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Review

Green Metalworking Fluids for Sustainable Machining Operations and Other Sustainable Systems: A Review

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Abstract: Many efforts have been made over the years to minimize the usage of mineral oil-based MWFs. This includes the trail of its alternatives, such as vegetable oil-based MWFs, nanofluids, etc. These alternatives have shown comparable results to mineral oil-based MWFs in producing a better surface finish and machining efficiency. Apart from the conventional flooding of MWFs, several alternative techniques have been developed by researchers to minimize or eliminate the usage of MWFs, including dry machining, high pressure coolant technique, minimum quantity lubrication, etc. which have also demonstrated promising results. This review attempts to highlight the drawbacks of mineral oil-based MWFs and to assess the applicability of vegetable oil-based MWFs in machining applications. Furthermore, other sustainable machining techniques are discussed in the literature review section, which highlight the main issues associated with the mentioned machining operations and their shortcomings based on the most recent literature. From the comprehensive and critical review that was performed, we inferred that the alternative methods are not mature enough at this stage and that they fall behind in some associated outcomes, some of which may be the tribological properties, surface finish or surface roughness, the cutting forces, the amount of working fluid consumed, etc. More efforts are still needed to fully eliminate the use of MWFs. Moreover, the applications of nanofluids in machining operations have been reviewed in this paper. We concluded from the critical review that nanofluids are an emerging technology which have found their place in machining applications due to their excellent thermophysical properties, but are still in their developmental stage, and more detailed studies are needed to make these a cost-effective solution.

Keywords: metalworking fluids; sustainability; machining; nanofluid; vegetable oil; mineral oil

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1. Introduction

Sustainable machining is being adopted all over the world in manufacturing units as a common practice, as all economic and business activities demand sustainability. It would not be wrong for sustainable manufacturing to be characterized as a branch or extension of the sustainable development philosophy [1]. The sustainable manufacturing philosophy adds value to the final product while keeping the quality environment for the upcoming generations [2]. A wide range of parameters are included in sustainable manufacturing, such as the personal health of the workers, environmental issues, and the safety related to machining operation. As all the basic ingredients of sustainability are an integral part of sustainable manufacturing processes, which include the cost associated with machining operation, safety of the environment, and society, it therefore has a broader perspective than just green and eco-friendly machining operation [3]. The beginning of sustainable manufacturing processes start from the selection of the raw materials, into the early process of manufacturing, and until the finishing of the final product, keeping in view the integrity and objectives of the organization and its performance. The major manufacturing activity is machining, which encompasses a wide range of operational variables that have the room or potential for transformation towards sustainable development. These operational variables include but are not limited to the cooling and lubricating fluids used in machining operation, disposal of water or other working fluids, energy conservation, life of the tool, and recycling of the chips [4]. MWFs are generally used to cool the workpiece during the machining process and serve to lubricate the workpiece from the beginning, and it is well-known that these fluids are generally required to achieve a high quality output as well as a smoother and higher efficiency in the machining process. Additionally, MWFs are used to decrease the friction between the tool and the workpiece during machining operation, thereby reducing the potential for detrimental effects such as adhesion, galling, and welding; they remove the heat generated at the interface and carry away the chips and other debris that are generated during the machining operation [5,6].

The widely used mineral-based MWFs are the primary cause of many diseases in the machine operators such as skin infections, lung problems, and may also lead to the development of cancer. In addition, studies have found that they are not biodegradable, therefore it is required to treat them before disposing them off into the environment. Otherwise, they may cause serious issues to the environment [7]. In order to achieve sustainability in machining operation, several improvements are needed in this regard, such as developing new materials and applications methods; newer technologies are also needed to dispose-off MWFs [8]. Furthermore, green MWF development will also allow for cutting-edge technology to make processes more sustainable and ensure the safety of the workers and environment. The opportunities for performing sustainable machining are illustrated in Figure 1, and these opportunities can be used in order to address the issues pertaining to MWFs that are based on mineral oil. The most important aspect, in terms of the quality and economical perspectives, is the dimensional exactness of the workpiece [9,10]. Therefore, the machining operators should be able to identify the conditions which result in the precise dimensions for most of the used working materials [11–13].

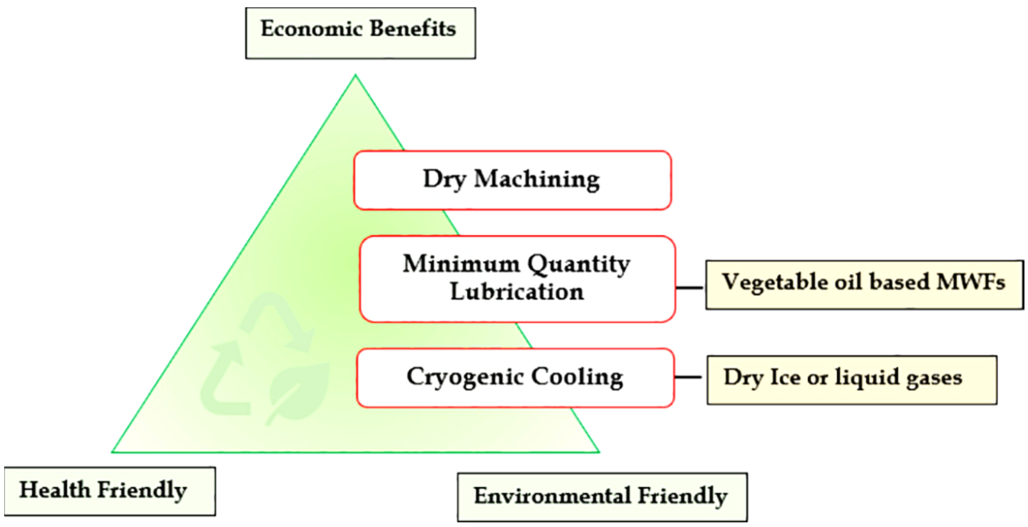

Figure 1. The opportunities for performing sustainable machining.

MWFs hold a major percentage of the effluents that are disposed into the environment [14], and in a study by Cheng et al. [15], it was quoted that the volume of MWF waste had been estimated to be more than 20 billion liters. To curb this issue, environmental regulation authorities have been urging companies to adopt or develop new ways of controlling and discharging the industrial MWFs to mitigate their detrimental effects to the environment and natural habitats. Consequently, there is a need for environmentally friendly MWFs to achieve sustainability in machining operations [16]. New MWFs such as the ones based on vegetable oil provide better results than mineral oil-based MWFs. This is because of the fact that a far more effective layer of lubricant is formed between the tool and workpiece, developed by the saturated fatty acids present in vegetable oil [17–19]. The vegetable oil-based MWFs have shown an enhanced performance compared to the mineral oil-based MWF for the drilling operation performed on AISI 316L steel, increasing tool life up to 177% and reducing the thrust force up to 7%. It was also demonstrated by Lawal et al. [12] that the presence of triglycerides in the vegetable oil gives better properties that are needed in the lubricants.

