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ORIGINAL ARTICLE

Developments in the formulation and application of vegetable oil-based metalworking fluids in turning process

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Abstract In the beginning, metalworking fluids consisted of simple oils applied with brushes to lubricate and cool the machine tool. As cutting operations became more severe, metalworking fluid formulation became more complex. There are now several types of metalworking fluids in the market and the most common can be broadly categorized as cutting oils or water-miscible fluids. In this paper, attention is focused on recent research work on formulation and application of vegetable oil-based metalworking fluids in turning process. In addition, the performances of various vegetable oil-based metalworking fluids based on some process parameters such as thrust force, surface roughness, temperature developed at the tool chip interface, and tool wear during turning process using different tool materials were highlighted.

Keywords Formulation · Vegetable oils · Additives · Machining

1 Introduction

Reports indicate that nearly 38 million metric tons of lubricants were used globally in 2005, with a projected increase of 1.2 % over the next decade [1]. Due to their advantages, the consumption of metalworking fluids (MWFs) is increasing in machining industry. It is reported that European Union alone consumes approximately 320,000 tons per year of MWFs of which, at least two thirds need to be disposed [2]. Despite their widespread use, they pose significant health and environmental hazards throughout their life cycle. Bennett [3] observed that the question of whether machining operations and exposure to water base cutting fluids constitutes a human health problem is a complex one. He maintained that this complexity is due to difficulty in creating a study group of workers large enough to develop statistically significant information, because several years between exposure to cutting fluids and the appearance of medical problems are needed to gather data. However, HSE [4] report indicated that about 80 % of all occupational diseases of operators were due to skin contact with MWFs. Estimation says that in the USA alone about 700,000 to one million workers are exposed to MWFs [5]. As metalworking fluids are complex in their composition, they may be irritant or allergic. Even microbial toxins are generated by bacteria and fungi present, particularly in water-soluble MWFs [6], which are more harmful to the operators. To overcome these challenges, various alternatives to mineral-based MWFs are currently being explored by scientists and tribologists. Such alternatives include synthetic lubricants, solid lubricants, and vegetable-based lubricants. Approximately 85 % of lubricants being used around the world are mineral-based oils [7]. Enormous use of mineral-based oils created many negative effects on environment. The major negative effects is particularly linked to their use, which results in surface water and groundwater contamination, air pollution, soil contamination, and consequently agricultural product and food contamination [8].

Hence, there is a growing public interest in environmentally friendly lubricants due to awareness of environmental problems associated with conventional mineral oil-based lubricants [9]. Even though the toxicity of lubricants is low, their accumulation in the environment may cause damage in the long run. A large proportion of the lubricants pollute the environment either during or after use. In many countries, there are well-defined guidelines and legislations for environmentally friendly lubricants [10]. Several organizations around the world are working to improve such lubricants by evaluating their potential for environmental

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hazard. Examples include the German “Blue Angel”, USA “Green Seal”, and Canadian “Environmental Choice” [11]. Mineral oil-based lubricants contain many kinds of additives such as antioxidant, antiwear, detergents, dispersants, antifoams, extreme pressure agents, friction modifiers, and viscosity improvers. Some of these additives are toxic and harmful to human health, wildlife, and environment [12]. The environmental and toxicity issues of mineral oil-based lubricants and their additives as well as their rising cost related to a global shortage have led to renewed interest in the use of vegetable oils [13], such as soybean oil, canola oil, sunflower oil, coconut oil, sesame oil, castor oil, etc. as environmentally friendly lubricants and industrial fluids [14]. Vegetable oils generally possess some excellent lubricating properties, for example, good inherent lubricity, low volatility, high viscosity index, excellent solvency for lubricant additives, and easy miscibility with other fluids [15]. The growing demand for biodegradable materials has opened an avenue for using vegetable oils as an alternative to mineral oil-based polymeric materials [16], most especially in machining operations. The public awareness in environmental issues has been constantly growing [17]. Lubricants are used in many diverse areas; therefore, their environmental acceptability has become increasingly important. As a result, research on biodegradable functional fluids emerged as one of the top priorities in lubrication in the early 1990s which led to a lot of growing number of environmentally friendly fluids and lubricants in the market [18]. Vegetable oils, especially rapeseed [19] and canola [20], are some of the more promising candidates as basestocks for the biodegradable lubricants. They are readily biodegradable and less costly than synthetic basestocks. They often show quite acceptable performance as lubricants [21]. Cutting fluids are normally classified into three main groups; that is; (1) neat cutting oils (2) water-soluble fluids, and (3) gases. The water-soluble fluids can be classified as emulsifiable oils (soluble oils), chemical (synthetic) fluids, or semichemical (semisynthetic) fluids. Fluids within these classes are available for light, medium, and heavy duty performance [22]. In general, Norrby [23] maintained that vegetable oil-based lubricants offered an opportunity to address environmentally problems posed by mineral oil-based lubricants. Matthew et al. [24] experimentally observed that vegetable oils are highly attractive substitutes for petroleum-based oils because they are environmentally friendly, renewable, less toxic, and readily biodegradable.

