNMQL cooling as opposed to dry conditions. The GnP and ZrO_2 nanoparticles' "flake–spheres–flake" structure improved cooling, lubrication, and friction characteristics, which in turn improved overall machining performance. When turning Haynes 25 superalloy, Senol Serin [84] examined the effectiveness of cermet cutting tools in a variety of ecological cutting conditions, such as MQL, graphene nanoplatelet (GnP)-doped mono nanofluids, MWCNT-doped mono nanofluids, GnP/MWCNT-doped hybrid nanofluids, gaseous N_2, and mono/hybrid nanofluids mixed with N_2. The study

assessed tool wear, cutting forces, chip morphology, and surface roughness and the viscosity, pH, thermal conductivity, and wettability characteristics of the cutting fluids. In comparison to dry machining, the results showed that combining hybrid nanofluids with gaseous N_2 greatly enhanced machining performance, reducing cutting forces by 16.59%, tool wear by 14.53%, and surface roughness (Ra) by 31.84%. According to the study's findings, using hybrid nanofluids with gaseous N_2 effectively reduces unwanted side effects and improves tool life and machining efficiency for superalloys that are challenging to machine. Figure 13 shows the wear morphology.

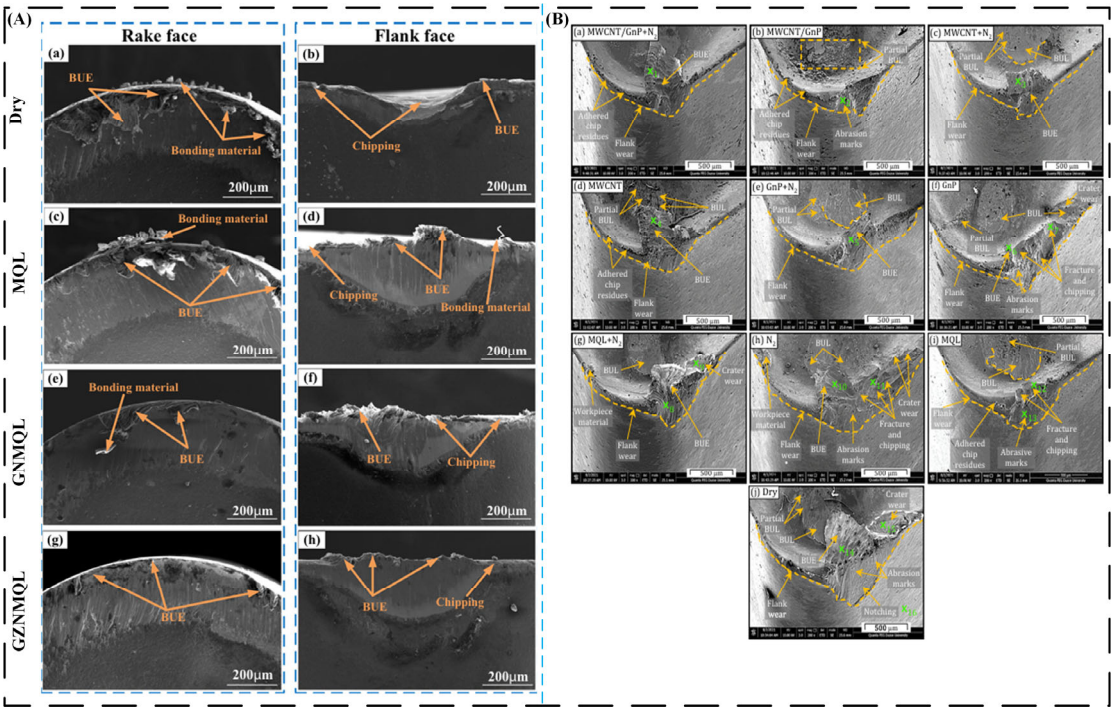


Figure 13. (**A**). Wear morphology of the rake and flank face after tool failure under (**a**,**b**) dry, (**c**,**d**) MQL, (**e**,**f**) GNMQL, and (**g**,**h**) GZNMQL conditions [83]; (**B**). SEM images of worn cermet tool under different cutting environments (after 25,000 mm^3 chip vol.); (**a**) MWCNT/GnP + N_2; (**b**) MWCNT/GnP; (**c**) MWCNT + N_2; (**d**) MWCNT; (**e**), GnP + N_2; (**f**) GnP; (**g**) MQL + N_2; (**h**) N_2; (**i**) MQL; (**j**) Dry [84].

The combined use of Al_2O_3-CuO hybrid nanofluid minimum quantity lubrication (HNMQL) and multi-axial ultrasonic-vibration-assisted machining (UVAM) for slot milling Inconel 718, a difficult aerospace superalloy, was examined by Ramazan et al. [85]. The study compares this innovative method to conventional machining (CM), pure-MQL, and conventional cutting fluid (CCF) to assess machining performance based on surface roughness, topography, burr formations, and cutting forces. By decreasing surface roughness, minimizing burr formation, and lowering cutting temperatures because of its intermittent cutting mechanism, the results show that multi-axial UVAM continuously performs better than CM. In a similar vein, HNMQL outperforms pure-MQL and CCF due to improved lubrication from the nanoparticles, decreased friction, and enhanced heat transfer, which results in lower cutting forces, improved surface quality, and lower burr heights. The combination of multi-axial UVAM and HNMQL produced the most substantial improvements in machining performance, including a 69% reduction in burr heights and a 56% reduction in surface roughness when compared to CM-CCF. This was because the intermittent cutting mechanism of UVAM improved the hybrid nanofluid's penetration and efficacy. Ramazan et al. [86] further investigated the potential advantages of combining hybrid nanofluid minimum quantity lubrication (HNMQL) with multi-axial ultrasonic-vibration-assisted

machining (UVAM) to improve the machining efficiency of Ti-6Al-4V, a rugged aerospace alloy. Axial, feed, and multi-axial UVAM vibration directions are systematically compared in the study, and the efficiency of UVAM in conjunction with Al_2O_3 and CuO nanoparticle-infused NMQL and HNMQL is assessed in comparison to traditional machining techniques. The experimental findings show that multi-axial UVAM and HNMQL greatly enhance machining performance, resulting in notable decreases in surface roughness (up to 37.4%) and cutting forces (up to 37.6%). Furthermore, this combined method results in extremely uniform and homogeneous surface textures with few flaws and considerably fewer burr formations, underscoring its potential to improve the accuracy and efficiency of the production of aerospace components. Figure 14 shows the surface morphology. Table 2 shows the findings of various other researchers.

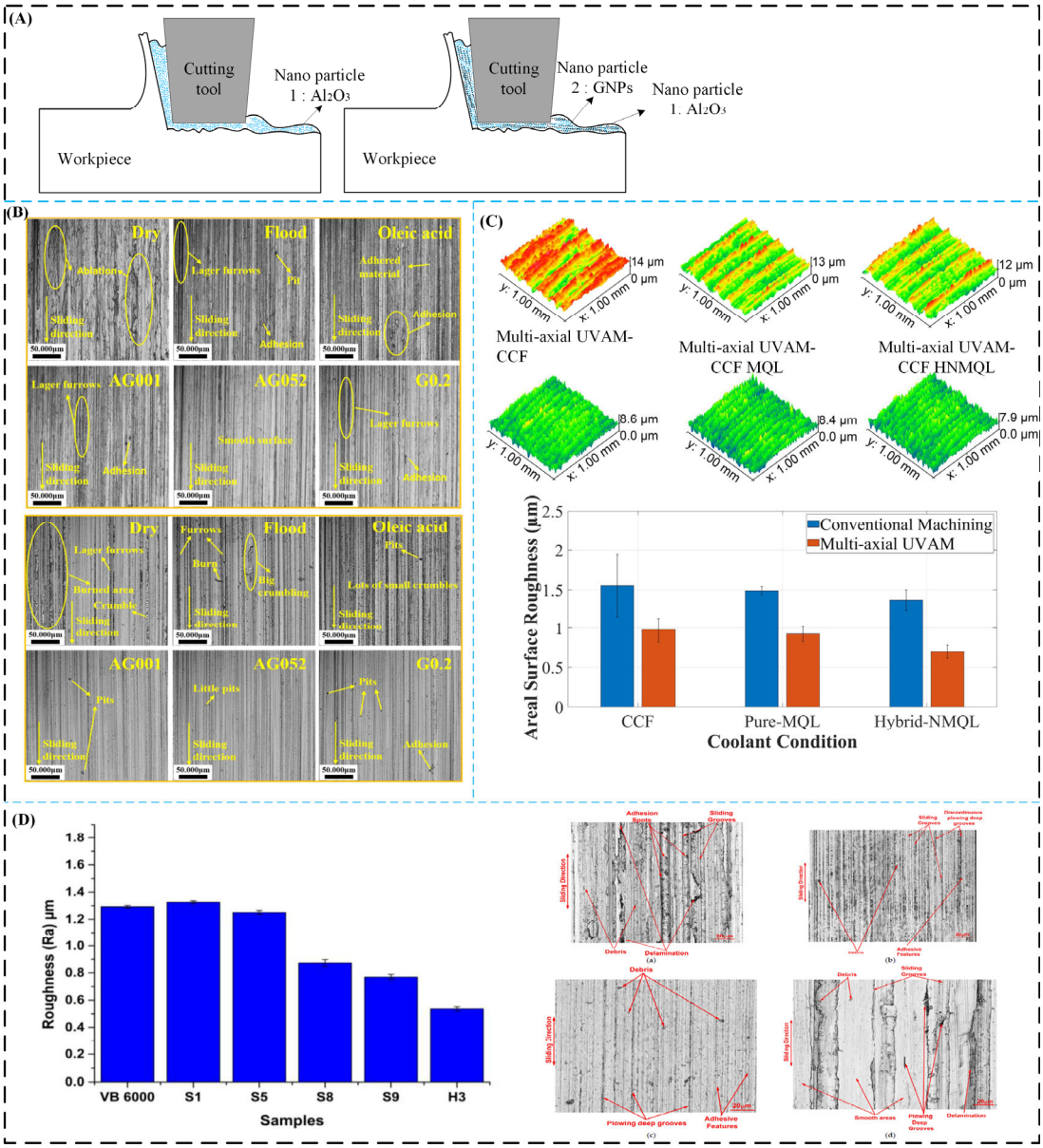


Figure 14. (**A**) Nanofluid lubrication mechanism: schematic diagrams of single nanofluid and (graphene–Al_2O_3) hybrid nanofluid lubrication mechanisms; (**B**). Surface morphology of Ti-6Al-4V after grinding under dry, flood, and different MQL conditions; Surface morphology of ZrO_2 after grinding under dry, flood, and several MQL conditions [82]; (**C**). Surface roughness and topography [85]. (**D**) Average roughness values for the worn surfaces and Surface morphology of wear scars for (**a**) S1; (**b**) VB 6000; (**c**) S9; (**d**) H3 [87].

Table 2. Studies on hybrid nanofluids.

Researchers	Nanofluids	Processing	Key Results
Aberoumand et al. [88]	Ag-WO_3	KD_2 Pro	The thermal conductivity of hybrid nanofluids is increased by 41%.
Gupta et al. [89]	Ag + MWCNT	Forced convective experiment	To measure the improvement in heat transfer performance in NFs containing Ag, Ag MWCNTs, and MWCNTs, correlations were developed. The outcome showed that a higher degree of heat transfer enhancement was correlated with an increase in Re number.
Asadi et al. [90]	MWCNT/ZnO	Brookfield cone and plate viscometer	As the temperature increased, dynamic viscosity decreased by 85%, but it increased by 45% when the concentration of solids was increased.
Arif et al. [91]	Fe_3O_4-Zn Au (blood)	Casson fluid model with a couple stresses	Blood-based ternary hybrid, spherical-shaped Fe_3O_4, platelet-shaped (Zn) nanoparticles, and cylindrical-shaped gold (Au) nanoparticles all showed an increase in heat transfer of 8.05%, 4.63%, 8.984%, and 10.407%.
Arshad et al. [92]	$Cu-Al_2O_3-TiO_2$	MATLAB with boundary value problem method (BVP-4c)	Tri-hybrid nanofluids outperform hybrid and single nanofluids by 33% in terms of heat transfer rate and reduced skin friction.
Kashyap et al. [93]	1. Al_2O_3-Cu-SiC 2. Al_2O_3 -Cu- MWCNT 3. Al_2O_3-Cu-Graphene 4. Al_2O_3-MWCNT-Graphene (Water as base fluid)	Engineering equation solver (EEC)	The combination of Al_2O_3/MWCNT/Graphene nanofluid reaches a maximum energy efficiency of 48.6%.

The results of these investigations reveal that the machinability of materials that are difficult to cut and aerospace superalloys that present challenges has been significantly enhanced by the utilization of combined hybrid nanolubrication systems and machining processes. Especially the results of investigations performed on Ti-6Al-4V, ZrO_2 ceramic, GH4169, Haynes 25, and Inconel 718 show the higher performance of NMQL. This particularly applies to hybrid nanofluids consisting of graphene, Al_2O_3, ZrO_2, CuO, and MWCNTs. These nanofluids can improve surface quality, reduce friction, and increase heat transmission. UVAM is a highly effective technique for lowering cutting forces, burr development, and surface roughness, especially in multi-axial configurations. This is because UVAM uses an intermittent cutting mechanism. It has been found that the combination of hybrid nanofluids with gaseous N_2 or multi-axial UVAM has a substantial synergistic impact that considerably improves machining efficiency, tool life, and surface quality in contrast to the conventional procedures. This highlights a promising path for high-performance, sustainable manufacturing of critical components for industries like aerospace.