Several studies have been conducted to assess the economic impact of MWFs. Adler et al. [20] provided figures that over two billion gallons of machining fluids were consumed by manufacturers in North America in the year 2002. Similarly, another research by Marksberry and Jawahir [6] showed that the total annual consumption of MWFs was 640 million gallons globally in 2007, whereas around 100 million gallons were utilized in US manufacturing sectors; the actual consumption was far larger than this figure, according to other sources. Lawal et al. [21] revealed that in 2005, the global consumption of MWFs was quite high, i.e., more than 1200 million gallons, and the projected increase over the decade was 1.2 percent. The actual estimate was not possible, due to the pervasive nature of filed processes. Pusavec et al. [22] revealed that 15% to 20% of the overall cost of machining processes is due to the MWFs utilized for cooling and lubrication purposes. Replacing the cutting fluids with sustainable machining processes so that it can save up to 20% of overall machining costs would be a huge achievement for manufacturers. King et al. [23] also discussed that about 7% to 17% of the total manufacturing costs is related to the cutting fluids, and 4% is related to tooling expenses. Fluid expenses in industries include the purchase of fluids, setup of a fluid dispensing system, maintenance, waste treatment, and fluid disposal [10]. Brinksmeier et al. [24] showed that MWFs have expenditures of around 16.9% of the overall manufacturing sectors in European automotive industries. Hence, it is obvious from all of these studies that the cost for the handling of MWFs is almost 17–20% of the total manufacturing cost.

2. Scientometric Analysis

Scientometric analysis [25–28] is usually carried out after importing the databases from authentic libraries. Usually, the Scopus and Web of Science databases are selected for the analysis, but it has been reported and observed that Scopus provides a wider and more inclusive coverage of content. The access to profiles of all authors, institutions, serial sources, and the availability of the interrelated databases interface makes the use of Scopus more convenient and comfortable for practical use [29]. Therefore, the Scopus database has been selected for analysis.

Scientometric analysis usually starts by selecting some of the most frequent or widely used keywords on the topic. Therefore, some relevant keywords were used to start the analysis after a preliminary literature review. A total of 1834 documents were filtered out and only the published articles were selected. Articles that were in press were omitted from the analysis. After the search was complete, the database was exported to the commercially available integrated development environment (IDE) R Studio [30], which was used to analyze the database.

2.1. Annual Scientific Publication

Figure 2 shows the annual scientific publications, which range from 1975 to 2021. It can be seen from the figure that research on metalworking fluids and sustainable machining started from 1975 and only had a few articles published until the early 2000s. However, a spike was observed in the research from 2003 onwards, where the number of annually published papers increased and in the past seven years, a substantial advancement has been made in the research area of sustainable MWFs and sustainable machining operations. Therefore, the prime focus of this article was to review the papers published in the past

10 years, but for the sake of establishing some basic concepts and forming the bases, some earlier literature has also been cited.

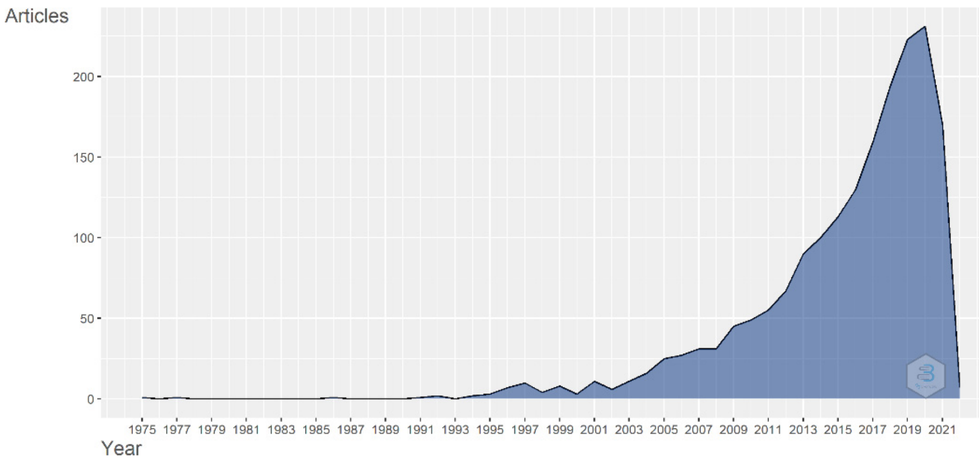

Figure 2. Annual scientific publication on metalworking fluids and sustainable machining operations.

2.2. Sources of Documents

The comparison of different journals and the number of documents in the journals can be seen in Table 1. Among other journals, the highest number of papers have been published in the *International Journal of Advanced Manufacturing Technology*, with a total of 106 articles. After that, the second highest number of publications has been in the *Journal of Cleaner Production*, with a total of 101 articles; the lowest number of articles has been in the *Wear* journal, i.e., 15 articles. It can be deduced from the analysis that most of the articles targeted the sustainability and machinability aspects of the different metalworking fluids, and therefore a limited number of articles have been published that examine the wear characteristics.

Table 1. Most relevant sources and their number of published articles.

Sources	Number of Articles
International Journal of Advanced Manufacturing Technology	106
Journal of Cleaner Production	101
MATERIALS TODAY: PROCEEDINGS	73
PROCEDIA CIRP	64
Journal Of Manufacturing Processes	38
Advanced Materials Research	32
Lecture Notes in Mechanical Engineering	32
Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture	32
IOP Conference Series: Materials Science and Engineering	29
Journal Of Materials Processing Technology	29
Procedia Manufacturing	29
AIP Conference Proceedings	25
Materials And Manufacturing Processes	24
International Journal of Machining and Machinability of Materials	21
Tribology International	21
Key Engineering Materials	20
Applied Mechanics and Materials	17
Journal of the Brazilian Society of Mechanical Sciences and Engineering	15
Machining Science and Technology	15
Wear	15

2.3. Word Cloud

To pictorially illustrate the representation of the different keywords used in the different articles related to metalworking fluids and sustainable machining operation, a word cloud highlighting the different keywords is shown in Figure 3. It can be seen from the figure that the most frequently used keywords are "cutting tools", "minimum quantity lubrication", "sustainable development", etc. Therefore, it can be inferred by the word cloud that a considerable amount of research work has been conducted on transforming conventional machining operation to a more sustainable machining operation through the adoption of different strategies such as nanofluids, minimum quantity lubrication, dry machining, and vegetable oils, among others.

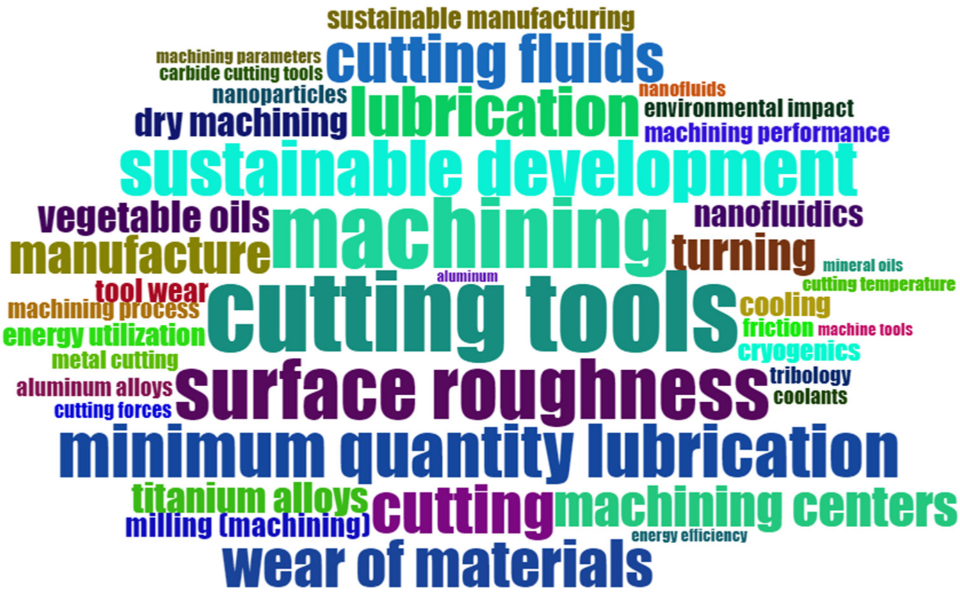

Figure 3. Pictorial representation of the most frequently used keywords.

