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Importance of Lubricity Additives in Performance of Nonedible Oil Based Cutting Fluids -A Review

Rajasekhar Mettlu
PhD scholar, Department of Polymer science and technology, Jss science and technology university, Sri jayachamarajendra college of engineering, Mysuru, Karnataka-570006, India

Abstract - Cutting fluids (CFs) are playing a major role in machining and other industries' economic development, mainly by providing lubrication and cooling between the cutting tool and workpiece. More than 50% of CFs were mineral oil based. Mineral oil-based CFs were non-biodegradable, which had huge negative effects on the environment and worker health. The increasing attention to the environment and health impacts leads to the development of eco-friendly CFs derived from non-edible oils to replace the use of mineral oils. Sustainability was an important factor in the machining industries' replacing petroleum-based CFs with bio-based CFs from plants and animal sources. This review focuses on various inedible oils being developed to promote biodegradable CFs. The performance of nonedible oils with respect to lubrication and machining and the behavior of nonedible oils that influence the lubricity and machining performance through the incorporation of lubricity additives in the metal working process has been studied and reported. According to the review, nonedible oils are the best potential sources for providing an alternative, eco-friendly, and sustainable CFs for the future of manufacturing.

Key words: Lubricity, ecofriendly, Sustainability, Non-edible oils and Cutting fluids.

INTRODUCTION

Cutting fluids are used in machining processes to increase tool life, enhance machining efficiency, surface quality and dimensional accuracy by providing both cooling and lubrication. CFs are composed of base oil and an additive package (1% to 30%) and are generally used to reduce the friction of two working surfaces contacting each other. The base fluid is mineral oil that contains a mixture of hydrocarbons (paraffinic or naphthenic) with 20–30 carbon atoms. More than 50% of CFs used globally are mineral oil based and have adverse effects on the environment due to improper disposal, toxicity, and non-biodegradability. Hence, there is an increasing demand for environmentally acceptable and biodegradable products suitable for use as CFs [1]. Nonedible oils are triglycerides of long-chain carboxylic acids combined with glycerol. The use of non-edible oils as base fluids was highly anticipated from the viewpoint of increasing global environmental pollution. They are biodegradable [2], nontoxic, have a high viscosity index [3], and have shown excellent tribological properties [4,5].

The lack of heavy use of inedible oil is largely due to poor performance characteristics of the oil. Research has shown that most of these vegetable oils are unstable at higher temperatures. The main factor that causes instability at high temperatures has been found to be the glycerol part of the triglyceride molecule. Triglycerides are the main component of most vegetable oils. The arrangement of the hydrogen atom in the hydroxyl group of glycerol molecules was found to be the main characteristic of instability [6]. To overcome the limitations of nonedible oils, chemical modifications, namely hydrogenation, epoxidation, and transesterification, and additives can be applied to further enhance their lubrication and machining properties. Vegetable oils offer a high amount of biodegradability (95%), which is safe for the environment and helps reduce the cost of used cutting fluid disposal [6]. The use of edible oil to produce CFs was not feasible in view of the large gap in demand and supply of such oil [7]. Non-edible oils like pongamia, jatropha, mahua, castor oil, linseed oil, rape seed, and neem are being considered as the sources of straight vegetable oil [8]. Vegetable oil-based CFs are potential replacements [9] [10]. The performance of a variety of mineral and vegetable oil-based CFs in a vast range of machining operations was evaluated [11] and it was found that vegetable-based oil formulations show better performance than commercial mineral oil in all operations. The scope of this paper is to study and review the properties of non-edible oils and the performance of nonedible oil-based CFs with lubricity additives like nanoparticles and extreme pressure additives (EP).

PROPERTIES OF NON-EDIBLE OILS

Nonedible oils offer properties like high viscosity index, good lubricity, low volatility [12 - 14] and advanced properties like low toxicity, high flash points, and high biodegradability [15]. Table 1 presented different types of inedible oilseed plants, their scientific names, and their oil content. The polar nature of triglyceride structure in inedible oil arranged in a closed-packed monomolecular layer, forming the strong surface-like base fluid found in CFs [16 - 18]. The composition of fatty acids present in non-edible oils is the main responsible for their performance as CFs. Long, polar fatty acid chains provide high strength lubricant films that interact strongly with metallic surfaces, reducing both friction and wear [19]. The fatty acid composition of different inedible oils has been tabulated in Table 2. Due to its large molecular weight, they have low volatility and better viscosity properties. The pure versions of nonedible oils are not suitable for the CFs because of their poor oxidation stability. Poor oxidation stability leads to increased

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viscosity of oil by the formation of acid spices when exposed to high temperatures. Many researchers find different processes like hydrogenation, additive treatment, and chemical modifications to improve the performance of non-edible oils as CFs. Figure-1 represent the general composition and preparation process of cutting fluids.