5.3. Synergy of NMQL with CO_2-Based Cryogenic Machining

Integrating hybrid cooling and lubrication systems is a new and very promising trend in manufacturing. This means combining cryogenic cooling (using CO_2 or LN_2) with MQL

enhanced by nanofluids (TiO_2, Al_2O_3, GO/CNT, MWCNT/GNP etc.). This solves the biggest problems with traditional machining fluids. This synergistic technique greatly improves performance by lowering cutting temperatures, tool wear, and power use, all while enhancing the integrity of the surface. Its hybrid sustainability benefits are huge: it cuts down on fluid use, uses eco-friendly base oils and non-toxic nanoparticles, and often involves acquiring CO_2 from sustainable sources, eliminating the need to throw away dangerous chemicals. Additionally, the increased efficiency leads to significant energy savings, which helps to reduce the carbon footprint. Another reason for using cryogenic cooling with NMQL is because of the machining process's cleanliness. In cryogenic cooling, there are fewer dirt particles with a smaller particle size [94]. Many researchers have recently worked on nanofluids with cryogenic machining and have gotten promising results. Velmurugan et al. [95] performed their research by combining MQL with CO_2 and TiO_2 nanofluid during the machining of API L80 pipe specimens. They achieved near-perfect surface roughness of 0.4 µm and extended tool life by 79.68% accompanied by a significant reduction of tool wear. Sharma et al. [96] used cryo-MQL with eco-friendly Al_2O_3 NFs while grinding AISI D2 tool steel. Here, 0.5 wt.% and 1 wt.% concentrations of Al_2O_3 NPs and liquid nitrogen (LN2) were sprayed through two individual nozzles. It was observed that 1 wt.% Al_2O_3 NFs improve tangential force, normal force, grinding energy, surface roughness, and grinding temperature by up to 32.71%, 20.33%, 32.71%, 23.55%, and 6.81% in comparison to 0.5 wt.% Al_2O_3 nanofluids in the cryo-MQL mode. Moreover, minimal chip adhesion on completed surfaces was observed with 0.5 wt.% and 1 wt.% Al_2O_3 nanofluids during cryo-MQL grinding. Serroune et al. [97] found that liquid CO_2 combined with graphene oxide and carbon nanotubes enhances the thermal conductivity by approximately 77% over liquid CO_2, and their research also supports the viability of this nanofluid as an advanced heat transfer medium. Sarikaya et al. [98] investigated the machinability of Haynes 25 under various sustainable cooling and lubrication techniques. They found out that hybrid systems combining cryogenic CO_2 with nanofluids minimized tool wear by 38% and achieved up to a 44% reduction in cutting temperature and a 32% reduction in power usage compared to dry machining. All these studies point out that the usage of hybrid cryogenic nanolubrication for its hybrid sustainability benefits is now becoming an emerging trend. Nanofluids with different cryogenic-based machining processes are the main point of discussion in the following sections. Figure 15 shows a schematic diagram of a nanofluid with cryogenic cooling in different machining processes.

In CO_2-based cryogenic machining with nanoparticles, the nanoparticles usually work with liquid CO_2, CO_2 ice blaster, $SCCO_2$, etc. to increase the heat transfer benefits of the cryogenic system. As nanoparticles have an exceptional ability to transfer heat, they benefit the machining process by lessening tool wear, increasing tool life, and also producing a better surface finish, which in turn makes the cutting process more sustainable by reducing energy consumption and carbon emission. Because of these benefits, many researchers have conducted research on mixing nanoparticles in a CO_2-based cryogenic machining method. Huang et al. [99] looked into a new system called supercritical CO_2 mixed with nanofluid minimum quantity lubrication ($SCCO_2$-NMQL). They used it to machine Ti-6Al-4V alloy, which is tricky to work with since it conducts heat well and reacts swiftly with chemicals. The study examined the effects of $SCCO_2$-NMQL, dry cutting, $SCCO_2$, and supercritical CO_2 mixed with minimal quantity lubrication ($SCCO_2$-MQL) on the cutting zone temperature, cutting force, surface roughness, and tool wear. The results showed that $SCCO_2$-NMQL lowered cutting temperatures by more than 25% compared to dry machining, 15% compared to $SCCO_2$, and 12% compared to $SCCO_2$-MQL. It also decreased cutting forces and produced a better surface finish, especially at medium to high cutting speeds. $SCCO_2$ acts as a carrier for nanofluids, which improves thermal conductivity and

lubrication in the cutting zone. This is why it works better. The study finds that $SCCO_2$-NMQL is a good and long-lasting way to cool and lubricate machines that work with tough materials like Ti-6Al-4V. Musfirah Abdul Hadi [100] worked on the machinability and tribological behavior of Ti-6Al-4V alloy during end milling, utilizing a novel nanohybrid cryogenic-MQL cooling system. The study examined the system's impact on tribology, tool wear, tool life, and surface roughness through experiments conducted at varying cutting speeds and feed rates. The results show that adding nanoparticles to MQL made the coefficient of friction much lower. Using specific cutting parameters (130 m/min cutting speed and 0.2 mm/rev feed rate) also made the tool last about 50% longer and enhanced the surface roughness. The study's results show that the nanohybrid cryogenic-MQL system is a good, eco-friendly, and sustainable cooling method that improves the machinability and also meets the industrial demand. Noor et al. [101] looked into how tool wear changes over time when end milling Ti-6Al-4V alloy with a nanohybrid cryogenic-MQL system. This study attempted to improve tool life and surface roughness by optimizing cooling and lubrication. This is because titanium has great qualities but is hard to machine because it generates a lot of heat and wears the tool out quickly. The cutting speeds of 130 and 150 m/min were selected for the experiments, with feed rates of 0.2 and 0.5 mm/rev and the depth of cut constant at 0.5 mm using a single insert carbide tool. The results indicate that a cutting speed of 130 m/min and a feed rate of 0.2 mm/rev resulted in the tool lasting approximately 50% longer and achieving a surface roughness superior to other parameters. The study's results emphasize that the nanohybrid cryogenic-MQL system meets industry standards and is a feasible, sustainable, and eco-friendly cooling system for titanium alloys during machining. Figure 16 shows comparisons between temperature, surface quality, and tool wear.

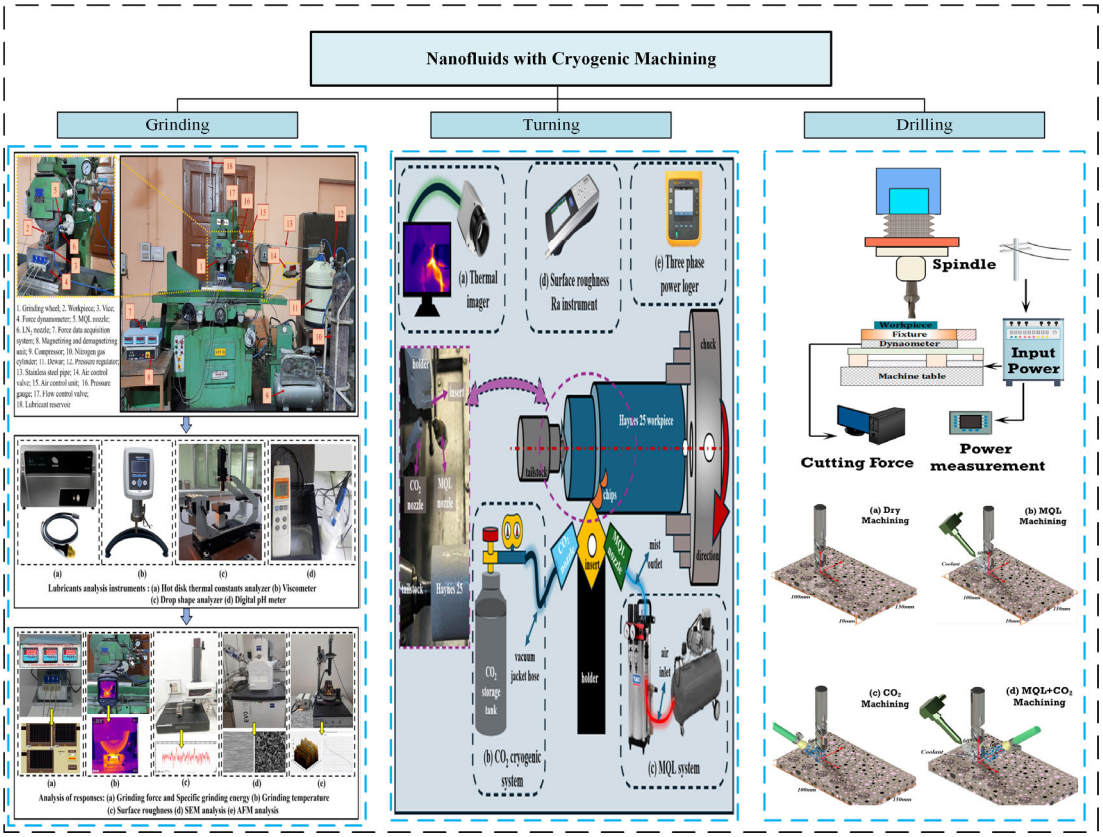


Figure 15. Cryo-NMQL in various machining processes.

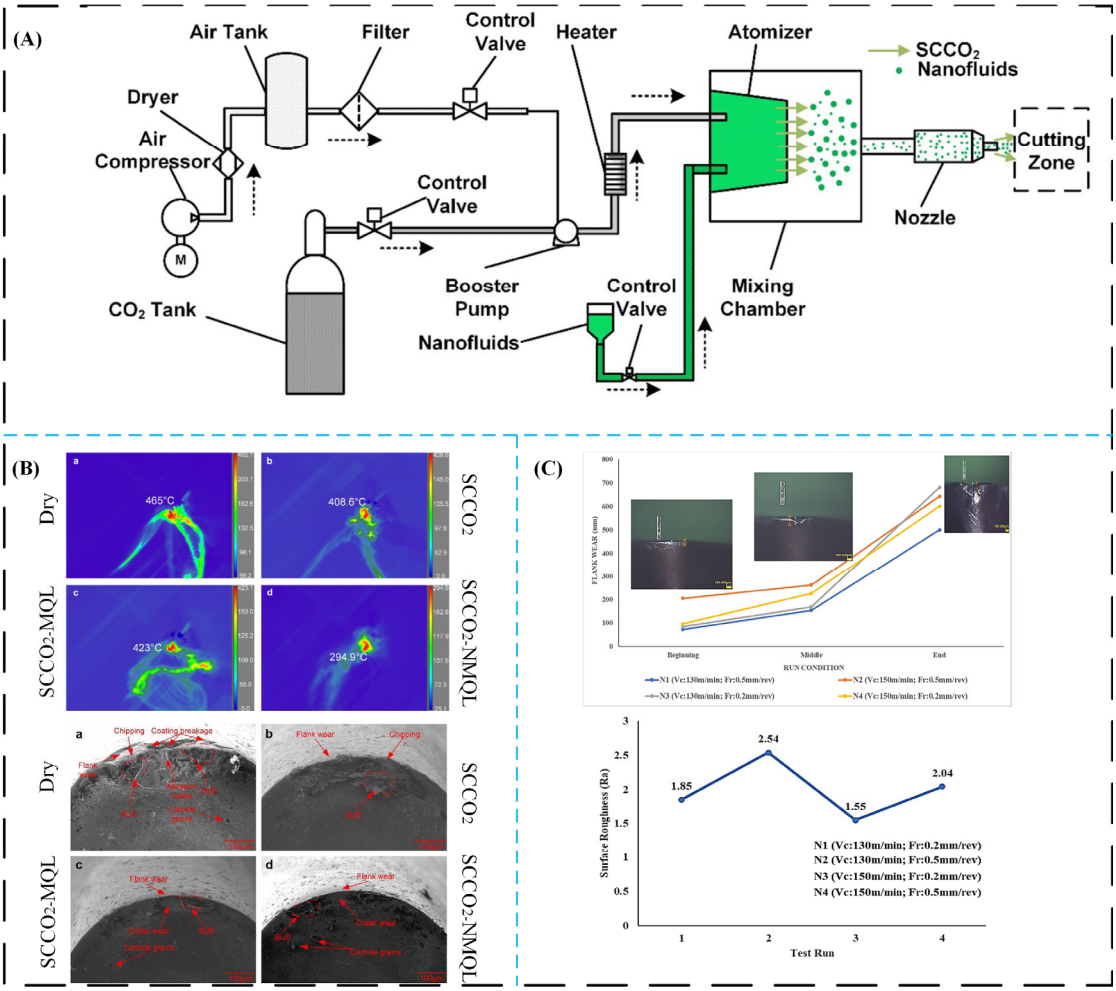


Figure 16. (**A**). Schematic of CO_2-assisted nanofluid-assisted machining system [99]; (**B**). Thermal images and SEM images of the coated tool captured in (**a**) dry, (**b**) SCCO2, (**c**) SCCO2-MQL, and (**d**) SCCO2-NQMLenvironment in turning Ti-6Al-4V [99]; (**C**). Graph of flank wear measurement and average surface roughness for all runs in cryogenic nanolubricant environment in milling Ti-6Al-4V [100].

To make it easier to work with hard-to-cut materials like Ti-6Al-4V, new cooling and lubrication methods are needed. Researchers have observed that nanohybrid cryogenic-MQL and $SCCO_2$-NMQL are two examples of systems that work well. These new technologies routinely show significant benefits, like lower cutting temperature and force, smoother surfaces, and longer tool life. The better performance is due to better heat conductivity and lubrication in the cutting zone. This, in turn, leads to long-lasting solutions that meet the industry's needs for machining titanium alloys in an environmentally friendly manner. The research on CO_2 cryogenic-based nanoparticles is very limited, so more research is suggested to be performed in this area.