From the scientometric analysis, it is evident that a considerable amount of research has been carried out in the area of metalworking fluids for the development of machining and different sustainable techniques and is still in progress. Therefore, considering the substantial amount of research output, a comprehensive review is needed which summarizes the impact of mineral oil-based MWFs, comparing it with its counterparts (i.e., vegetable oil-based MWFs) and also shedding light on the different sustainable machining techniques available in the market.

This paper reviews the adverse effects of mineral oil-based MWFs and compares it with vegetable oil-based MWFs, highlighting the tribological performances of the vegetable oil-based MWFs. The paper also highlights the potential of other sustainable machining operations such as dry machining, high pressure coolant technique, minimum quantity lubrication, and the potential use of nanofluids in machining operations.

3. Relevant Literature

3.1. Adverse Effects of Mineral Oil-Based MWFs

Almost all of the available MWFs are derived from petroleum products, and the elements that are present in mineral oil-based MWFs are the major cause of the moisture and oil smoke observed during machining operation, which causes an uncomfortable environment for machine operators [31]. The health and environmental aspects are of the utmost importance in most countries, and regulations pertaining to the use of MWFs have aimed to guarantee the health of workers and to protect the environment [32,33].

There are several methods to apply MWFs onto the interface of the workpiece and the tool. This can be in the form of flooding, through a jet, or through mist in the several directions, as illustrated in Figure 4 [34]. In 1987, the International Agency for Research on Cancer (IARC) declared that the mineral oil-based MWFs, which were widely used in machining operation, were carcinogenic [31]. In an experimental investigation conducted on laboratory animals to investigate the toxicity of water-based MWFs by Bennett [35], it was reported that the specific additives and surfactants present in the MWFs caused cancer to the animals. In a review study by Park et al., the authors reported that nitrosamine and other amines in MWFs were carcinogenic, which are formed by the nitrates and are also used as corrosion inhibitors [33]. In 1984, the US Environmental Protection Agency (USEPA) fully banned the usage of nitrites that contained alkanol amines for cutting fluid, due to the detrimental effects they have on human health [31]. It was also reported in a review article that the mineral oil-based MWFs are composed of constituents which are suspected to be carcinogenic, and which favor the spread of tumors [33]. Any combination of sulfur, nitrosamines, long chain aliphatic compounds, formaldehydes, and Polycyclic Aromatic Hydrocarbons (PAHs) release biocide contaminants, which are also regarded as carcinogenic in nature, thereby posing a serious threat to machine operators [36,37]. The use of acid-refined MWFs results in the development of skin cancer. In order to decrease the PAHs present in crude oil, refining is performed. However, acid-refined MWFs contain a substantial amount of PAHs, which are a cause of skin cancer. Skin irritation is thought to be the most common health related issue resulting from the use of mineral oil-based MWFs during machining operation. These can be caused by the direct contact of the operator with MWFs [33,38]. It has been found that almost all of the mineral oil-based used in metalworking are found to have pH levels ranging from 9.5 to 11.0, where the higher acidic MWFs cause skin-related problems and, in the worst case scenario, can lead to skin diseases. Therefore, researchers around the globe are working to develop MWFs that can ensure the safety of workers and avoid any undesirable outcomes for machine operators [31].

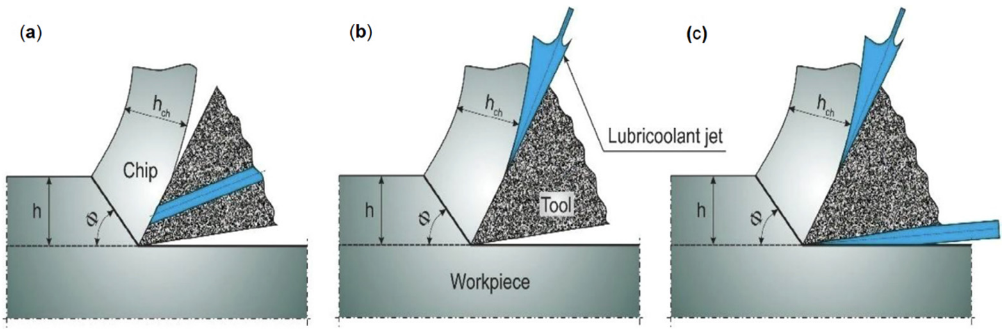

Figure 4. The methods of supplying a lubricating medium to the work–tool interface, inserted from: (**a**) from the side of the rake face; (**b**) on the rake face; (**c**) on the flank and rake face [39].

Certain elements are added to enhance the properties of the mineral oil-based MWFs, e.g., sulfur, which increases the heat capacity of MWFs and also increases their ability to lubricate under extreme pressure conditions [40]. Another problem related to the health of machine operators is linked to the inhalation of MWF vapors, which has also increased since the increase in machining speed. The inhalation of mineral oil-based MWFs may lead to digestive problems and respiratory system diseases and may also lead to the development of cancers. Choi et al. [41] reported that the presence of dissolved ions of Co, Cr, and Ni in mineral oil-based MWFs are the potential source of skin disorders, and that many skins reactions occur when neat mineral oil-based MWFs are used.

3.2. Vegetable Oil-Based MWFs

A considerable amount of research around the world has been aimed at developing alternatives of the harmful mineral oil-based MWF in order to make machining processes sustainable. Recent studies on sustainable machining have revealed that the vegetable oil-based MWFs have shown a better performance [42–48]. The vegetable oil-based MWFs have demonstrated better cooling and lubrication characteristics when used during machining operation compared with the mineral oil-based MWFs. As a result, they have gained much attention, and they have been a topic of interest for many researchers. Over the years, it has been the practice to choose the MWFs based on the cutting process, the tool material, the work material, and the operation conditions [49,50]. This was the old trend, but as the research is progressing in this area, the selection of MWFs is also changing. Now, the selection of MWFs is more concerned about their impact on the environment and on the health of the machine operators, in addition to other process requirements.

One of the most important advantages of a vegetable oil-based MWF is that it can easily be broken down into eco-friendly species with the aid of enzymes or chemical reactions. The residue can easily be disposed-off in an environmentally friendly manner without posing any serious challenge to the environment, therefore maintaining sustainability. Furthermore, the toxicity level of the vegetable oil-based MWFs is considerably less than that of the mineral oil-based MWFs [51]. Vegetable oil-based MWFs are also less severe than mineral oil-based MWFs when machine operators become exposed to the bio-degradable vegetable oil-based MWF. Another advantage of vegetable oil-based MWFs is that filtration is not required before it is disposed-off, which considerably reduces the costs associated with it. The environmental and economic benefits of vegetable oil-based MWFs, compared with the mineral oil-based MWFs, is shown in Figure 5. The figure illustrates that the environmental impact of mineral oil-based MWFs is considerably lower than that of vegetable oil-based MWFs; because different additives are also added to minimize the environmental impact of mineral oil-based MWFs, they prove to be less economical than vegetable oil-based MWFs. In a study by John et al. [52], it was concluded that by using a vegetable oil-based MWF, better cooling rates were achieved and improved lubrication characteristics were observed due to their higher retention time. In a study by Mannekote and Kailas [53] on the effect of oxidation on the tribological properties of vegetable oil-based MWFs, they reported that when compared to mineral oil-based MWFs, the vegetable oil-based MWFs had a higher tendency to oxidize when exposed to oxygen, and they can easily be converted to compounds like H_2O, CO_2, and CH_4. On the other side, Erhan et al. [54] showed that vegetable oil-based MWFs have a lower ability to maintain their characteristics in high temperature and high humidity environments, which are properties that are needed to perform cooling and lubrication operations. One of the solutions to address the shortcomings of vegetable oil-based MWFs is through the formulation of water-soluble MWFs, where the surfactants are other introduced additives, resulting in the modification of the chemical structure; this method makes the MWF capable of operating satisfactorily in extreme conditions without jeopardizing its lubrication and cooling characteristics, and it has been confirmed in different studies [55,56].