Consequently, vegetable oil-based cutting fluids are more potential candidates for use in industries as lubricants. Many investigations are in progress to develop new biobased cutting fluids from various vegetable oils available around the world. Because of environmental concerns and growing regulations over contamination and pollution, the increased need for renewable and biodegradable lubricants cannot be over stretched. Vegetable oils are a viable and renewable source of environmentally favorable oils. The majority of vegetable oils consist primarily of triacylglycerides, which are molecular structure with three long chain fatty acids attached at the hydroxyl groups via ester linkages. Asadauskas et al. [25] observed that the fatty acids in vegetable oil triglycerides are all of similar length, between 14 and 22 carbons long, with varying levels of unsaturation. This was in agreement with Allawzi et al. [26] research report on physicochemical characteristics and thermal stability of Jordanian jojoba oil. The triglyceride structure of vegetable oils provides qualities desirable in a lubricant. Long, polar fatty acid chains provide high-strength lubricant films that interact strongly with metallic surfaces, reducing both friction and wear. The strong intermolecular interactions are also resilient to changes in temperature providing a more stable viscosity or high viscosity coefficient. The similarity in all vegetable oil structures means that only a narrow range of viscosities are available for their potential use as lubricants. The strong intermolecular interactions whilst providing a durable lubricant film also result in poor low-temperature properties. The fluid also remains biodegradable with low toxicity throughout all stages of its life. Lubricant formulations are being developed based on the benefits and limitations of vegetable oils. Without additives, vegetable oils out performed mineral oils in antiwear and friction [27], scuffing load capacity [28], and fatigue resistance [29]. Fully formulated vegetable oil lubricants, in comparison to mineral oil counterparts, display a lower coefficient of friction, equivalent scuffing load capacity, and better pitting resistance [30], but also poorer thermal and oxidative stability [31]. At extreme loads, vegetable oil-based lubricants become significantly less effective [32]. Vegetable oils are particularly effective as boundary lubricants as the high polarity of the entire base oil allows strong interactions with the lubricated surfaces. Belluco and de Chiffre [33] evaluated the performance of a range of mineral and vegetable oil-based cutting fluids in a range of machining operations and vegetable-based oil formulations displayed equal or better performance than the reference commercial mineral oil in all operations. In summary, vegetable oils display many desirable characteristics, which make them very attractive lubricants for many practical applications. Table 1 shows the advantages and disadvantages of vegetable oils as cutting fluids.

Fox and Stachowiak [34] observed that low temperature properties and narrow range of available viscosities limit the potential application of vegetable oil as industrial lubricants. To address these limitations, Lou [35] suggested three methods namely: (1) reformulation of additives, (2) chemical modification of vegetable-based oils, and (3) genetic modification of the oil seed crop to enhance the performance of vegetable oil lubricants. Lawal et al. [36] carried out a

Table 1 Advantages and disadvantages of vegetable oils as lubricants [34]

Advantages	Disadvantages
High biodegradability	Low thermal stability
Low pollution of the environment	Oxidative stability
Compatibility with additives	High freezing points
Low production cost	Poor corrosion protection
Wide production possibilities	
Low toxicity	
High flash points	

thorough review on the application of vegetable oil-based MWFs in machining ferrous metals. The review highlighted the advantages of MWFs and their performances during machining processes with respect to various grades of ferrous metals. The authors concluded that the use of vegetable oil-based MWFs could be an environmentally friendly mode of machining, with performance rating similar to that obtained from the use of mineral oil-based MWFs. In this review, trends in the developments of vegetable oil-based metalworking fluids formulation have been highlighted and applications of vegetable oil-based MWFs in turning process are reported. The question is why focusing on formulation and turning process in this review? The available literature on the use of vegetable oil-based MWFs during machining processes provides little or no information on the formulation procedures. Sharma et al. [37] averred that out of all machining processes, turning process still remains the most important operation used to shape metals because in turning, the conditions of operation are most varied. Hence, turning process was chosen to establish the performance ability of vegetable oil-based MWFs.

2 Developments of vegetable oil-based MWFs formulation

Historically, vegetable-based lubricants have not exhibited sufficient performance for industrial applications. There were several reasons for this inability. The first reason is that vegetable-based lubricants were misformulated. Early formulators in the vegetable-based lubricant market used the same chemistry that was used for mineral lubricants for vegetable base oils. This approach was not effective as the characteristics of vegetable oils are vastly different from those of mineral oils. Typical characteristics of vegetable oils as compared with petroleum oils are summarized in Table 2.

Table 2 Characteristics of petroleum and vegetable oils [38]

Characteristics	Petroleum oil	Vegetable oil
Lubricity	Low	High
Oxidative stability (RPVOT)	300	50
Viscosity Index (VI)	100	200
Hydrolytic stability	High	High
Polarity	Low polar	High polar
Saturation	Saturated	Unsaturated
Flash point (°F)	200	450
Pour point (°F)	−35	−35

RPVOT Rotary Pressure Vessel Oxidation Test

Similarly, conventional knowledge has focused on the limitations of vegetable oils as base stocks for lubricants, such as weakness of the oxidative stability, the cold temperature performance, and incompatibility with elastomers. For instance, all triglyceride vegetable-based lubricants have temperature limitations; there are some that are better than others. Most vegetable-based lubricants have a maximum operating temperature of 60 °C, though; there are some that offer protection as high as 104.44 °C [38]. Therefore, vegetable oils have to be formulated for their individual characteristics. However, improvements in vegetable basestocks, performance chemistry, and formulation expertise have allowed for the development of biodegradable products with performance similar to or better than conventional petroleum fluids. When chemists began to look at colloidal system around 1905, the scientific basis of cutting fluids formulation began to unfold [39]. The growing body of knowledge on colloid and surfactant chemistry led to the compounding of various “soluble oils” using natural fatty oils. This led to the granting of patent to Hutton for the process of producing water-soluble oils. He compounded sulfonated and washed castor oil with any sulfonated unsaponified fatty oil (other than castor oil) and then saponifying the sulfonated oils with caustic alkali [40].