5.4. Synergy of NMQL with LN_2-Based Cryogenic Machining

In LN2-based cryogenic machining with nanoparticles, nanoparticles work with liquid LN2, where LN2 works as the coolant and also sometimes as the medium for carrying the nanoparticles to the working zone, and the nanoparticles work on heat transfer and heat dissipation. In recent studies, many researchers have worked with LN2-based cryogenic machining with nanoparticles because of its sustainable properties and eco-friendliness. Sen et al. [102] investigated the effects of combined lubrication and cooling during the machining of Hastelloy C276 superalloy. In this study, a comparison between dry (MQ),

NMQL, and cryo-NMQL (LN_2-NMQL) conditions has been drawn. The results showed that the cutting force, cutting temperature, and surface roughness were significantly reduced by 25.49%, 29.84%, and 42.50%, respectively, under cryo-NMQL conditions compared to dry cutting, and tool wear was also decreased by 44.55%. The better performance is due to the combined effects of cryogenic cooling and nanofluid lubrication, which improve the shape of the chips, the structure of the grains, and the microhardness. An ANOVA showed that feed rate and cutting speed were the most important factors. A multi-objective response surface methodology (MORSM) optimization found the best machining parameters. This confirmed cryo-NMQL as a very promising and effective way to machine superalloys. Sirin et al. [103] looked at numerous ways to cool and lubricate Ti-6Al-4V alloy while milling it, using dry, pure-MQL, LN_2, hBN, CuO-doped nanofluids, and different hybrid techniques. When the nanofluids were first looked at, the CuO-doped nanofluids stood out because they had better thermophysical and rheological properties, especially when it came to their viscosity and pH levels. Because of this, the LN_2 and CuO hybrid cooling–lubrication configuration had the best results for important machinability indicators, including tool wear and surface quality. This improved performance was thought to be due to the unique flow properties of the CuO-doped nanofluid working seamlessly with the intense cooling provided by LN_2 cryogenic cooling, ultimately pointing to a very effective way to make this challenging superalloy easier to machine. Suhaimi et al. [104] introduce a clever new way to machine Ti-6Al-4V titanium alloy using an indirect cryogenic cooling system. This approach was created to tackle the common problem of the workpiece getting too hard when traditional, direct cryogenic methods are used. The performance of this innovative system, which sends liquid nitrogen (LN_2) directly to the cutting tool (keeping it away from the workpiece itself), was then compared to older methods like flood cooling, MQL, and even the usual external and internal cryogenic sprays. What was found was pretty significant: this new indirect cryogenic method boosted the machinability of Ti-6Al-4V. A remarkable 54% reduction in cutting force was achieved, and the tool's lifespan was extended by an impressive 90% when compared to the old-fashioned flood coolant approach. So, this "indirect" strategy is being put forward as a smart fix to stop the workpiece from hardening, which has often been an issue with direct LN_2 cooling. Sirin et al. [105] further dug into how different eco-friendly cooling and lubrication strategies impact the drilling process for a hard-to-cut material called Hastelloy X superalloy. They looked at things like MQL, LN_2, hBN, and GNP nanofluids. First, they examined the properties of these nanofluids, including their viscosity, pH, heat conductivity, and surface lubrication. Then, the actual drilling performance was put to the test, with a close eye on factors such as cutting force, the smoothness of the drilled surface, the overall quality of the holes, and the extent of tool wear. What emerged from the study was clear: the hybrid methods, particularly when LN2 was used with MQL containing nanofluids, consistently delivered top-notch results for both cooling and lubrication. This ideal setup was found to have a positive effect on all the drilling outcomes, showing the promise these environmentally friendly cooling and lubrication techniques hold for making challenging materials like Hastelloy X easier to work with sustainably. Korkmaz et al. [106] looked into how to make Ti-6Al-4V alloy work better when it rubs against a tungsten carbide (WC) abrasive ball. They produced new nanofluids that cleverly combine the unique features of hBN and graphene to make a lubricating environment that works better. Furthermore, they carefully studied how Ti-6Al-4V alloy surfaces wear by utilizing tribology and advanced characterization techniques in a number of situations, such as dry, MQL, cryo-MQL, and a specific cryo-nano-MQL blend. It was clear that the most important finding was during the use of cryogenically cooled lubricants with nanoparticles that resulted in the least amount of wear and friction. Their higher viscosity was directly responsible for this amazing

performance. This showed that combining cryogenic cooling with hBN/graphene-based nanofluids is a great technique to greatly improve the tribological performance of Ti-6Al-4V alloy. These studies make it evident that there is a big trend in advanced machining: the move toward hybrid cooling and lubrication techniques, especially those that combine cryogenic cooling with nanofluids. Consistent improvements can be seen in a wide range of difficult-to-machine materials, including Hastelloy C276, Hastelloy X, and Ti-6Al-4V alloy, as well as in varied techniques, such as milling and drilling. These benefits are evident in decreasing cutting force, cutting temperature, surface roughness, and tool wear, as well as improving tool life and the quality of the holes overall. The underlying mechanisms, which are often connected to higher viscosity, better heat dissipation, and the creation of protective tribo-films, show how these eco-friendly methods work together to solve the inherent machinability problems of superalloy. This is a big step toward more sustainable manufacturing practices. Indirect cryogenic cooling is another important new idea that solves a specific problem with hardening workpieces. Figure 17 shows the results of milling and drilling processes while using LN_2 with nanofluid.

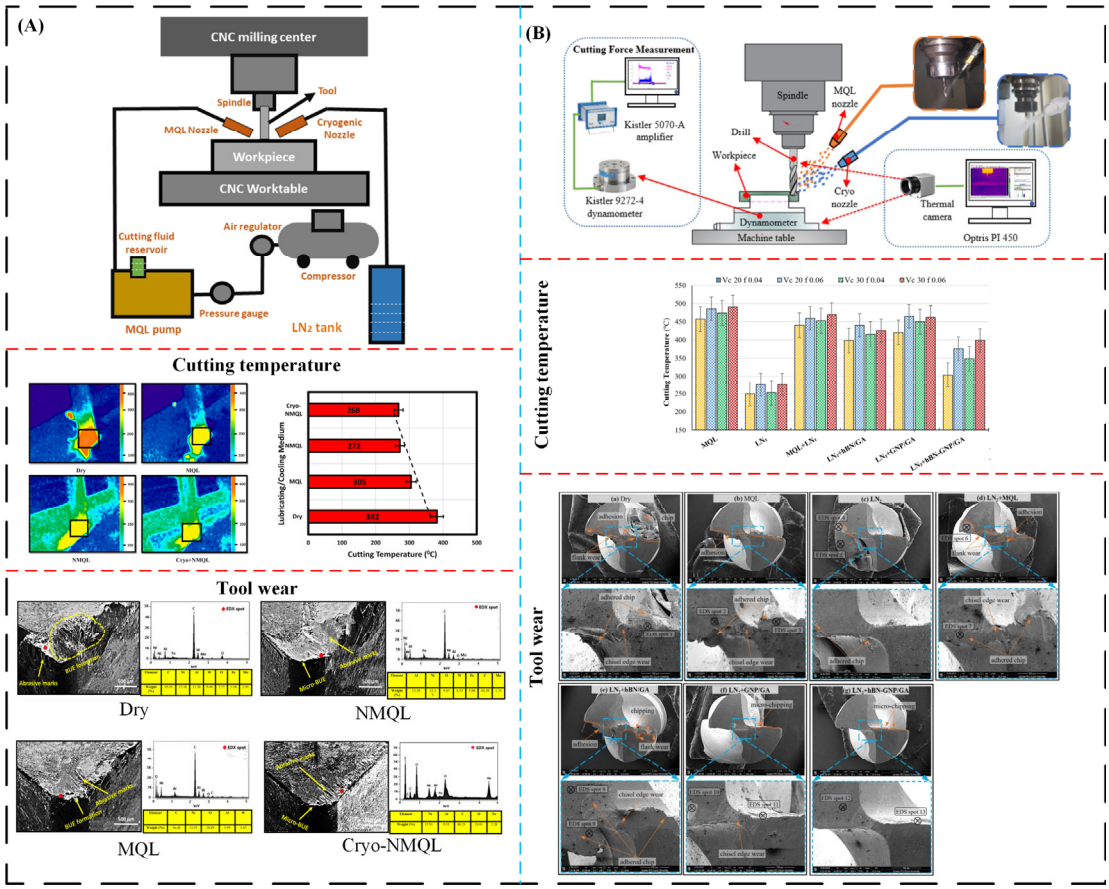


Figure 17. (**A**) Milling procedure of Hastelloy alloy in LN_2 and nanofluid environment [102]; (**B**). drilling procedure of Hastelloy alloy in LN_2 and nanofluid environment [105].

5.5. Synergy of NMQL with Hybrid Cryogenic

A hybrid cryogenic and nanofluid system exhibits superior machining performance compared to methods such as dry, flood, MQL, and cryogenic systems, which were discussed in previous sections. In this section, the focus will be on chip formation and tool wear. Korkmaz et al. [107] worked on turning of Inconel 601 in different cooling and lubrication conditions. In Figure 18b, it is evident that, with the increase in feed rate and cutting speed, the tool wear increases in every cutting condition, but one thing is constant

in all the experiment results: the cryo-nano-MQL showed the lowest tool wear with all the different parameters compared to other cooling and lubrication conditions. They also found the chip formation shown in Figure 18a, where the chip formation of every cooling and lubrication process is shown, and number 3, which is cryo-nano-MQL, had a discontinuous spiral chip. When machining difficult-to-cut materials, it is desirable to form segmented chips. This indicates that the material is fracturing ahead of the tool in a controlled manner, which can lead to lower cutting forces and better chip control. Yildrim [108] worked on turning of Inconel 625 in 16 different cooling conditions. These consist of dry, pure-MQL, LN_2, NMQL, cryo-MQL, and cryo-NMQL. The different conditions were based on various concentrations of nanoparticles and also single or hybrid nanofluids. From Figure 18c, we can see the lowest tool wear was in C11, which is the mixture of 0.5% hBN + LN_2. The results he found indicate that, among all the conditions the experiments were performed in, the best result of tool wear was yielded by the hybrid cryogenic and nanofluid system. Sen et al. [102] performed milling on Hastelloy C276. Their findings are also similar to those of previous authors. During the experiments, the best results in tool wear and chip morphology were found during the cryo-NMQL condition. Figure 18d shows that the cryo-NMQL chips have fine lamellae and negligible serration, making them superior to the other chips found in dry, MQL, and NMQL conditions. Ma et al. [109] also found similar results, indicating that cryo-NMQL produces thinner, curled, and segmented chips during the turning of GH4169, as shown in Figure 18e.

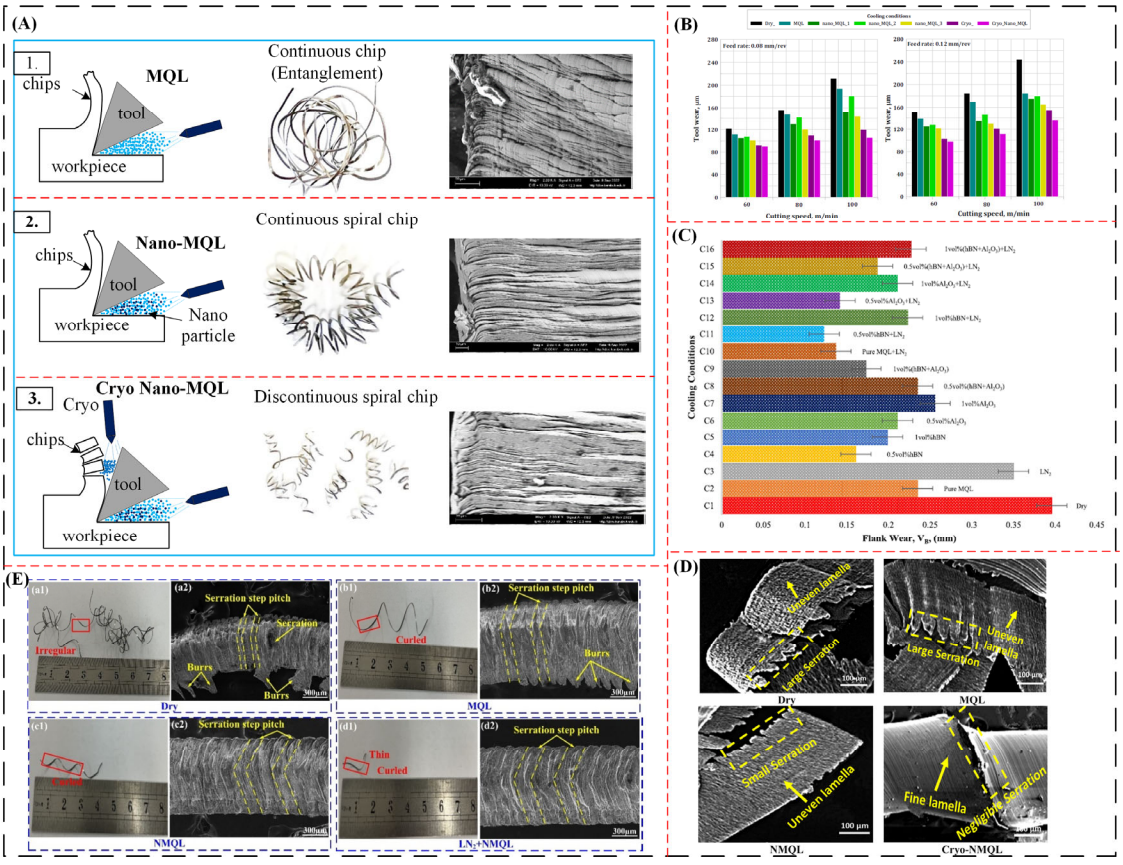


Figure 18. (**A**) Chip formation in MQL, Nano-MQL & Cryo-Nano-MQL machining; (**B**) tool wear in different cutting speed; (**C**) tool wear in different cooling condition; (**D**) chip formation in dry, MQL, NMQL & Cryo-NMQL system; (**E**) chip formation in dry, MQL, NMQL & LN_2-NMQL system.

From all these studies, it can be said that the hybrid system of cryogenics and nanofluid has the best effect on tool wear and chip formations during the machining process of hard-to-cut materials like nickel, titanium alloys, etc.

5.6. Application of Nanofluid with EMQL

Nowadays, during machining processes, many technologically advanced lubrication systems are being used. These systems show great promise in the advancement toward greener machining. However, many researchers have been integrating nanofluids into these already environmentally viable systems to get better and improved results. The following sections talk about the integration of nanofluids in advanced lubrication systems and their effect on the environment.