One of the most successful methods for the formulation of vegetable oil-based, water-soluble MWFs is the process of emulsification. In this process, the aquatic and oleic phases are mixed and are rigorously shaken to disperse oil droplets in water and vice versa. The addition of water plays a crucial role in altering the properties of the MWF. Water acts as the cooling agent as it possesses a higher specific heat capacity [57]. However, one of the challenges associated with emulsification is effective mixing or, in other words, the homogenization. The main reason for this is the dispersion resistance of the vegetable oil droplets during the mixing process. As a result, ultrasonic technology was introduced into the market to obtain effective homogenization and thus obtain stable emulsified products [39,58]. In the criterion for determining the stability of the emulsion, one of the parameters used is the hydrophilic-lipophilic (HL) value. The values of the HL can be used to identify whether or not the surfactants or additives have a higher inclination towards the vegetable oils [14,59]. To highlight the basic components of the emulsifier, it should be noted here that it consists of the hydrophilic group in the case of water and lipophilic group for oil. The hydrophilic group has a stronger affinity towards water, whereas the lipophilic chain has a higher proclivity towards oil [60]. The emulsifiers can be classified based on their hydrophilic and/or their lipophilic value [61].

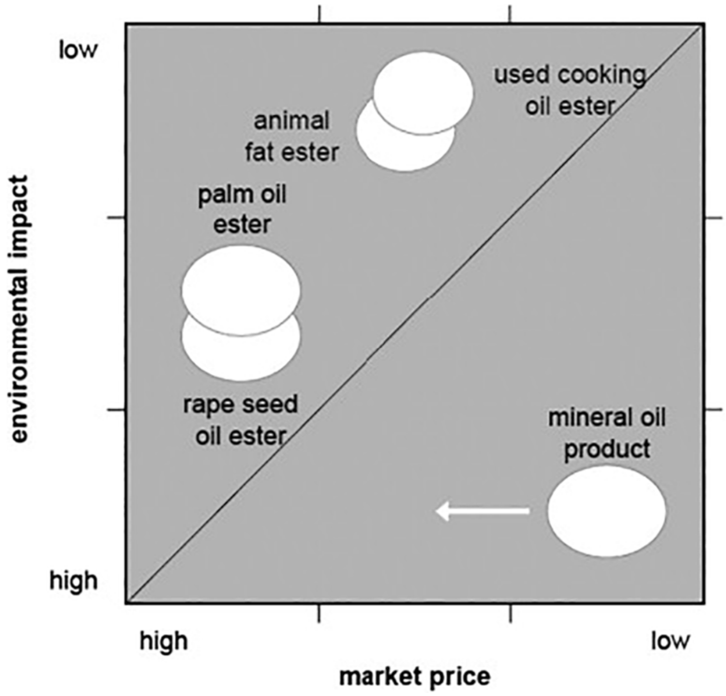

Figure 5. The economic and environmental impact of vegetable oil-based MWFs and mineral oil-based MWFs [51].

In order to represent the relative composition of the hydrophilic group and the lipophilic group, a parameter known as the hydrophilic-lipophilic balance (HLB) is used. The HLB scale ranges from 1 to 20, and it shows the affinity of the emulsifier towards water or oil. One way to explain the parameter is that emulsifiers with higher HLB values are more effective for oil in water emulsions, and less useful for water in oil emulsions [62]. The HLB value plays a significant role in the synthesis of the vegetable oil-based MWFs. The surfactants or additives that are to be added and the base oil can be selected based on the HLB values, which are a good indicator of solubility during the preparation of stable emulsions for bio-lubrication purposes [63]. The hydrophilic head points out towards the water phase, while the hydrophobic tail points out towards the oleic phase [64].

3.3. Characteristics of Vegetable Oil-Based MWFs in Machining Applications

It has been shown that vegetable oil-based MWFs have shown superior cooling and lubrication properties compared with mineral oil-based MWFs. This is mainly because of the fact that the presence of saturated fatty acids in vegetable oil aid the formation of the lubricant layer at the work–tool interface, and the structure of the triglycerides provides the desired lubrication characteristics [65]. In a study by Sani et al. [66], it was shown that by using modified jatropha oil with ionic liquid, the cutting energy was reduced. Ionic liquids consist of acidic ionic liquids (AIL) and protic ionic liquids (PIL). The authors also reported that better results were obtained when the mixture consisted of 10% AIL with jatropha oil and 1% PIL with jatropha oil. They highlighted that the specific cutting energy was reduced around 4 to 5%, the cutting temperatures were reduced by 7 to 10%, the friction coefficient was reduced by 2 to 3%, and the tool–cup contact's length was reduced by 8 to 11% when the results were compared with the reference mineral oil-based MWF. Their results are also shown in graph form in Figure 6.

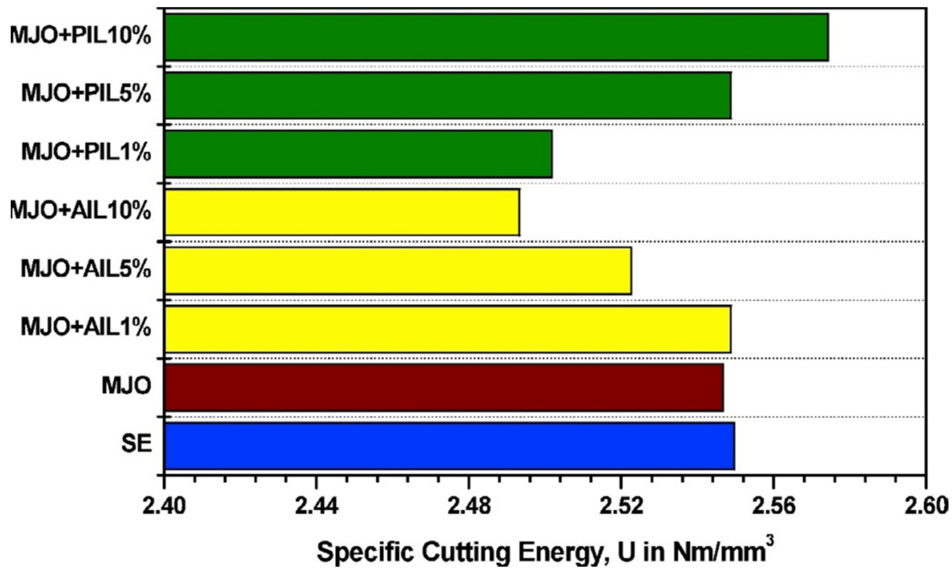

Figure 6. The variation of the specific cutting energy with respect to the mixture of modified jatropha oil (MJO) and AIL/PIL [66].

Vamsi Krishna et al. [67] showed in their research that better surface quality was obtained when using nano-boric acid in coconut oil compared with the surface quality obtained from the industrial lubricant SAE 40, and their results are shown in Figure 7. It can be seen from the figure that the coconut-based oil resulted in lower values of surface roughness while also changing the cutting speed.