Table 1. Non-edible oil plant and oil content [20]

Non-edible oil plant	Oil content (wt%)
Jatropha	40–60
Mahua	35–50
Candlenut	60–65
Rubber	40–50
Soapsuds	23–30
Jojoba	40–50
Tobacco	35–49
Neem	25–45
Karanja	30–50
Castor	45–50
Polanga	65–75
Cotton	17–23
Kusum	51–62

The performance limitations of vegetable-based lubricants stem from their inherent inferior physicochemical properties to those based on mineral oil. A lot of research and development is being carried out to overcome the limitations of nonedible oils for use as CFs. Many contributions are cited for improving the performance of nonedible oils with the aid of various nanoparticles, anti-wear, and extreme pressure additives. Effect and importance of lubricity additives like nano materials and EP are discussed further.

Table 2. Non-edible oil plants and its fatty acid composition [20]

Non-edible oil plant	Palmitic acid	Stearic acid	Oleic acid	Linoleic acid	Linolenic acid
Jatropha	14.6	7.6	44.6	31.9	0.3
Jojoba	1.59	4.14	42.84	31.52	NA
Candlenut	6.23	2.23	26.26	39.71	24.86
Karanja	9.8	6.2	72.2	11.8	NA
Mahua	21.36	18.97	38.98	19.47	0.16
Cotton oil	24.15	2.90	19.32	50.72	1.45
Neem oil	14.9	14.4	61.9	7.5	0
Polanga	12.01	12.95	34.09	38.26	0.30
Rubber	10.2	8.7	24.6	39.6	16.3
Rice bran	21.76	2.31	41.86	30.99	NA
Tobacco	10.96	3.34	15.54	69.49	0.69

MACHINING PERFORMANCE OF NON-EDIBLE OILS WITH NANO PARTICLES

Solids have good thermal conductivity. So, the thermal conductivity of CFs can be enhanced by dispersing solid nanoparticles in them. Nano fluids are the fluids in which nanometer-sized particles (Nano particles, Nano fibers, Nano wires, Nano rods, and Nano sheets) are dispersed in the CFs. Rahmati et al. [21] studied the effect of the incorporation of nano molybdenum di sulphide particles in Computerized Numerical Control (CNC) milling and found that the temperature and cutting forces are reduced. Vamsi Krishna et al. [22] found that the addition of nano boric acid in SAE-40 and coconut oil in turning with a carbide tool significantly reduces the temperature, surface roughness, and flank wear. Prasad et al. [23] studied the effect of inclusion of nano graphite and increase in percentage inclusion of the nano graphite leads to better performance of the fluids with respect to machining responses like cutting forces, temperatures, surface roughness, and tool wear. Gajrani et al. [24] studied the effectiveness of calcium difluoride (CaF_2) and molybdenum disulfide (MoS_2) mixture-based vegetable oil CFs in minimum quantity lubrication (MQL) machining of hardened AISI H-13 steel work material. Results found that the surface quality of the machined workpiece material when machining with green cutting fluids is improved by about 37.2% when compared to machining with mineral-based cutting oils.

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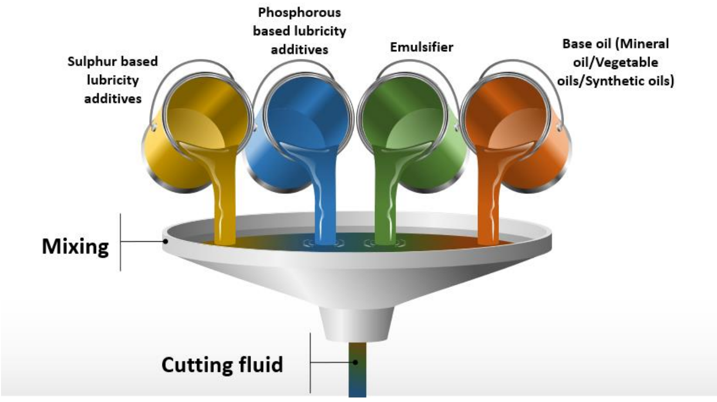
Figure 1. Preparation process of cutting fluids.



Padmini et al. [25] studied the different samples of nanofluids that were formulated using dispersions of nano molybdenum disulphide in coconut, sesame, and canola oils at varying nanoparticle concentrations. Cutting forces are approximately reduced by 37% by using coconut + nano MoS_2 at 0.5% compared to dry machining. Talib et al. [26] evaluated the performance of chemically modified crude jatropha oil and crude jatropha oil. The results showed that when compared with synthetic ester, the performance of the chemically modified crude jatropha oil was comparable with synthetic ester in terms of cutting force. Sadeghi et al. [27] evaluated vegetable and synthetic ester oils based on the surface quality properties. The results showed synthetic ester oil to be the optimal cutting fluid for MQL grinding of Ti-6Al-4V with aluminum oxide (Al_2O_3) grinding wheels for MQL applications.

Alves et al. [28] developed a castor oil-based cutting fluid for grinding SAE 8640 using a vitrified cubic boron nitride (CBN) wheel. A significant reduction in radial wheel wear compared to semi-synthetic cutting fluid was observed. Khan et al. [29] applied copper nano-additives (Cu-np)-based MQL in conventional machining to improve the surface quality and machinability. Findings have demonstrated superior surface quality under nanofluid-assisted machining. They have reported that the application of Cu- nano particles in biodegradable oil extended tribological film formation as well as thermal properties.