2.1 Formulation, composition, and characterization of vegetable oil-based MWFs

2.1.1 Formulation

Cutting fluids formulation is an important first step toward achieving the best fluid performance and the extension of fluid life by using correct fluid concentration efficiently. Oils and fats are water-insoluble substances derived from vegetable and animal sources. Thus, almost all lubricants require further additives to impart other characteristics of a nontribological nature, such as oxidation resistance, corrosion protection, and detergency. Most cutting fluids, vegetable- and petroleum-based, are compounded or modified to achieve these requirements. Several methods are available to modify these oil lubricants. The important and most commonly used methods are sulfurization and phosphate modification [41]. Vegetable oils and other fats are triglycerides that are essentially triesters of fatty acids and glycerol, which are soluble in most organic solvents and are insoluble in polar substrates such as water. They can have a broad range of fatty acid profiles, but most commonly used vegetable oils have C18—oleic, linoleic, or lineleic acids. The proportion of each of these acids depends on the vegetable type, the growing season, and the geography. These factors can dramatically affect the performance of the vegetable oil in terms of oxidative stability, cold flow, hydrolytic stability, and other features of the final product. For example, the higher the oleic acid content, the better the oxidative stability, but the higher (worse) the pour point [42]. In order to solve these limitations of vegetable oil-based cutting fluids, it was recommended or necessary that the chosen additives were not problematic, dangerous for the environment or health. According to Bartz [43], there were groups of problematic substances that were included in cutting fluids formation in the past, such as: nitrosamines, formaldehyde condensate materials, organic chlorine-containing substances, organic phosphorous-containing substances, polycyclic aromatic hydrocarbons (PAH), such as benzopyrene–PAH, and others. These substances should be avoided in the formulation of environmentally friendly cutting fluids.

2.1.2 Composition

Childers [44] stated that the type of additives used in formulation of cutting fluids contribute to their properties and that these properties are usually mutually exclusive. Table 3 shows some additives commonly used in vegetable oils. The general composition of water-miscible cutting fluids can be characterized as an addition of base oil and emulsifier. Other components such as solution improvers, neutralization agents, corrosion and rust inhibitors, lubricating additives, biocides, fungicides, and foam inhibitors may be added to the fluid to improve stability in hard waters.

The soluble oils (also referred to as emulsions, emulsifiable oils, or water-soluble oils) are generally comprised of 60–90 % based oil, with emulsifiers and other additives [45]. A concentrate is mixed with water to form the cutting fluids, when mixed; emulsifiers cause the oil to disperse in water forming a stable “oil-in-water” emulsion [46]. They also cause the oils to cling to the workpiece during machining. The emulsifiers’ particles refract light, giving the fluid a milky, opaque appearance. But sometimes, water-miscible fluids may consist of up to 99 % water, and then the quality of water used to dilute concentration becomes an important consideration in fluid preparation [47]. This is because dissolved minerals and gases, organic matter, microorganisms, or combination of these impurities in water can lead to problems. The hardness and dissolved solids of water quality should be monitored to achieve the best fluid performance and extend fluid life. The hardness of the water depends on its content of water-soluble calcium and magnesium compounds. The total hardness of water has the greatest effect on the cutting fluids. In hard water, the calcium and magnesium ions react with components of the emulsifying oil. This reaction forms compounds which are not soluble in water and may be precipitated in the circulation system. Since these reactions use up part of the emulsifier, it reduces the stability of the emulsion. This may lead to de-mulsification and oil separation or fluid components segregation. Soft water will increase the risk of foam. The term “soft” is used for water, if it has a total hardness of less than 100 ppm or the term “hard” if total hardness exceeds 200 ppm. Milacron [48] suggested the ideal hardness of water for making cutting fluids to be between 80 and 125 ppm. The stability of the emulsion system depends on the size of the droplets produced during emulsion formation. In order to produce an emulsion with an average diameter of several micrometers, a mechanical or electrical overhead stirrer should be used for mixing the compositions.

Table 3 Additives in vegetable oils [74]

Additives	Function
Zinc diamy dithiocarbamate (ZDDC)	Anti-wear and antioxidant abilities
Antimony dialkyldithiocarbamate (ADDC)	
Zinc-dialkyl-dithio-phosphate (ZDDP)	Anti-wear/extreme pressure (AW/EP)
S-[2-(acetamido) thiazol-1-yl] dialkyl dithiocarbamates	Anti-wear
Palm oil methyl ester (POME)	Anti-wear
Dibutyl 3.5-di-t-butyl-hydroxy benzylphosphate (DBP)	Anti-wear
Butylated hydroxyl anisole (BHA)	Chain-breaking antioxidants
Butylated hydroxyl toluene (BHT)	
Mon-tert-butyl-hydroquinone (TBHQ), propyl gallate (PG)	
Zincdithiophosphates (DTP)	Peroxide decomposers antioxidant
Dithiocarbamates (DTC)	

2.1.3 Characterization

Alves and de Oliveira [49] observed that some properties of the formulated fluids, such as pH value, viscosity, corrosion, and biodegradability are important properties of oil in water. pH value, which is a measure of the acidity or alkalinity, is a good indicator of the condition of cutting fluid. They suggested a pH value of between 9 and 11 for cutting fluids, while Milacron [50] suggested pH value of between 8.4–9.5 and 8.8–9.2, respectively. It has been reported, that whatever pH value adopted for oil-in-water cutting fluids, it would have any of these implications on both worker's health and material.