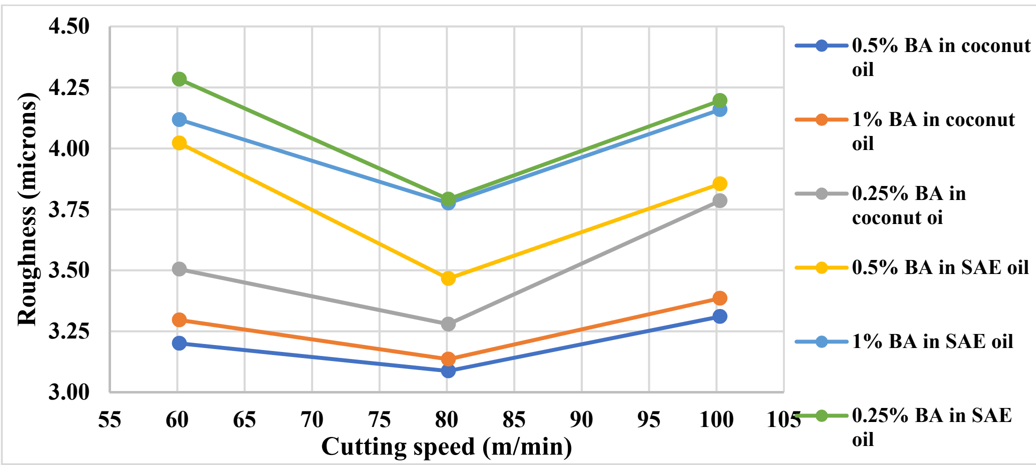

Figure 7. The variation of the surface roughness with the cutting speed [67].

3.4. Sustainable Machining Techniques

As in the machining process, the heat produced is a major problem, and it can incur economic and technical costs either directly or indirectly [68]. Taylor [69] in the early 1900s pointed out that heat generated in the cutting zone plays a significant role in the cutting process. MWFs were used to address this, which imposes a serious challenge to the environment and the machine operators as discussed above in detail. In order to minimize the use and side effects of MWFs, several potential methods are available, including dry machining, machining with minimum quantity lubrication, machining with high-pressure jet assistance, and machining with alternative fluids such as gas, vapor, and solid lubricants.

3.4.1. Dry Machining

As the name suggests, dry machining does not make use of conventional cutting fluids during the machining process. This process is only accepted by companies if it makes sure that the quality of the product is better or at least the same as when cutting fluids are used [70]. Several techniques are adopted to improve the dry machining process, such as the tool material and tool coating. In terms of the tool material, it is important to optimize the flute width, number of flutes, and margin size to have an extended tool life. Since cutting fluids are absent in this process, different methodologies are adopted to achieve the desirable finish of the workpiece, of which include the use of diamond-like carbon (DLC) coatings on the surface of tools, among others. In an investigation by Fukui et al. [71], the tribological behavior and performance of the DLC-coated tools working on the aluminum alloy workpiece were assessed. They reported that the DLC coatings on the surface of the tool resulted in improved tool life when compared with uncoated tools during the dry machining process. The comparison of the surface roughness in both cases is shown in Figure 8. It can be seen from the figure that when a DLC coating is applied, the surface roughness is lower.

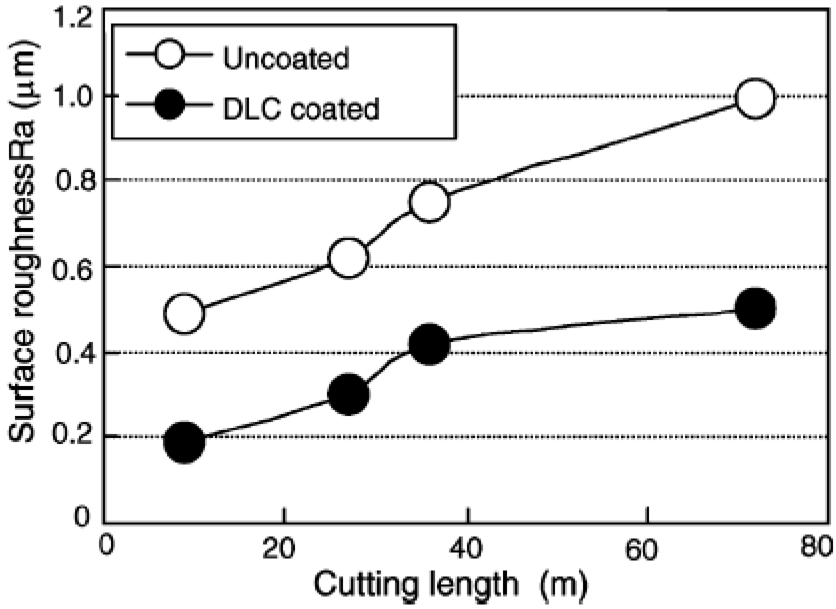

Figure 8. The variation of the surface roughness with along the cutting length [71].

Klocke and Eisenblätter [72] carried out several investigations to implement the dry machining process in the production of cast iron, steel, aluminum, and some other materials. They reported that for the case of uncoated tools, some unwanted built-up edges were formed, and that the surface quality was also disturbed. The improvements in the dry machining process were further discussed by Sreejith and Ngoi [73]. According to their study, the dry machining process cannot match the wet machining process in many aspects, and it is only acceptable if the surface finish and other desired properties are equivalent to that obtained by the wet machining process; the authors stated that if it was to be employed, several improvements were necessary. A new system was proposed by Vereschaka et al. [74] in which the cutting tool was coated with a multi-layered, nano-scale coating, along with an ionized gas dispensing system and exciting system. They reported an improved performance in terms of the surface finish when cutting titanium alloys, steel, and nickel-based alloys. In a study by Devillez et al. [75] concerning the successful implementation of dry machining processes for Inconel®718 using a coated carbide tool, they reported that a reasonable surface finish and micro-hardness was observed, and that the values were comparable to the ones obtained in the flooded conditions. Additionally, no severe changes were observed in the microstructure. The authors had merged different cutting techniques to reduce the cutting forces and surface roughness.

From several studies on the dry machining process, it can be inferred that although many researchers have reported successful implementations of the dry machining process for different materials such as cast iron, steel, and aluminum, etc., major technological improvements are still necessary in order to minimize the cutting forces and cutting temperatures. Furthermore, improved methods are still needed to flush out the chips that are formed during the machining process. Researchers have also reported the improved performance of coated tools such as coated carbide tools and DLC-coated tools when it comes to the surface roughness, but a high tool wear rate was still reported by many researchers.