In recent years, significant effort has been dedicated to exploring and refining nanofluid-based MQL systems across diverse machining operations, including milling, micromilling, and various types of grinding, all driven by a pressing need to both improve machining performance and mitigate the environmental drawbacks commonly associated with conventional lubrication techniques. Lv et al. [110] investigated a novel magnetic minimum quantity lubrication (mMQL) strategy, employing water-based Fe_3O_4 nanofluid as cutting fluid, to mitigate oil mist and environmental impact in machining. The study investigated the influence of magnetic induction on the nanofluid's kinetic viscosity, atomization, and deposition properties. It was discovered that greater magnetic induction improved these qualities, resulting in lower PM10 and PM2.5 concentrations and better cutting performance during 430 stainless steel milling. This mMQL system outperformed traditional oil-based MQL in terms of tool wear, milling force, and surface roughness, demonstrating its potential as a greener and more efficient lubrication option. Huang et al. [111] looked into using a graphene nanofluid/ultrasonic atomization MQL system to micromill SKH-9 high-speed steel. It was shown that graphene's better ability to transfer heat decreases the temperature of cutting, makes tools last longer, and enhances the quality of micromilling products. To solve the problem of nanoparticles sticking together, a self-made ultrasonic atomization device was used to improve their dispersion and lubricating efficiency. A fuzzy-logic-based multi-objective design was used to find the best processing settings for many quality metrics. Compared to existing MQL systems, this system showed better performance in micromilling force, temperature, tool wear, and workpiece burr. Xu et al. [112] investigated the breakdown of electrically charged nanolubricants and their benefits in grinding GH4169 superalloy. It was found that the electric field has a significant effect on the properties of droplets, which enhances lubrication. A comparative study showed that grinding with electrically charged nanolubricant led to a substantial decrease in friction coefficients and specific grinding energy. Additionally, the ground components exhibited improved surface integrity. These results indicate that electrostatic atomization of nanolubricants has significant potential to enhance grinding processes by increasing efficiency and surface quality. Investigations into the surface grinding of hardened steels utilizing a pulse jet MQL nanofluid system were conducted, further enhanced by compressed air wheel cleaning, by Tushar [113]. This approach was employed to improve grinding efficiency and surface quality. The study aimed to assess the impact of the MQL nanofluid and wheel cleaning technique on key grinding characteristics. It was found that the combined system contributed to effective cooling and lubrication, resulting in enhanced grinding performance and improved workpiece surface integrity. Huang et al. [114] further examined the utilization of a nanofluid/ultrasonic atomization MQL technique for the grinding of Inconel 718 alloys. MWCNTs and molybdenum disulfide (MoS_2) nanoparticles were used as additions because they have better thermophysical qualities and are better at lubricating. It was found that MWCNTs are good at removing heat and lowering friction,

whereas MoS_2 makes film layers that resist wear and stop ploughing. The Taguchi robust design method, grey relational analysis, and fuzzy inference algorithms found the best settings for several performance variables. This shows that the system works nicely to improve grinding performance. For high-speed milling of 7075-T6 aluminum alloy, a nanofluid/ultrasonic atomization minimal quantity lubrication system was used by Ho et al. [115]. The goal of the study was to make the surface smoother and the machining process more efficient overall. It was discovered to be a good way to improve nanofluid dispersion and efficiency by stopping nanoparticles from clumping together. The method, which was a big step forward in lubricating technology for high-speed milling, helped the aluminum alloy get a better surface finish. Figure 19 shows the results of NMQL in non-traditional machining.

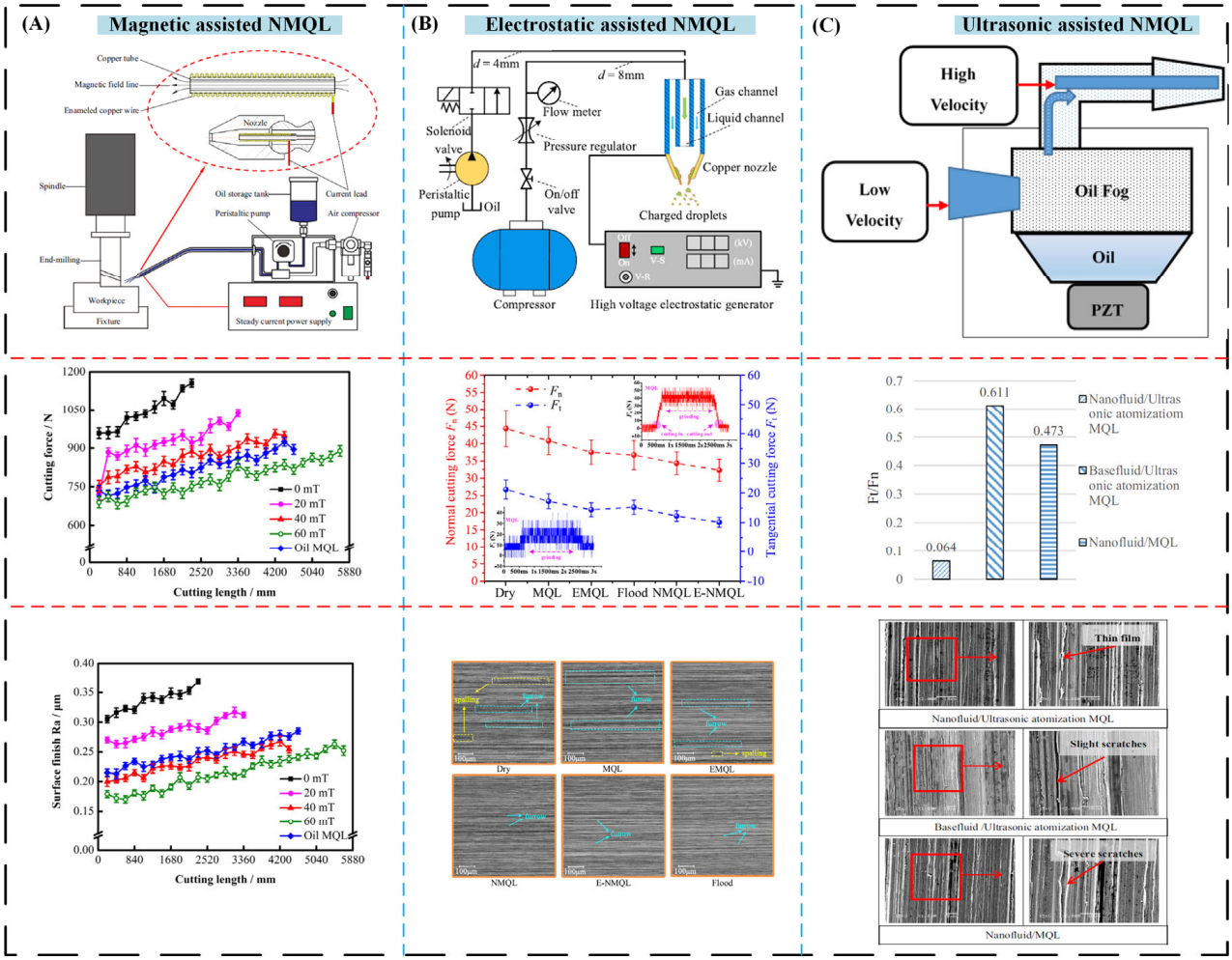


Figure 19. Nanofluid with enhanced MQL.

The findings show that there is a significant development in advanced manufacturing: the creative use of nanofluid-based MQL systems to improve machining operations and deal with environmental issues. Different nanofluids, like Fe_3O_4, graphene, MWCNTs, and MoS_2, have been proven to improve temperature management, lower friction and tool wear, and increase surface integrity in activities like milling, micromilling, and grinding. Moreover, the use of modern atomization techniques, including magnetic, ultrasonic, and electrostatic approaches, consistently enhances nanofluid dispersion and delivery, resulting in improved machining performance and a decrease in harmful emissions. These studies

show that modern machining is moving towards lubricating systems that are more efficient, environmentally friendly, and high-performance.

5.7. Application of Nanofluid with Multiple Nozzles

When combined with multiple nozzles in machining, nanofluids offer many advantages. The tool–workpiece interface and the chip formation zone are two crucial locations where the nanofluid can be delivered more precisely and effectively when multiple nozzles are used. By improving fluid penetration, this application maximizes the fluid's cooling and lubricating properties. Edelbi et al. [79] used a new dual-nozzle MQL system, shown in Figure 20a, to compare the machining performance of Ti-3Al-2.5V alloys during face milling. The application of an environmentally friendly ZnO nanofluid was the primary focus of the study, and its performance was closely compared to that of Al_2O_3 nanofluids. ZnO and Al_2O_3 nanofluids were found to have surface roughness values between 0.312 and 1.032 µm and 0.374 and 1.124 µm, respectively, while ZnO and Al_2O_3 nanofluids were found to have flank wear measurements between 0.088 and 0.182 mm and 0.098 and 0.235 mm, respectively, as shown in Figure 20b. In both nanofluid applications, abrasion was found to be the most common wear mode. Additionally, compared to Al_2O_3 nanofluid milling, ZnO nanofluid-assisted milling demonstrated improved flatness. By using grey PSO, the ideal input parameters for ZnO nanofluid MQL were found to be Q = 33 mL/h, ap = 0.4 mm, f = 250 mm/min, and N = 1800 rpm, while the perfect parameters for Al_2O_3 nanofluid were found to be Q = 31 mL/h, ap = 0.3 mm, f = 200 mm/min, and N = 1200 rpm. Conger et al. [116] performed a thorough examination on the sustainable milling of Al6061-T651 alloy, analyzing the effects of single and dual MQL nozzles in diverse machining environments, encompassing dry, MQL, and nanomolybdenum disulfide (MoS_2)-reinforced NMQL cutting conditions. The study concentrated on evaluating milling performance and sustainability, particularly regarding tool wear, surface quality, cutting forces, energy consumption, carbon dioxide emissions, and machining costs. A comparative analysis demonstrated that the dual-nozzle NMQL system substantially improves machining sustainability and performance, particularly by diminishing tool wear and enhancing surface finish in contrast to single-nozzle MQL and dry machining conditions, shown in Figure 20b–d. Figure 20e–g show the energy consumption, carbon emission, and machine cost, respectively. The dual-nozzle system's enhanced lubrication and cooling capabilities, combined with the MoS_2 nanofluid's superior properties, contributed to this improvement. Khatai et al. [117] assessed the effects of a dual-nozzle MQL system using ZnO nano-cutting fluid on flank wear, surface roughness, cutting temperature, cutting power consumption, and cutting noise during the hard turning of AISI 52100 bearing steel. Due to the hardness of the workpiece material, hard turning frequently encounters issues with high tool wear, cutting temperature, surface roughness, and cutting force. Tool flank wear was found to be extremely low (0.027 mm to 0.095 mm) when the dual-nozzle MQL with ZnO nanofluid was used to address these problems. Analysis of variance (ANOVA), interaction plots, and main effects plots were used to analyze the gathered data statistically. The ideal combination of input parameters was also found using a new weighted aggregated sum product assessment (WASPAS) optimization tool. The depth of the cut was set at 0.2 mm, feed at 0.05 mm/rev, cutting speed at 210 m/min, and flow rate at 50 mL/h.

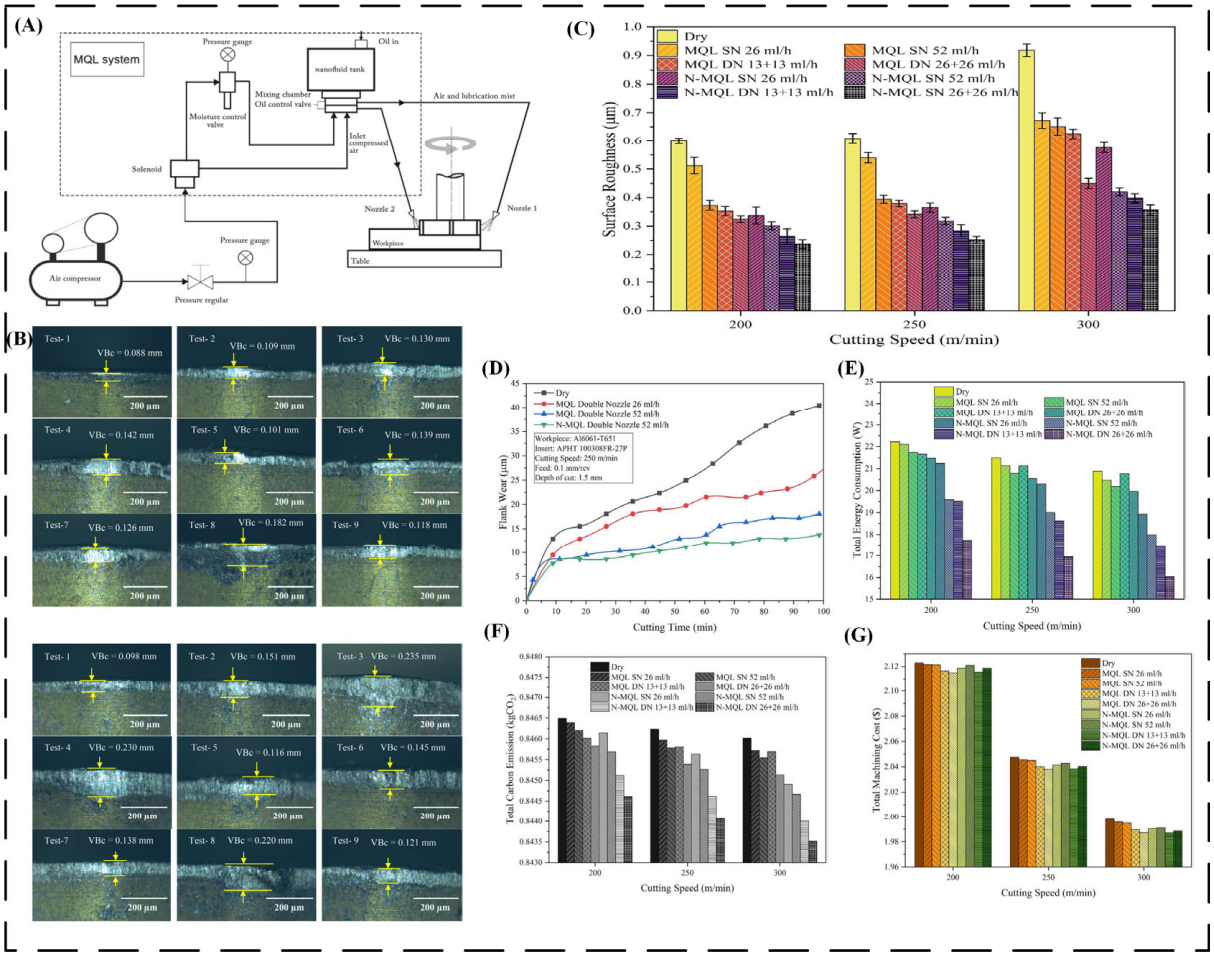


Figure 20. (**A**) Schematic diagram of NMQL with multiple nozzle; (**B**) tool wear of Ti–3Al–2.5V under ZnO & Al2O3 nanofluids; (**C**) surface roughness of Al6061-T651 in different cooling conditions and cutting speed; (**D**) tool wear of Al6061-T651 in different cooling conditions; (**E**) energy consumption of Al6061-T651 in different cooling conditions; (**F**) carbon emission of Al6061-T651 in different cooling conditions; (**G**) machining cost of Al6061-T651 in different cooling conditions.