1. If the pH value is too low (acid), the corrosion protection will be reduced as well as the long life stability.
2. If the emulsion is too high (alkaline), it will tend to degrease the skin and remove the natural skin protection.

If the pH value of the oil-in-water is low (acidic) the emulsion will be corrosive as shown in Fig. 1, which equally shows the implications of pH value on worker's health.

Miller [38] stated that although there are wide ranges of bio-based products, lubricants should be readily biodegradable, meaning that they are biodegradable above 60 % in 28 days as measured by the ASTM D5864 biodegradability test. The viscosity of any oil-in-water emulsion depends on oil concentration in the mixture and properties of the oil.

3 Examples of MWFs formulated from vegetable oils

3.1 Sulfonate castor oil-based MWF

Alves and de Oliveira [51] developed a new water-based grinding fluid formulation from sulfonated castor oil to meet both the performance and environmental requirements for CBN grinding. The resulting formulation of the proposed fluid consisted of the following percentage by volume; sulfonated castor oil (40 %), water (35 %), derivative of triasine (5 %), anticorrosive (synthetic ester; 15 %), and emulsifier agent (polyglycol of synthetic ester; 5 %). The oil was added first in water and mixed for 2 min and after all additives were added, they were mixed together for 15 min. The emulsion of oil-in-water was stable for 24 h without reposed, which indicated the stability of the mixture. The chemical and physical properties of the new formulated oil-in-water coolant were investigated and the results are shown in Table 4.

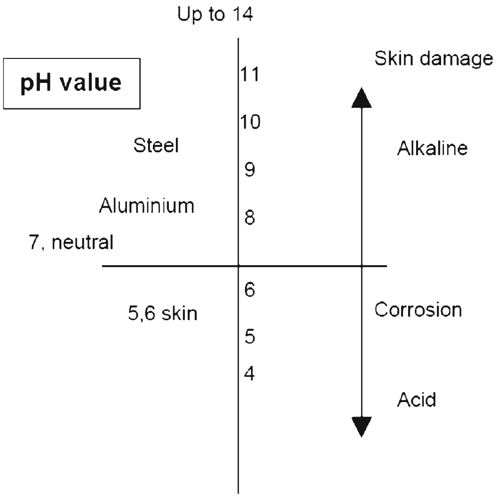

Fig. 1 Implication of pH value on worker's health and material [75]

The oil-in-water coolant does not have any banned products in its composition and the amounts of bactericide and anticorrosive are not far from the values used in commercial products. The biodegradability test was investigated using Ready Biodegradability, 301B CO2 Evolution Test adopted in 1992 [52]. The result showed excellent biodegradation as depicted in Fig. 2.

The corrosion test which was conducted using some grams of cast iron chips placed on a disk of filter paper in a Petri dish, humidified in 2 ml of the cutting fluid and left covered for 2 h, show that the new cutting fluid has good ability to inhibit corrosion as shown in Fig. 3. The corrosion grade of the cutting fluid was measured by counting the number of stained spots on the filter paper surface.

3.2 Crude soybean oil-based MWF

John et al. [53] studied emulsions containing vegetable oils for cutting fluids. Crude soybean and modified soybean oils samples were supplied by Volga Oil Processing Company, Volga, South Dakota and Urethane Soy Systems Inc, Princeton, IL, USA, respectively. Ozone-modified and sulfur-modified oils were prepared in the laboratory. The following emulsifiers were tested in the formulations; (1) Tween 40, a polyoxyethylene (20) sorbitan monopalmitate; (2) Tween 60, a polyoxytheylene (20) sorbitan monostearate (non-ionic) surfactant; and (3) Nikkol, a polyoxyethlene (40) sorbitan tetraoleate and Eccoterge 200, a nonionic ethoxylated fatty acid emulsifier. Soybean oil was modified using ozone treatment and sulfurization. A homogenizer was used at a rotational speed of 2,500 rpm for 10 min to produce an emulsion with an average diameter of several micrometers. The emulsion stability was judged by the appearance and by

Table 4 Characterization of new cutting fluid [51]

Aspect	Oily
pH	10.77
Absolute viscosity	129cP
Color	Chestnut
Stable solution	Yes

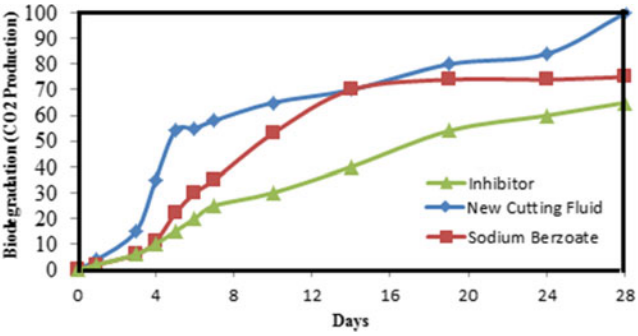

Fig. 2 Biodegradation test of new cutting fluid [49]

observing phase separation. The emulsions obtained using Nikkol and Eccoterge 200 were found to be stable for all oils (unmodified, sulfur modified, ozonized, and oxidized). The emulsions obtained for unmodified oil, were found to be stable only with Tween 60. Emulsion obtained with Tween 40, with modified oil was moderately stable and phase separated after 48 h. Table 5 shows the summary of the properties of emulsifiers used for preparing oil-in-water emulsions. The average droplet size for all the emulsion studied ranged between 7 and 10 μm. None of the emulsion study showed any rust formation within 24 h which was consistent with previous finding [54]. The phase diagrams constructed for the emulsions to determine the limits for the thermodynamically stable phases indicated that the nature of emulsion depends on the nature of the surfactant system employed.