3.4.2. High Pressure Coolant Technique

Out of the several techniques to increase the machining efficiency, one of the techniques is the high-pressure coolant technique [76]. High-pressure coolant refers to the pumping of coolant at pressures exceeding 300 psi. In general, the pressures are in the range of 1000 psi. In some ultra-high-pressure coolants, the pressure reaches up to 3000 psi and therefore, solely depend on the requirements of surface being machined. There are several advantages to using of the high-pressure coolant technique, such as optimal chip control, which is accomplished by virtue of the coolant at high pressure breaking the chips into smaller pieces, preventing the chips from wrapping around the workpiece and chuck. High-pressure coolant evacuates the chips from the work area before the cutting tool gets into contact with them, therefore resulting in a better surface finish. Because of the above two benefits, the high-pressure coolant technique allows machine operators to work at increased feed rates, resulting in faster cycle times. Dahlman and Escursell [77] reported in their study that when the high-pressure coolant technique was applied, the chip control and reduction in the amount of built-up edges considerably improved during the turning process of decarburized steel. They also reported that the surface roughness was reduced as much as 80%, and that the tool wear was significantly reduced, of which the tools were prone to high temperature cracking. Ezugwu et al. [78] investigated the high-pressure coolant technique for the machining of hard metal alloys, such as Inconel 718, AISI 1045, and Tie6Ale4V steel; they also used different tool materials, such as cubic boron nitride (cBN) and TiAlN-coated carbide tools. They reported that by increasing the supply pressure of the coolant, the cooling and lubrication conditions were enhanced, along with a reduction of the cutting forces. This also resulted in the improved separation of chips and improved the surface roughness values. Kramar et al. [79] experimentally investigated different machining techniques, including the dry machining, conventional flooded machining, and the high-pressure cooling techniques for performing turning operations on piston rods which were already surface-hardened. They reported that out of all of techniques, the high-pressure cooling technique showed promising results, as the chip deformation was enhanced and the fluid consumption was reduced. However, the only shortcoming of the high-pressure coolant technique as reported by them was in its inability to reduce the depth of cut notches. The graphical interpretation of their results is shown in Figure 9. Pusavec et al. [22] conducted an experimental investigation on the cost analysis of the high-pressure cooling, conventional flood machining, and cryogenic machining techniques. They reported that the high-pressure cooling technique was 30% less costly compared to the other two techniques. Ayed et al. [80] experimentally investigated the tool deterioration and wear patterns on uncoated WC inserts, employing the conventional flooded machining and high-pressure water-jet-assisted machining. They reported promising results when compared with flooded machining with respect to the plastic deformation and flank wear of the cutting tool. They also reported a drawback of this technique, which was in its inability to reduce abrasion and adhesion wear, which led to notch wear. In a study by da Silva et al. [81], they studied the effect of the high-pressure coolant technique while machining a Ti-6Al-4V alloy with a polycrystalline diamond under high-speed conditions.

They reported that by increasing the fluid pressure, the tool life increased, and the adhesion was considerably reduced, specifically at 20.3 MPa.

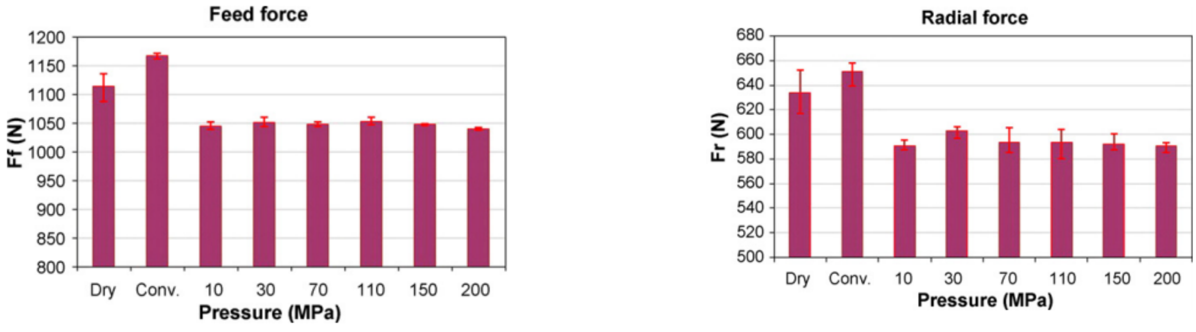

Figure 9. The effect of coolant pressure on (**a**) the feed force, and (**b**) the radial force [79].

3.4.3. Minimum Quantity Lubrication (MQL)

As has been discussed, efforts are being made by many researchers to achieve manufacturing goals that are eco-friendly in nature due to the polices regulated by governments for preventing pollution globally, with the long-term aspects of the environment in mind [82]. There are many examples of such countries, including the USA, EU, China, and Malaysia, in particular which is clearly shown by Figure 10 that the number of publications are increasing gradually on yearly basis. [83]. As machining is one of the main processes in manufacturing sectors, it is therefore considered to have a significant process and important role to play in the context of green metalworking and sustainability, as it has a direct impact over the cost, life, and performance quality of so many components [84–86]. Therefore, minimum quantity lubrication (MQL) is one of the highlighted techniques that is playing a key role in sustainable machining in the last two decades, and the research needs to work more on this process to make manufacturing environmentally friendly as per the demand of industrial sectors.

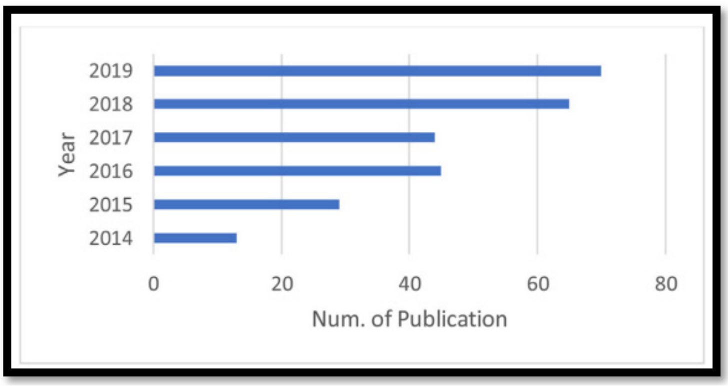

Figure 10. Research articles published about the advancements of MQL from 2014 to 2019 [83].

There are many researchers that are in agreement with the argument that MQL has the potential to replace the conventional methods of flooding which are used for machining processes i.e., grinding, milling, drilling, and turning [87–90]. Najiha et al. [91] reported that the MQL technique is one of the practical ways for a green manufacturing process, as it is one of the most cost-efficient techniques and also guarantees both sustainability and worker health. This claim has also been supported by many other scientists and researchers who believe that the minimum quantity of cutting fluid should be consumed in this way [88,92,93]. All of these studies depict that the MQL technique has importance in the emerging efficient and eco-friendly manufacturing techniques of the modern era. It can be seen in Figure 11 that around 7% to 17% of the cost of the manufacturing process constitutes cutting fluid, and if replaced by minimum quantity lubrication, it will save a substantial amount of budget. Hence, a substantial amount could be saved by switching the conventional methods with the MQL technique in industries to reduce budget costs.

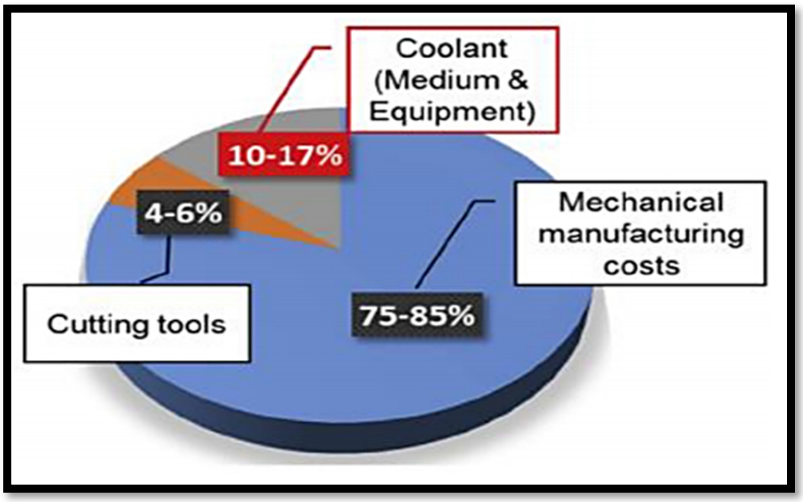

Figure 11. The quantitative distribution of manufacturing costs in industries [94].

Khan and Dhar [95] studied the benefits of using vegetable-based oil in manufacturing instead of cutting fluids, as they are very good pressure absorbents, have the ability to accelerate the material removal rate (MRR), and provide very minimum loss due to vaporization, misting, among other reasons. Moreover, many other researches have supported these advantages of MQL, especially in studies focusing on milling, drilling, and turning [19,96–98]. Dixit et al. [99] observed that synthetic oils are also very effective for machining and have similar properties to vegetable oil-based MWFs, having high boiling temperatures, low viscosities and better flash points. Moreover, some studies have revealed that synthetic oil machining is far better than both vegetable- and mineral-based oils [100].