The substantial advantages of using dual-nozzle MQL systems with different nanofluids in a range of machining operations are continuously emphasized in these studies. The dual-nozzle MQL approach shows superior performance in face milling of Ti-3Al-2.5V alloys, sustainable milling of Al6061-T651 alloy, and hard turning of AISI 52100 steel. Reduced tool wear, improved surface quality, and enhanced thermal management are seen. By reducing problems like high cutting temperatures, forces, and environmental effects, the studies also highlighted the importance of optimization techniques in determining the best machining parameters for particular nanofluid applications, resulting in more sustainable and effective processes. The effectiveness of dual-nozzle MQL with nanofluids as a viable approach for sophisticated and environmentally friendly manufacturing is strongly supported by analyzing these studies.

5.8. Application of Nanofluid Through Tool Delivery

In this technique, the nanofluid is delivered straight through openings or channels in the cutting tool. This guarantees that, during processes like drilling, milling, or turning, the coolant or lubricant reaches the crucial cutting zone, where extreme heat and friction are produced. It has been found by Octavio et al. [118] that the reduction of the tool temperature in the cutting zone when CO_2 is used as internal coolant is reduced ≈40% in comparison with the use of CO_2 as external coolant. So, using nanofluids internally will also improve machining quality. Peng et al. [119] investigated the use of a specially created environmentally friendly Al_2O_3/soybean oil nanofluid for pressurized internal cooling grinding of Inconel 718. The cutting fluid was supplied through the grinding wheel. This method guarantees adequate lubrication and cooling at the tool–workpiece interface. Comparing this method to traditional external cooling techniques, it was found that the Al_2O_3/soybean oil nanofluid produced a lower grinding temperature and better surface integrity. The efficiency of this internal cooling method was emphasized as having significant potential for application in the aviation manufacturing industry, particularly when combined with the customized nanofluid. Peng et al. [120] also developed a graphene nanofluid based on vegetable oil. They combined it with internal cooling and MQL technology to improve cooling and lubrication during the milling of 7075 aluminum alloy. The goal of this integration was to solve issues with high-speed machining, like high temperatures and tool wear. It was clarified that internal cooling technology makes it possible for coolant to be delivered directly through the tool, effectively piercing the air barrier formed by tool rotation and guaranteeing a precise fluid supply to the cutting zone. This accuracy reduces fluid loss, increases heat dissipation efficiency, and strengthens the lubrication film's stability. According to experimental results, cutting temperatures were lowered by 11.31% to 20.98% when the optimized nanofluid and internal cooling MQL milling were used together. It has been shown that this method greatly improves sustainability, surface quality, tool life, and machining efficiency. Furthermore, an effective cutting fluid for hardened steels, where excessive heat generation is a known problem, was created using a stable high-volume carbon-nanotube-based nanofluid by Sharmin et al. [107]. In order to solve this, 42CrMo4 hardened steel was subjected to a milling operation, and a specially made liquid applicator was used to deliver the nanofluid internally to the cutting zone. This internal delivery method allowed the 0.3% volume nanofluid sample to reduce cutting temperature by up to 29%, surface roughness by up to 34%, cutting force by up to 33%, and tool wear by up to 39%. Therefore, it was determined that the internal delivery of a 0.3% volume carbon nanotube-based cutting fluid was a suitable option for machining hardened materials. All of the research that has been provided demonstrates the significant benefits of using nanofluids in combination with internal cooling delivery techniques for a variety of complex machining operations. One recurring theme in the research by Peng et al. [119,120] and Sharmin et al. [121] is that internal cooling, whether via the cutting tool or the grinding wheel, proves to be very successful in precisely delivering nanofluids to the tool–workpiece interface. Using specific nanofluids like CNT-water, vegetable-oil-based graphene, or Al_2O_3/soybean oil, this targeted application consistently produces notable improvements. In particular, there are noticeable decreases in cutting and grinding temperatures, improved surface quality and integrity, less cutting force, and longer tool life, which enhance environmental sustainability and machining efficiency, highlighting the remarkable potential of internal cooling with nanofluids for advanced manufacturing applications. Figure 21 shows grinding and milling results with the internal NMQL system.

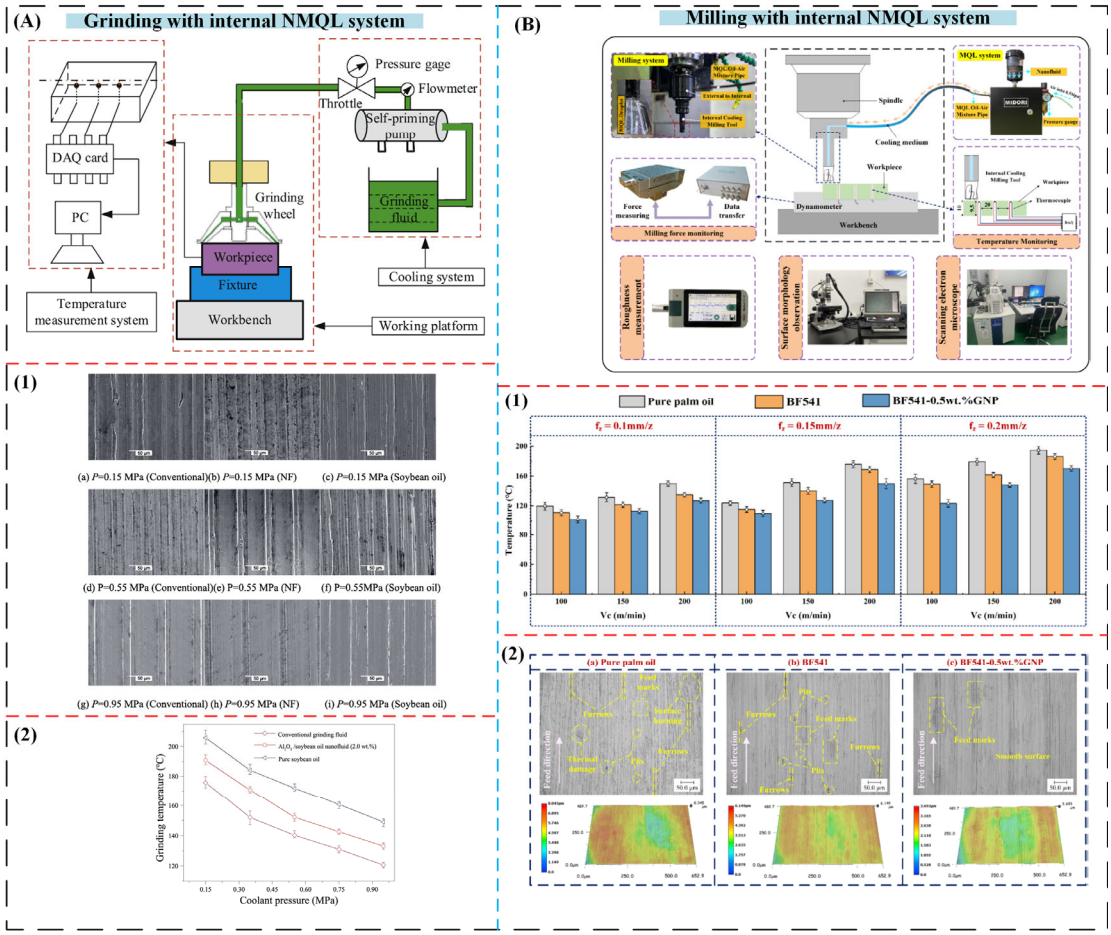


Figure 21. (**A**) Schematic diagram of grinding with internal NMQL system; (1) surface roughness of Inconel 718 under different coolant pressure; (2) effect of grinding fluid pressure on temperature; (**B**) schematic diagram of milling with internal NMQL system; (1) temperature of 7075 aluminum alloy depending on different lubricant and machining parameters; (2) surface morphology variation of 7075 aluminum alloy depending on different lubricant and machining parameters.

5.9. Other Applications of NMQL Technology in Machining

As advanced functional fluids, nanofluids are being investigated more and more for their improved tribological and thermophysical characteristics in a variety of engineering applications. Many types of nanofluids, such as those based on deep eutectic solvents, bioinspired graphene formulations, and biodegradable hybrid compositions, have been created and characterized through extensive research, with an emphasis on environmental friendliness. Jafari et al. [122] described the creation and characterization of new nanofluids based on deep eutectic solvents (DESs), which are composed of water, ethylene glycol (EG), and choline chloride (ChCl). Four distinct DES compositions, including those with and without water and with different molar ratios of ChCl:EG, were used to disperse spherical MgO nanoparticles. By measuring the size distribution over five days, the stability of these nanofluids was evaluated; MgO nanofluids dispersed in DES 1ChCl:5EG showed the best results. The effects of temperature, water content, and nanoparticle mass fraction were investigated, and thermophysical characteristics—specifically thermal conductivity and density—were measured. It was discovered that, while thermal conductivity stayed largely constant throughout the tested temperature range, density decreased as the temperature rose. Water-containing nanofluids made with DESs showed higher thermal conductivities, and it was discovered that a higher concentration of nanoparticles enhanced thermal conductivity. With the greatest thermal conductivity enhancement of 23%, the MgO/DES

1ChCl:2EG 10 weight percent nanofluid was ultimately determined to be the most effective. To attain high lubricity, a novel solvent-free graphene-based nanofluid was created by Liu et al. [123] using a bioinspired, three-dimensional assembly technique. To improve their dispersion stability and tribological performance, the graphene nanosheets were designed to self-assemble into a three-dimensional network inside the lubricating oil by utilizing several adsorption effects. The prepared nanofluid's lubricity was assessed experimentally in a variety of scenarios. It was shown that the special structural features and the robust bond between the graphene and the base oil greatly enhanced the nanofluid's anti-wear and friction-reducing properties, outperforming those of traditional lubricants. Popat et al. [124] developed and assessed biodegradable hybrid nanofluids using a two-step method. Sodium dodecyl sulfate (SDS) was used as a surfactant to ensure stability, and silicon carbide (SiC) and titanium dioxide (TiO_2) nanoparticles were dispersed in palm oil as the base fluid. At 1%, 2%, and 3% volume concentrations, a range of combinations were created, including single SiC and TiO_2 nanofluids and hybrid SiC + TiO_2 nanofluids. Fourier transform infrared (FTIR) and zeta potential analyses were performed to evaluate the stability and characteristics of the thermal and physical properties, such as density, calorific value, flash point, and thermal conductivity. Comparing the biodegradable hybrid nanofluids to the pure nanofluids, it was discovered that the SiC + TiO_2 + palm oil combination had better thermal conductivity and stability. There was a noticeable improvement in thermal properties, with the hybrid nanofluid's ideal volume fraction of 3% showing noticeably higher thermal conductivity. A novel, non-edible cactus-oil-based nanofluid was developed and evaluated as a sustainable alternative to conventional cutting fluids for machining H13 steel by ElBadawy et al. [125]. The research enhanced the physicochemical, rheological, and tribological properties of the cactus oil by dispersing activated carbon nanoparticles (ACNPs), derived from recycled plastic waste, at various concentrations. When tested under minimum quantity lubrication (MQL) conditions, the 0.05 wt.% ACNP blend demonstrated the most significant improvements, enhancing wettability by up to 60% over commercial soluble oil and showing superior thermal stability with a viscosity index of 283. These property enhancements led to superior machining outcomes, with the nanoenhanced fluid reducing surface roughness by 35% and flank wear by 57% compared to dry conditions, outperforming the conventional soluble oil benchmark. Verma et al. [126] used a new biodegradable nanofluid process cooling system made of copper oxide and sunflower oil to reduce the heat produced during friction stir welding (FSW) of AA6082 alloy. This nanofluid was sprayed onto the welding surface. During NMQL-FSW, a considerable temperature drop was accomplished, and asymmetrical heat transfer was also reduced. According to microstructural analysis, continuous dynamic recrystallization (CDRX) was the main mechanism by which NMQL-FSW facilitated the nucleation and growth of equiaxed grains in the nugget zone. Additionally, the frequency of high-angle grain boundary bulging was increased, and the average grain size in the nugget zone was significantly refined from 25.81 $\pm$ 3.69 μm for FSW to 21.36 $\pm$ 1.14 μm for NMQL-FSW. As a result, the NMQL-FSW joints' tensile strength increased significantly from 64% for conventional FSW joints to about 81% of the base metal. The thermophysical characteristics of an environmentally friendly clove-treated MWCNT (C-MWCNT) nanofluid were modeled and optimized using multiple criteria by Amani et al. [127]. In addition to empirical correlations, soft computing techniques like artificial neural networks (ANNs) and genetic algorithms were used to determine these properties, particularly thermal conductivity and viscosity. When compared to empirical correlations, the most accurate and precise predictions for thermal conductivity and viscosity were obtained using an optimal ANN model, which was determined to have two hidden layers with four neurons per layer. To attain conditions that maximize thermal conductivity and minimize viscosity, an evolutionary algorithm

was used to perform a multi-criteria optimization. The best results from the TOPSIS and LINMAP decision-making processes were found to be the ones that most closely resembled the ideal engineering solution. Figure 22 shows other application methods of nanofluids.