3.3 Raw and refined sunflower oil-based MWF

Kuram et al. [55] investigated the effects of the cutting fluid types and cutting parameters on surface roughness and thrust force with three different vegetable-based cutting fluids developed from raw and refined sunflower oil and two commercial types (vegetable- and mineral-based cutting oil) during drilling of AISI 304 austenitic stainless steel with high speed steel E-grade tool. The oil-in-water emulsion type developed from raw and refined sunflower oil-based contained a surfactant mixture (Tween 85 and Peg 400, Merck) and various additives in the formula to meet the specifications such as resistance to bacteria growth, corrosion, antifoaming agent and antiwear [56]. The additive concentrations used were below 10 % *w/w*. The appearance of the emulsion was that of a homogenous liquid with 100 μm size of droplets in the dispersion. Water content in the cutting fluid formulated contained 92 %. The characterization of vegetable-based cutting fluids is shown in Table 6.

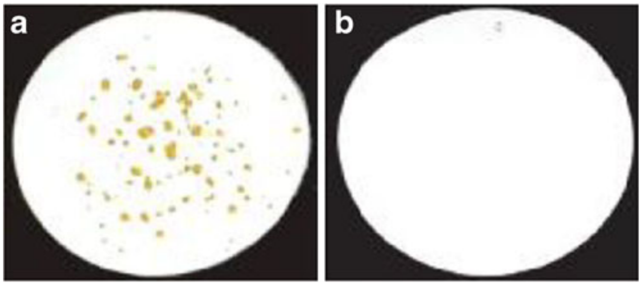

Fig. 3 Result of the corrosion test before (**a**) and after (**b**) the increase in the amount of anticorrosion additive [49]

4 Challenges in the formulation of vegetable oil-based MWFs

The properties of vegetable oils which are determined by their fatty acid composition [57] and the proportions of each of these fatty acids, which depend not only on the type of plant, but also on the climate, weather, and the food available [58] have impacted greatly on how vegetable oil-based MWFs can be formulated. For instance, the oxidative stability of particular oil grown in different locations may not be the same. Hence, in formulating MWFs from such oil, different percentage ratios of additives are required to get the same performance results. Another challenge in the formulation of vegetable oil-based MWFs is the refusal or failure of some researchers or authors to declare the name of vegetable oil used in their experiment. Examples, Kelly and Cotterell [59] only mentioned the use of vegetable oil in the mist lubrication method while, investigating the minimal lubrication machining of aluminum alloys. The experimental evaluation of minimum quantity lubrication in near micromilling by Li and Chou [60] reported the type of cutting fluid used as vegetable oil. Khan et al. [61] studied the effects of minimum quantity lubrication (MQL) by vegetable oil-based cutting fluid on turning performance of AISI 9310 low alloy steel. Khan et al. [61] was silent on the name of vegetable oil used for the experiment. Avila and Abrao [62] while investigating the performance of three types of cutting fluids in continuous turning of hardened AISI 4340 steel did not declare or specify the emulsion used, but rather choose to mention "emulsion without mineral oil".

In addressing these challenges, effort should be made to build a data bank for development of vegetable oil-based MWFs. Researchers should be opened in reporting their experimental sample of vegetable oil. Despite these challenges, vegetable oil-based MWFs have proved to be better alternative to mineral oil-based MWFs in term of performances as reported in the section below during turning process.

5 Application of vegetable oil-based MWFs in turning process

Machining is the most widespread metal shaping process in mechanical manufacturing industry. All over the world,

Table 5 Properties of emulsifiers used for preparing oil-in-water emulsion [53]

Trade name and class	Emulsifier composition	HLB[a]	Emulsion stability
Tween 40 (non-ionic)	Polyoxyethylene (20) sorbitan monopalmitate	15.6	Moderately stable for unmodified oil
Tween 60 (non-ionic)	Polyoxyethylene (20) sorbitan monostearate	14.9	Stable for unmodified oil
Nikkol (non-ionic)	Polyoxyethylene (40) sorbitan tetraoleate	11.4	Stable for all oils
Eccoterge 200 (non-ionic)	Ethoxylated oleic acid ester	~12.0	Stable for all oils

[a] HLB is the hydrophile–lipophile balance of an emulsifier

machining operations such as turning, milling, boring, drilling, and shaping consume large amount of money annually [63]. Out of these machining processes, turning still remains the most important operation used to shape metals, because in turning, the conditions of operation are most varied. Increasing productivity and reducing manufacturing cost have always been keys to successful business [64]. In turning, higher values of cutting parameters offer opportunities for increasing productivity but it also involves a greater risk of deterioration in surface quality and tool life [65]. This deterioration cannot be avoided but can be minimized by using appropriate MWFs. The application of vegetable oil-based MWFs will help to eliminate the effect of heat and friction, provide lubrication between chip–tool interfaces, and flush away chips during turning process and improve surface finish of the work material. The performance of vegetable oil-based MWFs in turning process as reported by authors is hereby highlighted under these subheadings.