Commercially, the MQL technique comprises five major parts, which are the cutting fluid tank, air compressor, flow control system, tubes, and spray nozzle [90]. It generally uses an atomizing method and a minimum amount of spraying, composed of an oil mixture and pressurized air sent at a flow rate below 1000 mL/h, and it directly sprays the mixture into cutting zone as has been described in many studies [101–103]. This consumes 10,000 times less cutting fluid volume as compared to the flooding technique. Furthermore, the MQL system is categorized into internal and external applications, as shown in Figure 12.

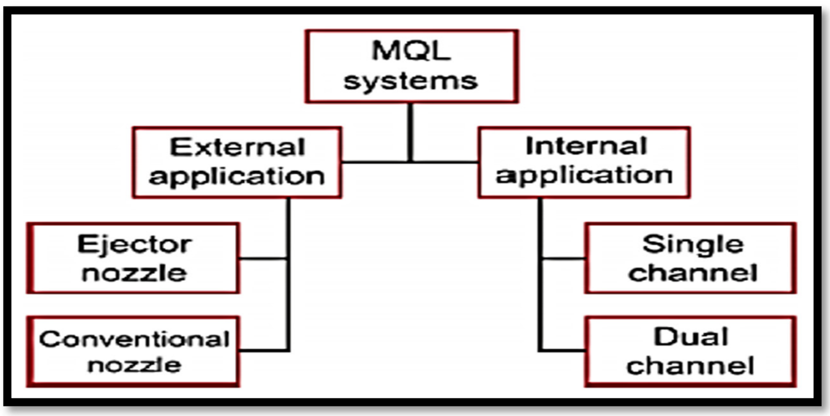

Figure 12. Minimum quantity lubrication delivery system categorizations [95].

All of these review studies indicate that the use of both vegetable oil-based MWFs and synthetic esters are safe to use for machining in place of conventional techniques and cutting fluids, as they are non-toxic and sustainable; MQL is a more feasible choice for machining applications due to being risk-free for the health of workers and environment.

3.5. Nanofluids

When the fluids are suspended with nano-sized particles, they are referred to as nanofluids. Nanofluids are the colloidal dispersion of the nanometer-sized particles, which are referred to as the nanoparticles in the base fluids [104]. The base fluids may include water, ethylene glycol, engine oil, or any other cutting fluid. The current recent advances in nanotechnology allows us to use nanofluids as conventional MWFs in conjunction with the minimum quantity lubrication technique in machining processes [105]. The inherent properties that nanofluids offer, such as enhanced heat transfer and improved tribological properties, allow them to be used in applications where better cooling and lubrication are required during the machining process, thus making the machining process more viable. Therefore, using nanofluids as an alternative to the conventional MWFs is one of the novel technological approaches in machining. Based on their heat transfer and tribological characteristics, nanoparticles that comprise MoS_2, CuO, ZnO, diamond, Ag, and titanium have been investigated for their use in machining operation. A considerable amount of research is being conducted to investigate the feasibility of nanofluids prepared from the colloidal dispersion of nanoparticles in the base fluid for machining operation. The decision to use nanofluids as a coolant is solely due to the enhanced thermal conductivity characteristics of the nanoparticles that are suspended in the base fluids [106]. It has been reported that the size of the nanoparticles also play an important role in determining the thermal conductivity of the nanofluids [107–110]. Furthermore, it has been reported that the nanofluids with smaller-sized nanoparticles have more enhanced thermal conductivity due to their extended specific surface area. Other factors which affect the thermal conductivity of nanofluids include the temperature of the nanofluid and the concentration of nanoparticles in the base fluid [111–115]. The thermal conductivity of nanoparticles and the base fluid also considerably affect the thermal conductivity of the nanofluid. The higher the thermal conductivity of the nanoparticles and thermal conductivity ratio i.e., the higher the ratio of the thermal conductivity of the nanoparticles and thermal conductivity of the base fluid, the higher the thermal conductivity of the resulting nanofluid will be [116,117]. Adding to the thermal conductivity, the pH of the base fluids and additives also play an important role. It has been observed that an increase in the pH of the base fluids and additives increase the thermal conductivity of the nanofluids. This is because of the fact that an increase in the pH value of the base fluids and additives results in the prevention of agglomeration and the improvement of the nanoparticle suspension [118–122].

In addition to thermal conductivity, other factors which affect the performance of nanofluids include the stability and viscosity of the nanofluids. The stability of the nanofluid is very important for improved heat transfer and thus the stability depends on various factors, such as the characteristics of the nanoparticles themselves, the methods of preparation, ultrasonication, stirring, etc. [123] Moreover, the viscosity of the nanofluids plays an important role in the performance of the nanofluids. Viscosity is defined as the internal resistance of the fluid to flow, i.e., the fluid’s internal friction to flow, expressed as the force per unit area, which resists the flow; this property is widely affected by external physical parameters, such as temperature. Therefore, viscosity is an important parameter to be considered in thermal and fluid flow applications. Several investigations have been carried out to investigate the viscosity of nanofluids, and these investigations have reported an increase in the viscosity of the nanofluids with an increase in the volume fraction. Additionally, the size of the nanoparticles was seen to have a minimal effect on the viscosity of the nanofluids [124–127].

Nanofluids are widely used in the MQL technique to minimize the amount of lubricant used, and numerous attempts have been made to perform machining operation using nanofluids under the MQL method. Various studies have reported better surface finish, lower cutting forces, lower power consumption, and a higher tool life wen nanofluids were used, compared with dry machining and machining using flooded cooling methods. Prasad and Srikant [128] performed an experimental investigation on the turning of AISI 1040 using nanographite particles mixed with cutting fluid using the MQL method. They reported that as the concentration of the nanoparticles was increased, there was a spike in the values of the pH, viscosity, and thermal conductivity, in addition to lower tool wear, surface roughness, nodal temperatures, and cutting forces. They also observed a better machining performance at 0.3% nanoparticle concentration and a flowrate of 15 mL/min. Rahmati et al. [129] performed the slot milling of Al6061-T6, allowing the use of nanoparticles under the MQL approach. They reported that at 1% nanoparticle concentration in the mineral oil, the lowest cutting forces were observed; the lowest cutting temperature was observed at 0.5% nanoparticle concentration. Similarly, Sarhan et al. [130] reported a considerable reduction in the coefficient of friction at the tool–chip interface and consequently a decrease in the cutting forces, specific energy, and power when using SiO_2 in tandem with mineral oil under the MQL method. Yücel et al. [131] performed a turning operation on the AA 2024 T3 aluminum alloy, using the MoS2-based nanofluid and the MQL technique, in order to investigate the tribological and machining characteristics. They reported that significant improvements were achieved in the surface roughness, surface topography, and maximum temperature. They also added that by using the nanofluid-based MQL, the built-up edges were eliminated, and they obtained less damaged edges compared with dry machining.