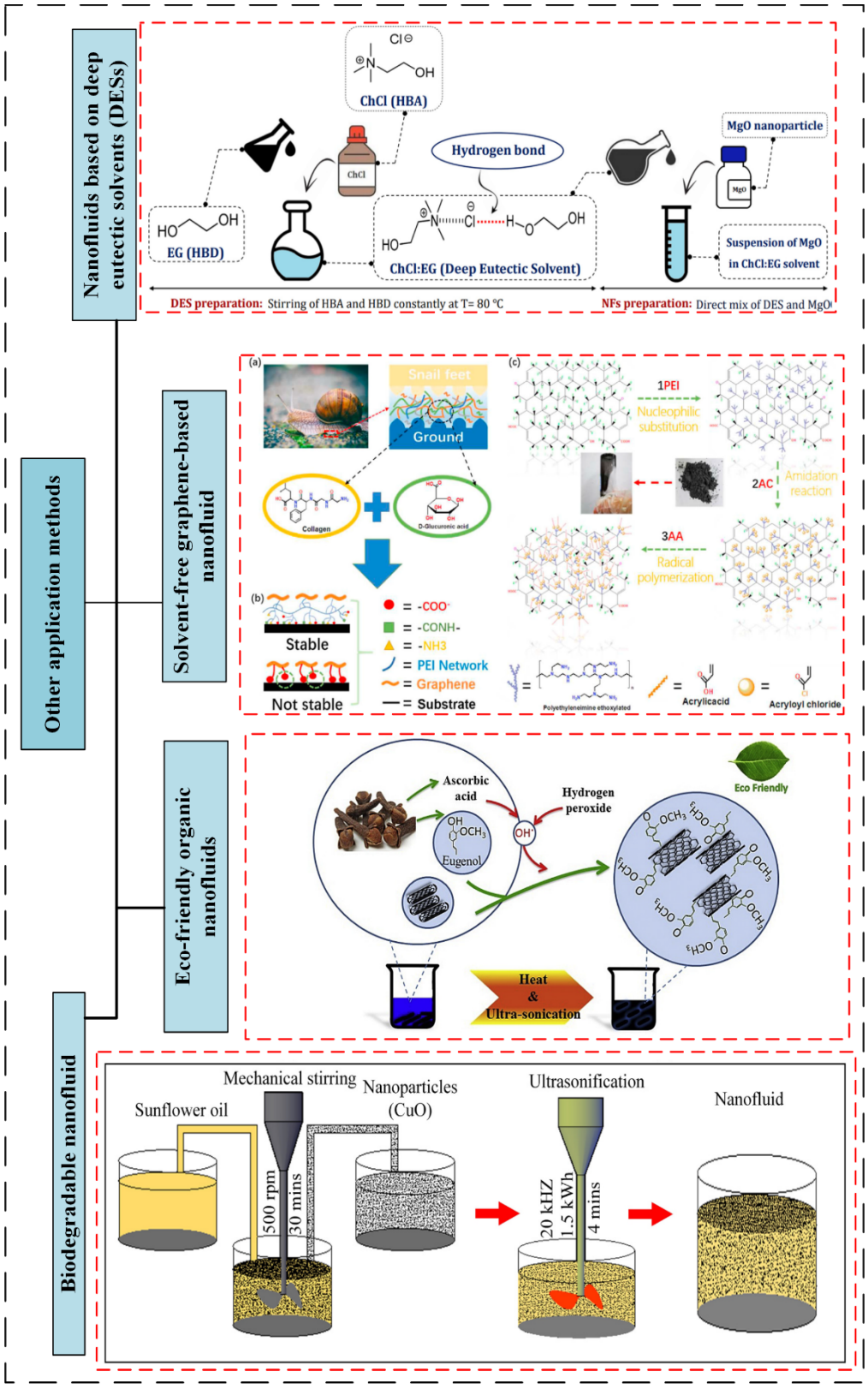


Figure 22. Other application methods of nanofluid. ((**a**) The main component of snail mucus and mussel byssus. (**b**) Schematic diagram of multiple adsorption mechanism. (**c**) Three-step method of preparing graphene solvent free graphene-based nanofluid.)

Recent developments in nanofluid research are highlighted in these studies, which are provided, showing a strong emphasis on creating innovative formulations with improved thermophysical properties and a wide range of applications. The growing potential of environmentally friendly nanofluids as adaptable solutions for tribological applications, energy-efficient heat transfer, and advanced manufacturing processes is highlighted by this research.

6. Sustainability in MQL Technologies

6.1. Environmental and Economic Assessment

When assessing the effects of emerging technologies, especially those involving nanomaterials, on the environment and human health, life cycle assessments, or LCAs, are essential. This field of study examines the trade-offs between improved performance and the environmental expenses related to the production and use of nanoparticles. Research has examined several cooling and lubrication methods in machining, such as conventional flood cooling, MQL using vegetable oils, and MQL using various nano-cutting fluids (NCFs). NCFs can be used for high-temperature cutting, but when compared to traditional methods, their energy-intensive production frequently has a greater overall environmental impact. Similar to this, LCAs of particular nanoparticle manufacturing processes, like those for titanium dioxide and MWNTs, show that the main factor influencing their ecological impact is energy consumption during production. Salem et al. [128] researched the effects of different cooling and lubrication techniques in machining on the environment and human health. MQL with vegetable oils, MQL with NCFs, and TFC with conventional cutting fluids were all compared using LCAs. Using cradle-to-gate LCA, the effects of MQL of MoS_2, MWCNTs, TiO_2, and Al_2O_3 NCFs were examined. Because of their energy-intensive synthesis processes, NCFs were found to have generally greater environmental impacts than vegetable oils and conventional cutting fluids. In particular, MWCNTs-NCF and Al_2O_3-NCF were found to have greater effects than TiO_2-NCF and MoS_2-NCF. Although TFC with traditional cutting fluids had the least negative environmental impact, this approach contributed to serious health issues for operators. On the other hand, MQL of vegetable oils is thought to be environmentally friendly because of its biodegradability, even though it has greater effects than TFC. MQL of vegetable oils was found to be the most sustainable approach for low to medium cutting temperatures. In contrast, MQL of TiO_2 and MoS_2 NCFs was found to be appropriate for high cutting temperatures. The environmental effects of MWNT growth by catalytic chemical vapor deposition (CCVD) were measured using an LCA by Griffiths et al. [129]. The synthetic reactant routes, process energy inputs, equipment infrastructure, and generated emissions were evaluated using a cradle-to-gate methodology. The environmental burden was found to be significantly influenced by the energy-intensive furnace operations as well as the embodied effects of the equipment infrastructure. Exhaust gases were found to largely affect photochemical oxidant formation and, to a lesser extent, human toxicity, while the impact of chemical reactants was found to be negligible. This study is considered more realistic due to its comprehensive capture of input materials and quantification of infrastructure impacts. To analyze the emissions, energy needs, and exergetic losses related to a new method for creating titanium dioxide nanoparticles from an ilmenite feedstock, the Altairnano hydrochloride process, an LCA was carried out by Grubb et al. [130]. The life cycle energy requirements of this process, which is intended for the production of nanoscale particles, were compared to those of conventional building materials on a mass-per-unit basis. While the energy analysis and environmental impact assessment highlighted the upstream life cycle's dependence on non-renewable fossil fuels, the exergy analysis showed that material losses, especially in the mining of ilmenite ore, were more substantial than fuel losses.

A life cycle inventory for a nanomanufacturing process and insights from a combined analysis using life cycle assessment, energy, and exergy methods were the study's main contributions. Further findings of other researchers are shown in Table 3.

Table 3. Studies on environmental impact of nanofluids.

Researchers	Nanofluids	Impact	Method/Software
Yang et al. [131]	Fe-Mn@Al_2O_3	Ozone depletion, GHG emissions, smog, acidification, eutrophication, carcinogenic and non-carcinogenic, respiratory effects, ecotoxicity, fossil fuel depletion.	TRACI 2.1/SimaPro version 8.5 Ecoinvent and US Life Cycle Inventory
Feijoo et al. [132]	Different magnetic nanoparticles (NPs) based on magnetite (Fe_3O_4)	Climate change, ozone depletion, acidification, eutrophication, toxicity, fossil fuel depletion.	IMPACT2001 and ReCiPe/SimaPro 8.2.0 Ecoinvent database
Gunasekara et al. [133]	HVFA–65 ns and HVFA–80 ns	GHG emissions, acidification, photochemical oxidant formation impact.	SimaPro Ecoinvent database
Huseien et al. [134]	BGWNP	CO_2 emission, energy consumption, fuel consumption.	Laboratory-scale primary study data
Ingrao et al. [135]	Nano-HA	GHG emissions, non-renewable energy, respiratory inorganics, human health, climate change, resources, ecosystem quality.	IMPACT2002+/SimaPro
Lee et al. [136]	nNaCl	GHG emissions, CO_2 emissions (sensitivity analysis included)	SimaPro Ecoinvent database
Petrakli et al. [137]	n-CFRP	depletion, GHG emissions, human health, ecotoxicity, acidification, eutrophication, land occupation, water consumption, NRE, mineral extraction, water turbine.	ILCD 2011 Midpoint +/SimaPro 8.0.4.26 Ecoinvent database
P. Rodrigues et al. [138]	AgNM	Water and soil emissions.	Toxicity Relationship Analysis Program (TRAPv1.22)/REST-MSC tool
Rossi et al. [139]	Nanogrid (NG)	Ecotoxicity, human health, resources (sensitivity analysis included).	ReCiPe 1.11 (2014)/OpenLCA version1.8 tool Ecoinvent database

To increase efficiency and environmental performance, the incorporation of nanofluids into solar thermal systems has been thoroughly studied in the field of renewable energy. A variety of metal oxide nanofluids, including ZnO, AlO_3, TiO_2, CuO, and CeO_2, have been used in experimental and theoretical analyses of evacuated tube solar collectors, flat plate collectors, passive double slope solar stills (DSSSs), and photovoltaic thermal (PVT) systems. In comparison to systems that use traditional fluids like water, these studies consistently show that the addition of nanofluids improves thermal efficiency, increases energy and exergy outputs, and can significantly reduce operational CO_2 emissions. Copper nanofluids have been found to increase heat energy output and shorten the cost payback period in evacuated tube collectors. At the same time, nanofluid-based PV/T systems have been demonstrated to reduce the energy payback period significantly. When employing various nanofluids and working fluids, multi-criteria optimizations have also been carried out on intricate integrated systems, like a solar-geothermal CCHP plant, to balance environmental, economic, and energetic goals. To examine the financial and environmental implications of employing different metal oxide/water nanofluids, an experimental setup for a photovoltaic thermal (PVT) system was created and constructed by Abadeh et al. [140]. Pure water, ZnO/water, Al_2O_3/water, and TiO_2/water nanofluids were the coolants chosen for this study. Nanoparticles were distributed in distilled water at a weight fraction of 0.2%. The payback period of PVT systems was contrasted with that of traditional PV units, and the annual emission reduction and cost savings related to various coolants were examined. It has been demonstrated that using PVT/nanofluid systems can reduce emission production by 17% more than using a traditional PV unit from an environmental perspective. In

particular, from an energy and exergy perspective, employing a suitable nanofluid, such as ZnO/water, can result in an emission reduction of roughly 12% and 7% for PV, respectively. From the energy and exergy perspectives, the ZnO/water nanofluid emission reduction values are roughly 5% and 2% lower than those of pure water, respectively. Water-based nanofluids containing Al_2O_3, TiO_2, and CuO nanoparticles are used to examine the environmental performance of a passive double slope solar still (DSSS) by Sahota et al. [141]. By contrasting the system with a traditional solar still that uses only base fluid (water), the study assesses the system's potential to mitigate CO_2 and its environmental impact over its lifetime. It was discovered that using nanofluids greatly increases the system's yearly energy, exergy, and productivity outputs, which increases the system's environmental benefits. Al_2O_3-water outperformed the other nanofluids in terms of productivity improvement (19.10%), followed by TiO_2-water (10.38%) and CuO-water (5.25%). Energy and exergy analyses showed that Al_2O_3-water nanofluid had the highest amount of CO_2 mitigated annually, at 2.84 tons (energy basis) and 0.231 tons (exergy basis), indicating its superior environmental performance. When compared to the base fluid system, the environmental cost, expressed in carbon credits, also showed greater savings for nanofluid-integrated systems, especially Al_2O_3-water. According to these results, by lowering greenhouse gas emissions, adding nanofluids to passive solar desalination systems can improve efficiency and environmental sustainability. Stalin et al. [142] examine the energy, cost, and environmental performance of a flat plate solar collector using a CeO_2/water nanofluid as the working fluid at different flow rates (1–3 L min^{-1}) and volume concentrations (0.01% to 0.1%). According to the study, using CeO_2 nanofluid considerably improves the system's thermal efficiency when compared to using just water, which results in greater energy savings and a less negative environmental impact. According to environmental analysis, using nanofluids in solar collectors reduces CO_2 emissions by increasing system efficiency and lowering dependency on energy sources derived from fossil fuels. Furthermore, the improved performance offered by the nanofluid gradually offsets the embodied energy and damage costs related to the solar collector's manufacturing. According to the results, adding CeO_2/water nanofluid to flat plate solar collectors may result in more environmentally friendly and sustainable solar thermal systems that have long-term potential advantages. Through a theoretical comparison of their performance with that of conventional PV and PV/T systems, the environmental advantages of nanofluid-based hybrid PV/T systems are investigated by Hassani et al. [143]. According to the study, nanofluid-based PV/T systems that are optimized for both optical and thermal characteristics can prevent about 448 kg of CO_2 emissions per square meter per year and drastically cut the energy payback period to two years. These systems produce approximately 1.3 MW h/m^2 of high-grade energy annually, which is higher than the ~0.36 MW h/m^2 produced by standard PV systems, thanks to the use of nanofluids as coolants and optical filters. The life cycle assessment demonstrates the exceptional sustainability of nanofluid-based configurations, which gradually mitigate the environmental impact of their manufacturing phase while also minimizing greenhouse gas emissions during operation. Using a copper/water nanofluid, an experimental study was carried out by Sharafeldin et al. [144] to evaluate the energy and environmental performance of an evacuated tube solar collector. The effects of different volume flow rates (0.6, 0.7, and 0.8 L/min) and different volume concentrations of copper nanoparticles (0.01%, 0.02%, and 0.03%) were investigated. It was shown that the useful heat energy increased from 417 W to 667 W, and the collector's output temperature increased by up to 50%. For the same energy output, a potential 34% reduction in collector area was found, and the heat removal factor significantly improved, reaching a value of 0.97. When the absorbed energy and removal energy parameters were raised, the highest values were observed at a volume concentration of 0.03% and a flow rate of

0.8 L/min. Ultimately, an economic and environmental analysis revealed that the use of copper nanoparticles could reduce CO_2 emissions and shorten the energy cost payback period by 30.8%. Exergy, exergoeconomic, and exergoenvironmental principles were used to analyze and optimize a solar–geothermal-driven combined cooling, heating, and power (CCHP) system that is integrated with flat plate collectors that contain a water/copper oxide (CuO) nanofluid by Boyagchi et al. [145]. Twelve system parameters were chosen as decision variables for the multi-objective optimization, and the daily energetic efficiency, total product cost rate, and total product environmental impact rate were selected as the objective functions. To determine the best solutions, the NSGA-II algorithm was used on four distinct working fluids (R134a, R423A, R1234ze, and R134yf). It was discovered that an increase in the nanoparticle volume fraction positively impacts all objective functions. With a total product environmental impact rate of 36.82 Pts/h, R1234ze was determined to be the optimal fluid from an exergoenvironmental standpoint based on the optimization results. With a minimum total product cost rate of USD 4496 per year, R423A was found to be the optimal fluid from an exergoeconomic perspective. Additionally, it was discovered that the best fluid for reaching the maximum daily energetic efficiency of 4.194% was R134a. Although nanofluids can greatly improve operational efficiency, resulting in advantages like lower CO_2 emissions and shorter payback periods during use, their energy-intensive production processes frequently cause a greater initial environmental burden than that of conventional fluids. These studies use comprehensive methodologies such as LCA, exergy, and exergoeconomic analyses, because they emphasize the value of a holistic approach that takes into account the full life cycle rather than just the operational phase. The analysis effectively illustrates how the "most sustainable" solution varies depending on the particular nanoparticle, the application, and the operating environment.