5.1 Tool wear, surface roughness, temperature, and chip formation mode

Xavior and Adithan [66] investigated the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel with carbide tool using three different types of cutting fluids (coconut oil, soluble oil, and straight cutting oil). The experimentation work was based on Taguchi's design of experiment with $L_{27}(3)^4$ orthogonal array using cutting speed, depth of cut, feed rate, and types of cutting fluids as input parameters. The levels of these parameters are presented in Table 7.

Based on multiple linear regression analysis, models were developed to determine the tool wear and surface roughness while analysis of variance (ANOVA) was used to determine the significant parameters that influenced the tool wear and surface roughness at constant depth of cut of 0.5 mm; feed rate of 0.2, 0.25, and 0.28 mm/rev, and cutting speed of 38.95, 61.35, and 97.38 m/min. The results indicated that coconut oil had greatest influence on the surface roughness and tool wear as shown in Table 8.

These results show an improvement in surface roughness of between 13 and 15 % and reduction in tool wear of between 1.5 and 2.2 times with coconut oil compared with soluble oil. Similarly, it is reported that in terms of surface roughness, straight cutting oils outperformed soluble oils with improvement of between 14.4 and 16 %, but with increase in tool wear of approximately 1.3 times. The following observations were obtained when ANOVA was used to determine the significant parameters that influenced the tool wear and surface roughness:

1. Feed rate had greater influence on surface roughness with 61.54 % contribution and cutting speed has greater influence on tool wear with 46.49 % contribution for all the cutting fluids.
2. The relative performance of the effectiveness of the cutting fluids in reducing the tool wear and improving the surface finish was better when coconut oil was used compared to conventional mineral oil.

Table 6 Characterization of vegetable-based cutting fluids [55]

MWFs	pH value (emulsion 8 %)	Density (g/ml)	Viscosity (40 °C) mm^2/s		Flash point (°C)	Refractive index
			Without additive	Emulsion 8 %		
CSCF-I	8.70	0.970	71	1.4	218	1.475
SCF-I	9.10	0.980	74	2.0	199	1.474
SCF-II	9.00	0.975	75	1.9	170	1.475
CVCF	9.32	0.960	85	1.5	205	1.476
CMCF	9.40	0.906	29	1.4	175	1.482

CSCF-I crude sunflower cutting fluid, *SCF-I* sunflower cutting fluid, *SCF-II* sunflower cutting fluid (a mixture of two surfactants), *CVCF* commercial vegetable cutting fluid, *CMCF* commercial mineral cutting fluid

Table 7 Critical parameters and their levels [66]

S/no.	Machining parameters	Unit	Level 1	Level 2	Level 3
1	Cutting speed V_c	m/min	38.95	61.35	97.38
2	Depth of cut, d	mm	0.5	1.0	1.2
3	Feed rate, f	mm/rev	0.2	0.25	0.28
4	Type of cutting fluids, D	–	Coconut oil	Soluble oil	Straight cutting oil

Krishna et al. [67] investigated the variation of cutting tool temperatures, average tool flank wear, and the surface roughness of AISI 1040 steel using cemented carbide tool (SNMG 120408) during turning process. The study was performed under nanoboric acid suspensions in SAE-40 and coconut oil environment with the following machining conditions: cutting speed (60, 80, and 100 m/min); feed rate (0.14, 0.16, and 0.2 mm/rev); and depth of cut (1.0 mm). Solid lubricants of boric acid with particle size of 50 nm, lubricating oil SAE-40 and coconut oil with flow rate of 10 ml/min were used for lubrication. It was observed that cutting temperatures increased with cutting speed irrespective of the lubricant and cutting temperatures were less with coconut oil compared to SAE-40 for identical cutting conditions as shown in Fig. 4. Also, cutting temperatures increased with increase in feed rate for all the lubricant conditions, but flank wear increased gradually with increase in speed and feed rate.

However, compared to 0.25 % SAE-40 lubricant, the combined effect of solid lubricant with 0.5 % nanoboric acid particles in coconut oil reduce the flank wear by 16–20 % in the range of cutting speed between 60 and 100 m/min. The authors observed reduction in surface roughness with coconut oil by 23 % at 60 m/min, 15 % at 80 m/min, and 23 % at 100 m/min compared to SAE-40 oil.

In the study by Khan et al. [61], it was reported that an average chip–tool interface temperature increased with increase of cutting speed and feed rate during the turning process of AISI 9310 low alloy steel using uncoated carbide tool. The study was conducted under vegetable oil lubricant using MQL technique, wet, and completely dry cutting. An improved surface roughness of about 31.6 % was obtained for vegetable oil MQL over wet cutting and about 18 % was obtained for dry cutting over wet cutting as shown in Fig. 5. The drastic deterioration of surface roughness under wet machining compared to dry cutting was possibly due to electrochemical interaction between tool and workpiece. The authors found that when machining with MQL, the form of ductile chips did not change appreciably, but their back surface appeared much brighter and smoother. The color of the chips became much lighter, i.e., blue or golden from burnt depending on the cutting velocity and feed rate, due to reduction in cutting temperature by MQL. The gradual growth of average principal flank wear, the predominant parameter to ascertain the expiry of tool life was observed under all the entire environments.