Recently, Şirin and Kivak [132] performed a milling operation on the Inconel X-750 superalloy to see the effects of hybrid nanofluids using the MQL technique. They investigated the combination of different nanofluids, cutting speeds, and feed rates, and reported that using the hexagonal boron nitride (hBN)/graphite nanofluids resulted in a better performance compared to their counterparts under all criteria. They also added that hBN/graphite nanofluids achieved 36.17% and 6.08% improvements in tool life, respectively, compared to the graphite/MoS_2 and hBN/MoS_2 nanofluids. Junankar et al. [133] conducted a performance evaluation of a Cu nanofluid in a turning operation of bearing steel using the MQL approach. They analyzed the effect of the cutting sped, feed rate, and depth of the cut to perform a multi-objective optimization; this analysis was conducted using the grey relational analysis technique, and it was performed to obtain the optimum conditions of operation and their impact on the surface roughness and the cutting zone temperature. They reported that Cu nanofluid in conjunction with MQL resulted in the most significant cooling environment compared with vegetable oil MWFs. They also reported that the surface roughness and the cutting zone temperature were considerably reduced when the machining operation was performed using a Cu nanofluid under the MQL method. Haq et al. [134] evaluated the effects of a nanofluid-based MQL technique while performing a milling operation on the Inconel 718 superalloy, and compared the results of the simple MQL and nanofluid-based MQL approaches. They investigated the effect of feed rate, speed, flow rate, depth of the cut on the material removal rate, and the surface roughness, and conducted the optimization using the response surface methodology. They reported that the nanofluid-based MQL approach was better as compared with the simple MQL method, and resulted in decreased surface roughness, temperature, and power. Barewar et al. [135] investigated the sustainable machining of the Inconel 718 superalloy using an Ag/ZnO-based hybrid nanofluid and the MQL method, and performed the optimization using the Taguchi method with the grey relational analysis. They reported that the nanofluid-based MQL method resulted in an improved surface finish, minimum tool wear, and lower cutting temperature when compared with the simple MQL method and dry machining. Tiwari et al. [136] performed a computational analysis to see the characteristics of the surfaces of different concentrations of different nanofluids in conjunction with the MQL technique. They analyzed different nanofluids such as Al_2O_3, CuO, and TiO_2 at different concentrations (1% to 6%, at an interval of 1%) through the MATLAB software. From their analysis, they reported that the nanofluid-based MQLs resulted in intermittent chips which were easy to remove in contrast to the normal MQLs, which resulted in continuous chips. They also added that by using the nanofluid-based MQL method, cutting power was reduced, and a better surface finish was obtained. Mohana Rao et al. [137] performed an experimental investigation to observe the effects of cutting parameters on the tuning of EN-36 steel using both dry MQL and nanofluid-based MQL methods. They performed the investigations at 6% and 8% volume concentration of Al_2O_3 nanofluid and used the Taguchi analysis to optimize the process. They reported that at the 8% volume concentration, the surface roughness, temperature, cutting forces, and tool wear was lower compared with the 6% volume concentration and compared with dry machining.

Khanafer et al. [138] investigated the micro-drilling of the Inconel®718 superalloy using a MQL-Al_2O_3 nanofluid, and reported that the thrust forces were lower in the case of MQL-based nanofluid cooling compared with simple MQL cooling and flood cooling. They also reported that burr formation, tool wear, and cooling rates were improved in the case of the MQL-Al_2O_3 nanofluid. Sharma et al. [139] compared three different types of nanofluids, namely Al_2O_3, TiO_2, and SiO_2, with varying volume fractions to be utilized in metal cutting fluids. They concluded that the Al_2O_3 nanofluid exhibited better thermal properties compared with SiO_2 and TiO_2. Sharma et al. [140] experimentally investigated the turning operation of AISI 1040 steel using Al_2O_3 nanoparticle-based cutting fluids and the MQL approach. They reported that the performance of Al_2O_3 nanofluids were better in terms of the surface roughness, tool wear, cutting force, and chip morphology when compared with dry machining and wet machining with conventional cutting fluid. Minh et al. [141] investigated the performance of 0.5% (by volume concentration) Al_2O_3 nanofluids in MQL in the hard milling of 60Si_2Mn steel using cemented carbide tools. They reported that the tool life was considerably improved, and they observed a reduction in the roughness and cutting forces in the range of 35–60% under the MQL conditions. They added that it could be attributed to the improved tribological behavior as well as the cooling and lubricating effect of the nanoparticles.

The above analyses indicate that cutting fluid applications, as well as cooling and lubrication media, can be customized by using properly selected nanofluids in varying amounts. For an enhanced cooling effect, i.e., for an enhanced heat removal rate, nanofluids can be tailored to meet the requirements. When the objective is to obtain more lubrication, nanofluids can be used as a cutting medium in the form of droplets with the MQL technique. From the above analyses, we inferred that the Al_2O_3 nanoparticles have shown promising results compared with their counterparts. However, nanofluids are still in the developmental phase, but the applications of nanofluids in machining have promising prospects compared to nano-coolants.

4. Conclusions

In this review, we attempted to highlight the properties and associated drawbacks of the mineral oil-based MWFs and to perform a comprehensive literature review on the potential alternatives to mineral oil-based MWFs, such as vegetable oil-based MWFs; and we attempted to investigate other sustainable machining operations, including the high-pressure coolant, dry machining, MQL, and the nanofluid methods. The pros and cons of all of the associated alternatives were critically reviewed in terms of their applicability, adaptability, cost-effectiveness, and environmental impact so that an unbiased analysis could be performed for the use of MWFs in machining applications. As seen from the comprehensive literature review, machining is one of the main parts of every manufacturing plant and it cannot be ignored, and MWFs play a key role in the cost of machining. Cutting fluids have widely been used in conventional machining process for cooling applications, but they are a main factor of increased costs along with adverse effects on the environment and health of workers/operators. Therefore, it is necessary to minimize the utilization of mineral oil-based MWFs, and instead adopt vegetable oil-based MWFs and other sustainable methods such as the MQL, dry machining, high pressure coolant, and nanofluid methods, among other alternatives. These alternative techniques not only have been shown to reduce the cost of manufacturing by 10% to 17%, but also have a more positive impact on the environment by eliminating issues concerning cutting fluid disposal and by minimizing the contact of the workers with the MWFs, contact that may result in severe diseases. These techniques demonstrated very promising results as compared with the conventional methods where mineral oil-based MWFs were used in the machining process. By keeping this in view with the latest demands of industrial sectors and modern machining process requirements, these techniques are one of the best options to opt for, allowing for the implementation of sustainable machining processes in replacement of traditional methods.

5. Future Recommendations

- It is evident that the utilization of vegetable oil-based MWFs have shown better performance in terms of decreasing the overall cutting temperature, cutting forces, and surface roughness, among other desired properties. They have also proved themselves to be more eco-friendly as well, but there are some shortcomings (which can be further studied), and there is room for improvement in these shortcomings. Little attention was paid to the oxidation and thermal stabilities of the vegetable oil-based MWFs.
- For the vegetable oil-based MWFs, it was seen that most of the research was carried out for ferrous materials and alloys, and little attention was paid to the non-ferrous materials, such as copper, brass, and aluminum.
- These days, super alloys are also being widely used due to their excellent properties. Therefore, consideration should be given in exploring the application of vegetable oil-based MWFs in the case of super alloys and other mentioned materials.
- Nanofluids have become an emerging technology due to their excellent thermophysical properties and they have proven themselves to be an excellent candidate in machining applications, offering desired properties such as decreased interface temperature, lower cutting forces, lower power consumption, and improved surface finish. However, the properties of the nanofluids can be further enhanced by tweaking different parameters such as the size of the nanoparticles, shape of the nanoparticles, volumetric concentration, and spray nozzle angle, among other parameters.
- The application of nanofluids has not been cost-effective up to this point, and some studies have reported a negative impact on the environment. Therefore, efforts can be made to develop novel nanofluids which are more eco-friendly and provide cost-effective solutions.
- A limited number of research has been done on hybrid nanofluids, i.e., the combination of different nanoparticles and their properties; therefore, efforts can be made to test different hybrid nanoparticles and their performance under different conditions, in terms of the thermal conductivity, stability, viscosity, material removal rate, cutting forces, cutting temperatures, and power consumption, among other attributes.

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