6.2. Toxicology, Safety, and Disposal

The most urgent immediate concerns associated with nanotechnology are toxicity and exposure of humans and the environment. This is primarily a health and safety problem rather than an ethical one; nonetheless, due to the apparent novelty of nanotechnology, there are heightened apprehensions regarding potential new hazards or exposure risks, leading to emerging questions about their management. Research has demonstrated that the physicochemical qualities of substances can affect their biological functions. These parameters encompass particle size, surface charge, surface area, and shape, among others. The primary reason nanotechnology has garnered attention is the distinctive features shown by materials at the nanoscale. The unique characteristics of nanosized materials, relative to their naturally occurring forms, are advantageous for the production of high-quality products but pose risks when they interact with the body or disperse in the environment. Although every substance might be harmful in excessive amounts, the pertinent question is: how toxic are nanoparticles at the potential concentrations for their application? The hazardous effects of nanomaterials are associated with their nanoscale type, shape, coating, and base material.

6.2.1. Toxicology

Due to their features, nanoparticles exhibit distinct characteristics compared to larger forms of the same substance from which they are derived. Nanosized particles have a significant capacity to infiltrate the body when presented as aerosols or through dermal contact, as found by Lau et al. [146]. Upon inhalation, they may accumulate in the respiratory system, resulting in pulmonary inflammation and lung tumors, a scenario less probable with larger particles, or they may be absorbed into the bloodstream and disseminate to other regions of the body. Murugadoss et al. [147] found that long-term exposure to nanosilica

can cause death of cell bodies, and these implications of nanoparticles have reduced their application and use in the oil and gas industry. According to McCarthy et al. [135], there is mounting evidence that amorphous silica nanoparticles (SiO_2-NP) can induce inflammation and harmful effects in lung cells due to their unique physiochemical profile and nanometer size. SiO_2 has been shown to cause cytotoxic and inflammatory effects in cells by increasing reactive oxygen species (ROS), which are followed by increased gene expression in terms of size, duration, and concentration. The study demonstrated that SiO_2-NPs may have an impact on the submucosal cells of the human lung. In contrast to bigger SiO_2-NPs of the same composite material, the study found that SiO_2-NPs are incredibly toxic to lung cells, and that the mechanism of toxicity was mainly based on oxidative stress and ROS generation [148]. Furthermore, nanoparticles can exhibit cytotoxicity, meaning they may induce necrosis or apoptosis, and genotoxicity, possessing the capacity to damage cellular DNA. Genotoxicity may induce mutations that can result in cancer, a phenomenon known as mutagenicity. The primary toxicity mechanism of nanoparticles arises from the generation of excessive reactive oxygen species (ROS) resulting from oxidative activities. Numerous physiological functions in living organisms are regulated by the presence of modest quantities of reactive oxygen species (ROS). Nonetheless, oxidative stress resulting from elevated ROS levels can be detrimental, leading to nanoparticle-induced cellular damage through protein alteration, cellular membrane impairment, DNA disruption, and even the induction of cancer or other disorders. Zhang et al. [149] investigated the impact of several metal oxide nanoparticles, each approximately 20 nm in size, within a concentration range of 0.25–1.50 mg/mL. The study encompassed ZnO, TiO_2, SiO_2, and Al_2O_3 nanoparticles, all of which induced cellular dysfunction and death in in vitro human fetal lung fibroblasts (HFL1 cells). Among these, ZnO exhibited the highest toxicity, followed by TiO_2, SiO_2, and Al_2O_3 nanoparticles in decreasing order. Kim et al. [150] investigated the cytotoxicity of ZnO, Al_2O_3, and TiO_2 in human lung epithelial cells, specifically A549 carcinoma cells and L-132 normal cells.

The results indicated that ZnO had the most remarkable cytotoxicity regarding cell survival; however, Al_2O_3 showed lower toxicity compared to the other nanoparticles, even after prolonged exposure. TiO_2 nanoparticles exhibited minimal detrimental effects on cell viability, while oxidative stress was induced contingent upon the concentration tested and the duration of exposure.

Karlsson et al. [151] examined the cytotoxicity of several metal oxide nanoparticles (CuO, TiO_2, ZnO, Fe_3O_4, Fe_2O_3) by subjecting the human lung epithelial cell line A549 to these substances.

CuO nanoparticles had the highest potency for cytotoxicity and DNA damage, resulting in oxidative lesions and a substantial elevation in intracellular reactive oxygen species (ROS). ZnO induced DNA damage and reduced cell viability, whereas TiO_2 particles solely resulted in DNA damage. Iron oxide particles exhibited minimal toxicity within the concentration range of 40–80 μg/mL. Identical contents of nanoparticles may exhibit varying toxicities due to differing physicochemical characteristics. For example, the iron oxide demonstrated to be biocompatible in a spherical form exhibits significant alterations when delivered in a rod shape, as indicated by Lee et al. [152].

6.2.2. Safety

Numerous investigations have recognized doping as an efficacious method to mitigate the cytotoxicity of industrially significant engineered nanomaterials, including ZnO, CuO, and SiO_2 nanoparticles. Doping is a simple yet effective technique employed to alter a material's crystal structure through the introduction of impurities, hence enhancing its catalytic, electro-optical, magnetic, chemical, and physical capabilities found by Babu

et al. [153]. Sun et al. [154] found that dopants, including iron (Fe), titanium (Ti), and aluminum (Al), are generally uniformly integrated into the host lattice to modify the binding energy of metal ions to oxygen or to diminish the density of reactive chemical groups on the particle surface. The mechanisms by which doping mitigates the cytotoxicity of engineered nanomaterials (ENMs) are based on altering the physicochemical properties of nanoparticles. This includes reducing nanoparticle dissolution and the release of toxic ions, modifying reactive surfaces to diminish the production of reactive oxygen species (ROS), or disrupting the cellular membrane, which can result in inflammation and cell death [154]. Flame spray pyrolysis (FSP) is a recognized method for doping nanomaterials, utilizing fast combustion in the synthesis process. Teoh et al. [155] found that a liquid precursor facilitates the creation of a self-sustaining flame characterized by elevated local temperatures and significant temperature gradients, enabling the synthesis of homogeneous crystalline nanoscale materials from droplets or gas to particles. This approach is ideal for industrial applications due to its straightforward one-step synthesis and the potential for scaling up the production of doped nanomaterials. Another principal surface modification technique for the construction of safer engineered nanomaterials (ENMs) is coating. In contrast to doping, which may be detrimental due to irreversible chemical alterations that can modify the intrinsic properties of engineered nanomaterials (ENMs), surface coating can be reversible through non-covalent changes. The dispersion state of nanomaterials is a critical element influencing their bioavailability, bioreactivity, and, consequently, their potential toxicological and pro-inflammatory reactions. Consequently, various non-covalent coatings can modify the dispersion state of nanomaterials, thereby affecting their toxicity. Adjustments of charge density and hydrophobicity are other mechanisms by which surface chemistry modifications can ameliorate nanomaterial toxicity and improve functionality. These surface chemistry properties can be adjusted by covalent binding of functional groups onto the ENM's surface. Functional groups include anionic, non-ionic, and cationic groups that can impact both the surface charge density and hydrophobicity. Enhancing the aspect ratio of a nanomaterial is an effective strategy to mitigate its cytotoxicity. The preparation and synthesis of nanomaterials in wire or rod configurations may expand their applications and foster novel uses found by Charehsaz et al. [156]. While both high and low aspect ratio nanomaterials can be internalized by cells, fiber-like particles with high aspect ratios can cause damage to intracellular organelles, such as lysosomes, as indicated by the research of Ji et al. [157]. These particles may not be entirely engulfed by macrophages, leading to "frustrated phagocytosis," which can result in inflammation and cytotoxicity [157]. Consequently, the tailoring of nanorod and nanowire dimensions to achieve ideal aspect ratios that do not elicit inflammatory reactions would facilitate the development of safer nanomaterials.

6.2.3. Disposal

The disposal of nanoparticles and materials containing them poses considerable environmental and safety challenges due to their distinct properties and the potential for unforeseen long-term effects. At present, there are no universally standardized regulations specifically addressing nanomaterial waste; thus, guidelines typically emerge from a precautionary approach informed by existing hazardous or chemical waste protocols. The main goal is to inhibit the discharge of free nanoparticles into the environment, especially in air and water systems. Common disposal methods involve placement in secure, lined hazardous-waste landfills to prevent leaching or high-temperature incineration, necessitating specialized filters to capture potential airborne particulate matter. Although practical guidelines continue to develop, analytical frameworks such as LCA and exergoenvironmental analysis have integrated the disposal phase as an essential element in assessing the

overall environmental impact of a product or system. Additional research is necessary to establish specialized, evidence-based protocols for the safe and responsible management of nanomaterials at the end of their life cycle. Figure 23 shows the LCA framework.

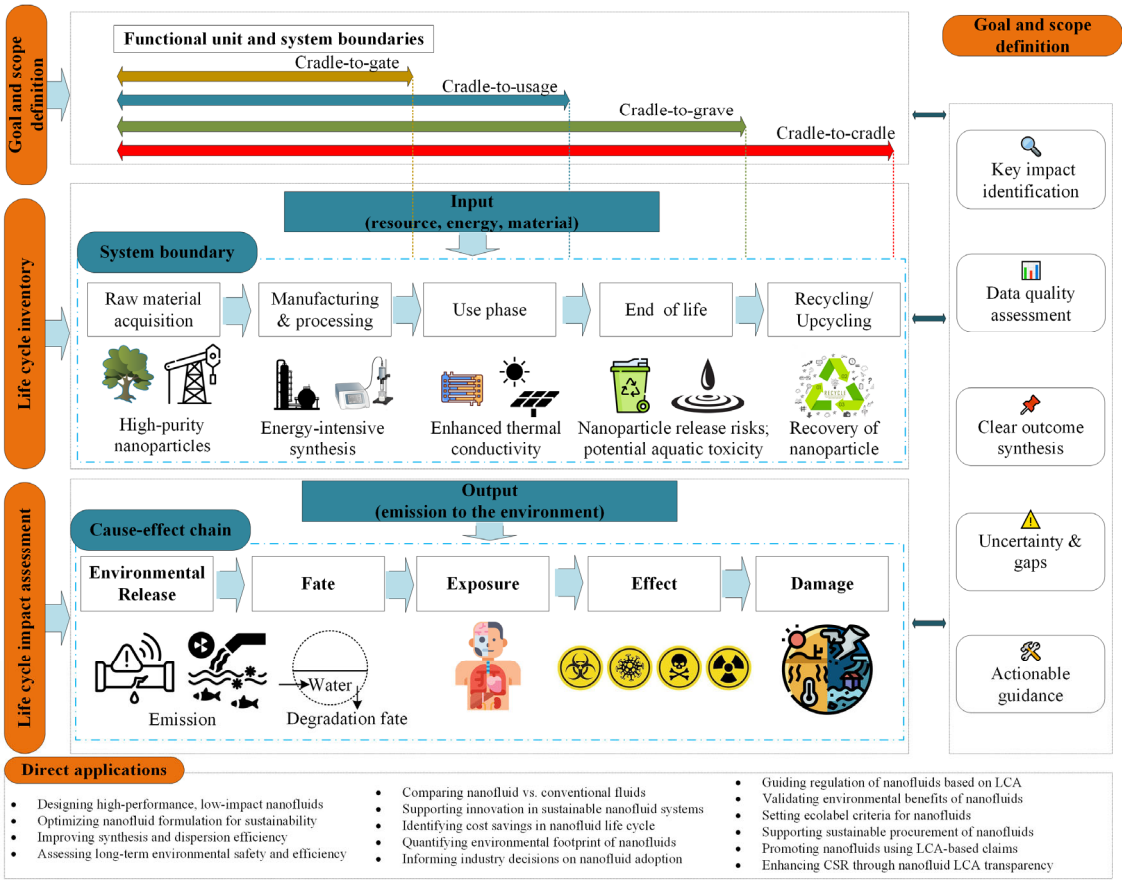


Figure 23. LCA Framework of nanofluids.