One of the conclusions made by the authors was that as a reduction of flank wear, there was a significant increase in the machining of AISI 9310 low alloy steel with carbide insert. Higher cutting velocity of 334 m/min and feed rate of 0.18 mm/rev were attained, which translated into improvement of metal removal rate (MRR). They argued that such reduction in tool wear was possible because of retardation of abrasion, decrease, or prevention of adhesion and diffusion type thermal sensitivity wear at the flanks and reduction of built-up edge formation, which accelerated wear at the cutting edges by chipping and flaking. Krahenbuhl [68] reported that vegetable oil-based cutting fluids were viable alternative to petroleum-based metalworking fluids due to the following reasons: (1) vegetable oil possess higher flash point, which give opportunities for increase in MRR, because of reduction in smoke formation and fire hazard during machining process, (2) vegetable oils provide lubricating film layer, which helps to improve workpieces quality and overall process productivity reducing friction and heat generation. Krahenbuhl [69] reported an instance, where vegetable oil technology made it possible to increase production volume by 10 %, because higher cutting velocity

Table 8 Result obtained for the three cutting fluids [66]

S/n	Cutting speed (m/s)	Feed rate (mm/rev)	Depth of cut (mm)	Coconut oil		Soluble oil		Straight cutting oil	
				Surface roughness (μm)	Tool wear (mm)	Surface roughness (μm)	Tool wear (mm)	Surface roughness (μm)	Tool wear (mm)
1	38.95	0.2	0.5	1.91	0.045	2.25	0.098	2.68	0.076
2	61.35	0.25	0.5	2.06	0.055	2.50	0.095	2.92	0.094
3	97.38	0.28	0.5	2.11	0.071	2.43	0.104	2.92	0.10

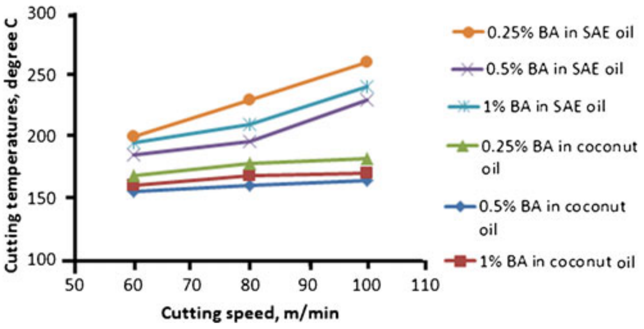

Fig. 4 Variation of cutting temperatures with cutting speed (feed rate= 0.2 mm/rev, d.o.c=1 mm, time=15 min) [67]

and feed rate were achieved and also reducing tool cost by 50 % in producing titanium and stainless steel medical implants. He reported that vegetable oils lubrications made possible a 15-fold increase in tool life, while tapping steel parts for an automobile application. He concluded that coolants based on vegetable oils had demonstrated an ability to deliver machining performance that in most applications was significantly superior to that of mineral oils and synthetic formulations.

Avila and Abrao [62] examined the performance of three types of cutting fluids (two emulsions and one synthetic fluid) and compared them with dry cutting during the continuous turning hardened AISI 4340 steel (49 HRC) using mixed alumina inserts (Al2O3)+TiC. They evaluated tool life, surface finish, tool wear mechanisms, and chips for both rough and finish machining. The rough machining test was conducted using varying cutting speed. The type cutting fluids used for the examination are shown in Table 9. The rough machining test was conducted using varying cutting speed (V_c) between 50 and 100 m/min for a feed rate (*f*) of 0.15 mm/rev and depth of cut (*ap*) of 2.0 mm. The finish machining setting was at V_c of 200–400 m/min for a feed rate of 0.05 mm/rev and depth of cut of 0.5 mm. The tests were conducted according to ISO 3685 [70] using a tool life criterion of average flank wear VBB=0.3 mm and tests were stopped after 60 min if criterion had not been met.

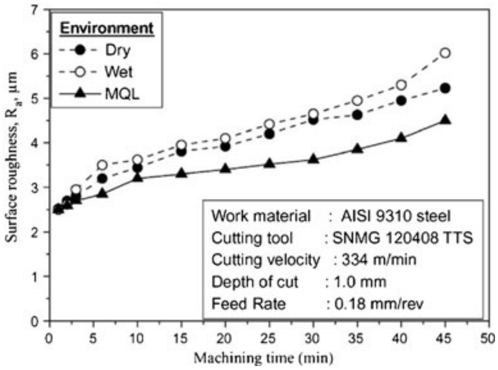

Fig. 5 Variation in surface roughness with progress of turning steel by SNMG insert under different cooling conditions at cutting velocity 334 m/min and feed rate 0.18 mm/rev [61]

Table 9 Types of cutting fluids [61]

Cutting fluid	Detail
Fluid A	Emulsion without mineral oil
Fluid B	Emulsion synthetic
Fluid C	Emulsion with mineral oil

The authors observed that during rough turning with feed rate of 0.15 mm/rev and depth of cut of 2.0 mm, cutting fluid A provided the longest tool life, followed by dry cutting and fluid B and while worst result was given by the emulsion containing mineral oil (fluid C). The same trend was observed when finish turning with feed rate of 0.05 mm/rev and depth of cut of 0.5 mm, with tool life criterion as VBB=0.2 mm. The effect of reduction in the concentration of fluid A from 5 to 3 % during finish turning gave the best tool life results as follows: Ra=1.7 µm (dry cutting), Ra=1.73 µm (fluid A), Ra=1.89 µm (fluid B), and Ra=2.14 µm (fluid C). This translated into about 19 % of surface roughness improvement for fluid A over fluid C and 8.4 % improvement for fluid A over fluid B. While there was no much difference between dry cutting and fluid A in the surface roughness reported. However, when the cutting speed was increased to 75 and 100 m/min, the best surface finish was obtained with fluid C. The reduction of concentration of fluid A from 5 to 3 % (during the finish turning tests) did not represent any considerable change on surface roughness irrespective of cutting speed and the average Ra value measured. The reduction in the cutting fluid concentration of emulsion without mineral oil from 5 to 3 % resulted in lower tool life, particularly at a cutting speed of 300 m/min.

5.2 Cutting force

Ojolo et al. [71] evaluated the effect of four vegetable oils (groundnut, palm kernel, coconut, and shear butter oils) on cutting force during cylindrical turning of three materials (mild steel, copper, and aluminum) using tungsten carbide tool. The input variables were spindle speeds of 250, 330, 450, and 550 rpm at constant feed of 0.15 mm/rev and 2 mm depth of cut for each of the workpiece of diameter 10 mm and length of 78 mm. They observed that the four vegetable oils were suitable for metalworking fluids, but the effects of oils on cutting force were material dependent. There was reduction of cutting force by 51 % with groundnut oil compared to palm kernel oil at feed rate of 0.15 mm/rev and depth of cut of 2 mm for aluminum material. While the reduction of cutting force by 34 % of palm kernel oil compared to coconut oil for the same machining condition was recorded for copper material, it was observed that coconut oil recorded the highest cutting force in all the three materials machined followed by shear butter oil. The results show that groundnut and palm kernel oils were effective in reducing cutting force during cylindrical turning of the three workpieces. These findings are in agreement with Lawal et al. [72].

5.3 Coefficient of friction between chip and rake face

The effect of cutting speed, feed rate, depth of cut, and rake angle on coefficient of friction between chip and rake angle were studied by Ojolo and Ohunakin [73]. Three work piece materials (mild steel, brass, and aluminum) with high-speed steel tool using palm kernel oil as cutting fluid during turning process were used in the study. Table 10 shows the lubricant performance at cutting speed, rake angle, depth of cut, and feed rate of 4.15 m/s, 9°, 1.5 mm, and 1.8 mm/rev, respectively, and their corresponding coefficient of friction.

A reduction of 33.3 % and increment of 13.8 % in coefficient of friction at cutting speed of 4.2 m/s and rake angle of 9° were observed for aluminum and brass, respectively. At a cutting speed of 4.2 m/s and depth of cut of 1.5 mm, there were 9.8 % reduction in coefficient of friction for brass and increment of 46.7 % for aluminum. While a reduction of 9.2 % coefficient of friction was recorded for brass and an increase of 30.4 % coefficient of friction was recorded for aluminum at cutting speed of 4.15 m/s and feed 1.8 mm/rev. Similar trends were observed by varying the cutting conditions. The study established palm kernel oil as a good metal cutting lubricant. It was observed that as turning parameters were varied, the performances of the lubricant were equally altered in term of the coefficient of friction.

6 Conclusions and future direction

Cooling and lubrication in machining are important in reducing the severity of the contact processes at the cutting tool–workpiece interfaces. Initially, water was used mainly as coolant due to its high thermal capacity and availability. The breakthrough in the development of vegetable oil-based metalworking fluids utilizing performance chemistry similar to those used in petroleum-based fluids was a positive development. This made it possible for vegetable oil-based lubricant to meet environmental and industrial performance requirements. The research reports discussed in this paper have the ability to meet the environmental and machining performance needs of the manufacturing industry. It will probably take more research and investigation along with government regulations on environmental impact of metalworking fluids to persuade industry to use vegetable oil-based metalworking fluids.

A critical analysis of the available literature shows that unlike surface roughness, tool wear, chip formation, and cutting force, which is one of the main performance criteria of any machining process has not received adequate attention, hence the need to carry out more investigations of the effect of vegetable oil-based cutting fluid on cutting force during turning process. Again, the process of lubrication techniques and variation in tool geometry require further research to benefit from the advantages offered by vegetable oil-based lubricant in turning process. However, findings from the literature can be summarized as follows:

1. Appropriate and correct percentages of additives are necessary in the formulation of vegetable oil-based metalworking fluids to obtain the best performance. It was observed that many of the characteristics of cutting fluid are mutually exclusive. For instances, if a fluid has excellent biological and hard water stability, it may be

Table 10 Analysis of lubricant performance [73]

	Rake angle variation			
Material	Coefficient of friction	Rake angle (O°)	Cutting speed (m/s)	Percentage (%)
Aluminum	0.56	9	4.15	33.3 (reduction)
Brass	0.65	9	4.15	7.9 (increase)
Mild steel	0.38	9	4.15	13.8 (increase)
	Depth of cut variation			
	Coefficient of friction	Depth of cut (mm)	Cutting speed (m/s)	Percentage (%)
Aluminum	0.94	1.5	4.15	46.7 (increase)
Brass	0.53	1.5	4.15	7.9 (reduction)
Mild steel	0.50	1.5	4.15	20.8 (increase)
	Feed rate variation			
	Coefficient of friction	Feed rate (mm/rev)	Cutting speed (m/s)	Percentage (%)
Aluminum	0.95	1.8	4.15	30.4 (increase)
Brass	0.64	1.8	4.15	9.2 (reduction)
Mild steel	0.56	1.8	4.15	14.5 (increase)

difficult to treat the waste. If it provides excellent lubricity, it may be difficult to clean.

2. The introduction of vegetable oil-based metalworking fluids in machining applications has made it possible to achieve better performance as reported by all researchers.
3. There was an improvement in surface roughness of between 13 and 15 % and reduction in tool wear of between 1.5 and 2.2 times with coconut oil compared with soluble oil, during the turning process of AISI 304 austenitic stainless steel with carbide tool.

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