7. Research Trends and Future Directions

Unquestionably, nanofluids have the potential to completely transform a variety of industries, including manufacturing and energy production. However, there are still numerous obstacles to overcome before their widespread, profitable use is realized. The urgent need for real-time life cycle assessment data in machining, overcoming cost and scalability obstacles, utilizing AI and machine learning to optimize processes, and establishing precise policy and standardization frameworks are the main topics of this section.

7.1. Lack of Real-Time LCA Data

One of the most significant gaps in current nanofluid research is the absence of real-time LCA data during manufacturing processes, particularly in machining. The integration of experimental trials with LCA supports decision making for more sustainable and efficient operations [158]. A comprehensive understanding of the immediate environmental and economic effects of nanofluids is still in its infancy. However, numerous studies have demonstrated that they can enhance machining performance by reducing cutting forces, friction, and tool wear [159–161]. Currently available LCA research on nanofluids in machining is primarily static and focuses on cradle-to-grave analyses, which often rely on estimates and assumptions. There is a severe lack of dynamic models that can show energy usage, aerosol production, and waste stream properties in real time while the machining process is taking place. At the machine-tool level, there are currently inadequately developed sensor technologies and methodologies for collecting in situ data on energy

consumption, nanofluid degradation, and nanoparticle release. Integrating this data into a logical, real-time LCA framework is still quite challenging. There are very few studies that directly compare the environmental impact and cost of conventional lubrication techniques and nanofluid-assisted machining under identical process conditions. Future studies should focus on incorporating sensors into machining environments to monitor significant LCA indicators continuously. This includes systems to analyze the composition of used nanofluids, air quality sensors to detect nanoparticle aerosols, and power consumption measurement devices. It is necessary to have sophisticated LCA models that can manage real-time data streams and provide timely feedback on the environmental and economic performance of the machining operation. This would enable dynamic process optimization for sustainability. Instead of focusing solely on specific performance metrics, research should concentrate on the "synergetic reduction" of electrical and embodied energy.

7.2. Scalability of Nanosystems and Cost Barriers

Issues with scalability and cost-effectiveness significantly hinder the transfer of nanofluid technology from the lab to the manufacturing floor. Large-scale manufacturing of stable, high-performing nanofluids is still a significant technical and financial challenge. A significant obstacle is the high cost of creating high-quality nanoparticles. Many synthesis techniques are unsuitable for production on an industrial scale because they require a lot of energy and produce comparatively small amounts. Preventing the agglomeration and sedimentation of nanoparticles and ensuring the long-term stability of nanofluids are ongoing challenges, particularly in large-volume storage and circulation systems. Stabilizing agent costs and environmental effects also require careful research. Although nanofluids' performance advantages are frequently emphasized, few thorough techno-economic studies take into account the entire cost of ownership, which includes production, upkeep, and disposal. The initial cost of nanofluids does not yet clearly offer an economic advantage over traditional fluids for a wide range of applications. Future studies should focus on developing scalable and environmentally friendly processes for nanoparticle production, such as continuous flow synthesis and biosynthesis. For industrial-scale nanofluid systems to remain stable over the long term, advancements in dispersion technologies, such as sophisticated ultrasonication and the creation of new, affordable, and biodegradable surfactants, are essential. In-depth techno-economic models that assess the life cycle costs and advantages of adopting nanofluids, in particular, for industrial applications, must be provided by future research. These models should balance the higher initial cost of the nanofluid against potential savings from longer tool life, better product quality, and lower energy consumption.

7.3. Integration with AI/ML for Process Optimization

A revolutionary chance to realize the full potential of nanofluids is presented by the combination of artificial intelligence (AI) and machine learning (ML). These technologies' predictive capabilities can be used to optimize complex processes in real time, which improves quality, lowers costs, and increases performance. More complex models are required to accurately predict the complex, non-linear behavior of nanofluids under varying process parameters, even though the use of AI/ML to predict machining outcomes with nanofluids is expanding. An understudied field is the design of application-specific nanofluids using AI/ML. This entails predicting the ideal nanoparticle size, type, concentration, and base fluid for a particular application using algorithms. Closed-loop control systems that dynamically modify machining parameters for optimal performance with nanofluids using real-time sensor data and AI/ML algorithms are still in their early stages of development. To accurately forecast essential performance metrics like surface roughness, cutting temper-

ature, and tool wear, future research should concentrate on creating and training robust AI/ML models (such as neural networks, random forests, and support vector machines) using sizable and varied datasets. One exciting area for further study is the application of generative AI models to investigate large design spaces and suggest unique nanofluid formulations with specific characteristics. AI/ML algorithms that continuously monitor and optimize the performance of nanofluid-assisted processes in real time are the ultimate goal of "smart" manufacturing systems, which will enable autonomous and highly efficient production. Many researchers have already conducted research using AI and ML and got promising results. In the work by Nguyen et al. [162] an ANN and a multi-objective glow worm swarm optimization algorithm were used to optimize an MQL system for the internal roller burnishing of 50Cr hardened steel. This approach successfully reduced the surface roughness by 17.0% and improved the Vickers hardness by 14.0%. Furthermore, Jogesh et al. [163] utilized ML to optimize nanolubricants. Their research found that these computational methods accurately predicted and improved lubricant properties, with graphene- and carbon-nanotube-based nanolubricants significantly reducing friction and wear compared to traditional lubricants, thus leading to energy savings. Lastly, Farooq et al. [164] utilized an AI-based strategy with machine learning algorithms to predict and reduce power consumption during the machining of Inconel 718. The decision tree algorithm was identified as the most accurate predictor, contributing to a predictive power consumption strategy for hard-to-cut alloys.

7.4. Policy and Standardization

The commercialization of nanofluids is significantly hampered by the absence of regulatory frameworks that are both precise and well-defined, as well as industry-wide certifications. As a result of this regulatory ambiguity, the international commerce of items that are based on nanofluids is restricted. Additionally, consumers, investors, and producers are exposed to dangers. At present, nanofluids are controlled by the general laws that govern nanomaterials. These rules may not fully account for the unique qualities and potential risks of nanosystems based on liquids. It is not possible to find regulations that particularly address the production, application, management, and disposal of nanofluids. When there are no generally recognized standards for describing the physical, chemical, and toxicological characteristics of nanofluids, it is difficult to compare the findings of research, guarantee the quality and consistency of products, and evaluate the potential risks that may be involved. To protect workers from the possibility of being exposed to nanoparticle aerosols during the manufacturing process, it is necessary to have specific rules for various safety measures that may be implemented in the workplace. In a manner analogous to this, there are no defined protocols for the safe removal and assessment of environmental concerns connected with nanofluids that have been employed. Industry stakeholders, regulatory agencies, and international standards bodies (such as ISO and ASTM) need to collaborate in developing a comprehensive set of standards for nanofluids. The processes for safety, performance assessment, approaches for characterizing, and terminology should all be included in these. Governments and regulatory agencies are obligated to proactively develop risk-assessment-based regulatory frameworks for nanofluids that are backed by scientific evidence. It is expected that these guidelines will provide the sector with clear guidance while also preserving public and environmental safety. The establishment of trust and the guarantee that the development and implementation of nanofluid technologies are carried out in a manner that is both ethical and sustainable are heavily dependent on open communication and engagement with the general public, the business community, and academic institutions. Included in this is an open and honest discussion of

the potential benefits and drawbacks associated with the use of these. Figure 24 shows a visual representation of the research guideline.

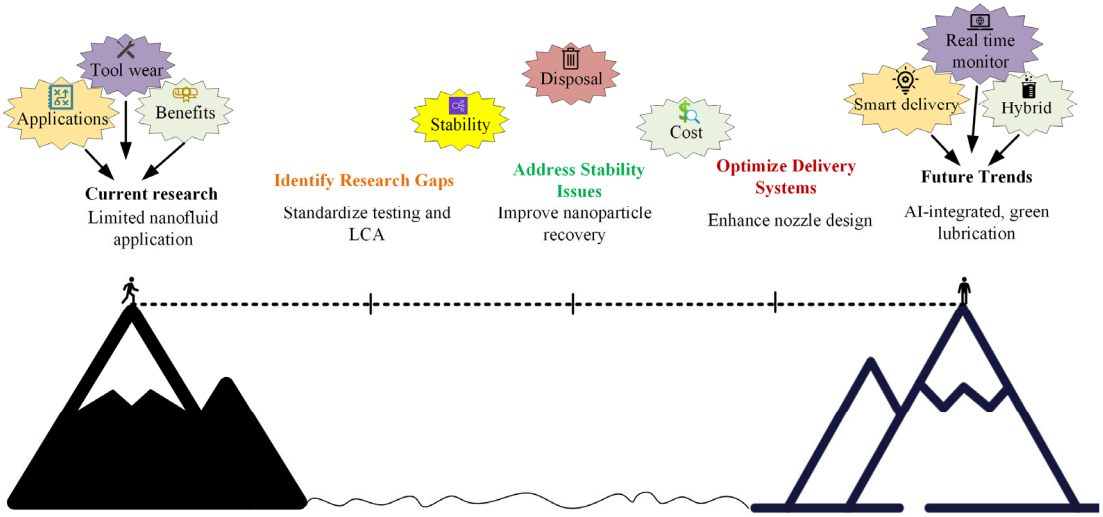


Figure 24. Research guideline of the proposed study.

8. Conclusions

Nanotechnology, especially the creation and use of nanofluids, is proof of industry's never-ending search for ways to be more efficient and environmentally friendly. Nanofluids, which are stable suspensions of metallic or non-metallic nanoparticles in a base fluid, are a big step up from regular heat transfer fluids, as this study shows. Nanofluids have shown great promise in a broad range of fields, from machining and electronics cooling to medical technologies and renewable energy systems. They do this by improving the thermal and physical characteristics of basic fluids. The main idea is simple but strong: produce an impact that is bigger than the sum of its parts. This has significantly improved thermal conductivity, convective heat transfer, and lubrication, making operations greener, more efficient, and cheaper.

Using both single and hybrid nanofluids in machining operations, typically with MQL, has produced some very outstanding outcomes. When machining tough-to-cut metals, research demonstrates that utilizing nanofluids may reliably make tools last longer, improve surface quality, and use less power. Using nanofluids with cutting-edge methods like cryogenic cooling or multi-nozzle delivery systems makes these advantages even stronger. This shows a straightforward way to high-performance, environmentally friendly production. In the renewable energy industry, adding nanofluids to solar thermal systems has been demonstrated to improve thermal efficiency, raise energy production, and cut CO_2 emissions. This shows how flexible and environmentally friendly they are.

However, several significant problems need to be addressed before nanofluids can be widely used in business. The stability of these nanoparticle suspensions remains a significant challenge, as aggregation could compromise their enhanced properties. There are many physical and chemical ways to make things more stable, but keeping that stability over time, particularly in industrial settings, is still a problem. Nanoparticles also have a big problem with their effects on the environment and on health. Making a lot of nanoparticles takes a lot of energy, which may have a big impact on the environment and may outweigh the advantages of using them. The possible toxicity of nanoparticles to people and ecosystems is a big health and safety issue. Studies have shown that factors such as size, shape, and substance may cause cells to break down and become inflamed.

Future research must focus on a few key areas to bridge the gap between lab capabilities and real-world applications. Real-time LCA data is urgently needed to have a better idea of the actual environmental and economic consequences of using nanofluids in manufacturing. To address the challenges of high cost and scalability in nanoparticle production, we must develop new, more efficient, and environmentally responsible methods. Combining AI and ML might be a great way to improve nanofluid design and process parameters in real time, getting the best performance while making the least amount of waste. Finally, it is crucial to have clear, comprehensive rules and regulations for the sector to ensure that this new technology is secure, facilitate easier trade with other countries, and foster public trust in it. In short, nanofluids are the key to a more efficient and sustainable future, but they will not work until scientists, economists, and regulators all work together to tackle these critical problems.

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Abbreviations

The following abbreviations are used in this manuscript:

MQL	Minimum Quantity Lubrication
NDM	Near-Dry Machining
SQL	Small Quantity Lubrication
HTF	Heat Transfer Fluid
MWCNT	Multi-Walled Carbon Nanotube
ϕ	Volume Fraction
μ	Viscosity of Nanoparticles
μ_{df}	Viscosity of Base Fluid
ρ_{nf}	Density of Nanofluid
ρ_{bf}	Density of Base Fluid
ρ_s	Density of Solid Particles
nf	Nanofluid
bf	Base Fluid
NF	Nanofluid
NP	Nanoparticle
CNT	Carbon Nanotube
DTAB	Dodecyl Trimethyl Ammonium Bromide
SDS	Sodium Dodecyl Sulfate
CTAB	Cetyl Trimethyl Ammonium Bromide
DES	Deep Eutectic Solvent
EG	Ethylene Glycol
FTIR	Fourier Transform Infrared
FSW	Friction Stir Welding
CDRX	Continuous Dynamic Recrystallization
C-MWCNT	Clove-Treated MWCNT
ANN	Artificial Neural Network
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
LINMAP	Linear Programming Technique for Multidimensional Analysis of Preference

AI	Artificial Intelligence
ML	Machine Learning
PVP	Polyvinyl Pyrrolidone
IEP	Isoelectric Point
NMQL	Nanofluid MQL
MWF	Metalworking Fluid
FE	Finite Element
CFD	Computational Fluid Dynamics
ADI	Austempered Ductile Iron
HNMQL	Hybrid Nanofluid MQL
UVAM	Ultrasonic Vibration Assisted Machining
CM	Conventional Machining
CCF	Conventional Cutting Fluid
BVP	Boundary Value Problem
EEC	Engineering Equation Solver
GNP	Graphene Nanoparticle
Cryo-MQL	Cryogenic MQL
Cryo-NMQL	Cryogenic NMQL
ANOVA	Analysis of Variance
MORSM	Multi Objective Response Surface Methodology
mMQL	Magnetic MQL
WASPAS	Weighted Aggregated Sum Product Assessment
NCF	Nano-Cutting Fluid
TFC	Traditional Flood Cooling
LCA	Life Cycle Analysis
CCVD	Catalytic Chemical Vapor Deposition
DSSS	Double Slope Solar Still
PVT	Photovoltaic Thermal
CCHP	Combined Cooling Heating and Power
ROS	Reactive Oxygen Species
ENM	Engineered Nanomaterials
FSP	Flame Spray Pyrolysis

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