Gajrani et al. [30] studied nano-green cutting fluid (NGCF) significant improvement in hard machining performance using combination of micro-textured tools with NGCF corresponding to forces, chip-tool interface friction, workpiece surface roughness and chip morphology by in-house developed minimum quantity cutting fluid (MQCF) environment.

Amrit Pal et al. [31] studied the effect of minimum quantity lubrication (MQL) with MoS_2-enhanced vegetable-oil-based cutting fluid on the drilling characteristics of AISI 321 stainless steel. It was found that 1.5 wt.% nano-MoS_2 in sunflower oil-based MQL condition provided better cooling–lubrication effect and improved the drilling characteristics followed by 1.0 wt.% and 0.5 wt.% nano-MoS_2 in sunflower oil-based MQL conditions.

MACHINING PERFORMANCE OF NON-EDIBLE OILS WITH EXTREME PRESSURE (EP) ADDITIVES

The role of additives in CFs is very significant. They are added to the base oil to optimize the performance of the CFs in certain applications. Most of the additives are used to improve the lubrication, anticorrosion, and oxidation stability performance of CFs. Additives of sulphur and organosulfur compounds have been used in commercial cutting fluids when the sensitivity of the machining operation requires the use of extreme pressure (EP) properties in the fluid. Additives used in cutting fluids are largely confined to sulphur or sulfurized fats. Sulfur additives are well-known for their anti-wear and strong EP characteristics. The simple steps in lubricity additive life cycle is represented in Figure-2.

Lubricity additives are an important class of additives widely used in metalworking and other lubricants. Their unique chemical structure is that they contain reactive elements such as halogens (e.g., chlorine), sulfur, and phosphorus [32 - 33]. Under extreme lubrication conditions (high pressure, high temperature, and low speed), lubricity additives undergo tribo chemical reactions with metallic friction surfaces and generate tribo-films in situ that lower friction between and prevent damage to friction surfaces. The effectiveness of lubricity additives is a complex function of their chemical structure, concentration, base stock, friction surfaces, and lubrication process conditions. Another factor that may influence the performance of lubricity additives is their interaction with the base fluid and other ingredients in the lubricant formulation.
Ozcelik et al. [34] compared the performance of EP additives included in canola oil and sunflower oil during the turning of AISI 304L austenitic steel. The performance of vegetable oil based cutting fluids (VBCFs) with 8% and 12% sulphur based EP additives was evaluated in terms of cutting and feeding forces, tool wear, and surface roughness. The obtained results were also compared to those obtained under dry cutting conditions. Results indicated that 8% of EP additive contributed canola oil based cutting fluid gave better performance than that of semi-synthetic and mineral oil based cutting fluids in terms of reduced surface roughness, feed force, and tool wear.

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Loan et al. [35] compared the lubricating capacity of rapeseed oil with mineral oil. The results found that rapeseed oil has superior performance to conventional cutting fluids, which reduces cutting forces, surface roughness, and tool wear, improving surface integrity and tool life. Umamaheswara et al. [36] studied the wear performance of alternative cutting fluids of edible (groundnut, sunflower oil) and nonedible (castrol, neem) oils. The comparison was made between traditional and proposed alternative cutting fluids. The alternative cutting fluids showed better in performance compared to traditional cutting fluids. Cambiella et al. [37] studied the performance of oil-in-water emulsions (anionic, non-ionic, and cationic surfactants) in machining operations. Results indicated that the performance of emulsions is like base oils and oil droplets plays a key role in their tribological behavior.
Lawal et al. [38] studied the effect of formulated cutting fluids with palm kernel oil and cottonseed oil on cutting force in turning AISI 4340 steel with coated carbide and found that palm kernel oil and cottonseed oil generated lower cutting force compared to mineral oil-based cutting fluid. Mahadi et al. [39] studied vegetable oil cutting fluids blended with boric acid powder in turning AISI 431 steel. The addition of boric acid powder to palm kernel oil has yielded a better surface finish compared to conventional mineral base oil. Jeevan et al. [40] evaluated two nonedible vegetable oils, Jatropha and Pongamia, in their chemically modified (epoxidized) versions as a cutting fluid for turning AA 6061. The results obtained under epoxidized versions of Jatropha and Pongamia oils and the result are compared with the mineral oil in terms of cutting forces and surface roughness. Experimental observations and statistical analysis show that, compared to mineral oil, the modified versions of vegetable oil-based cutting fluids are more effective in reducing the cutting forces and increasing surface finish.

Figure 2. Simple steps in lubricity additive life cycle

Bellucci et al. [41] evaluated the performance of six cutting oils in drilling AISI 316L austenitic stainless steel with different proportions of additives compared with mineral oil-based cutting fluid. The results indicated that vegetable oil CFs performed better than the mineral oil based cutting fluid, with a 177% increase in tool life and a 7% reduction in thrust force.
Bierla et al. [42] carried out physico-chemical analysis to evaluate the performance of various sulfur-containing EP additives, and to understand their mechanism of action in metal cutting. The results indicated that polysulfide additives exhibited the best efficiency in terms of decreased specific cutting energy and tool wear. Kuram et al. [43] studied the spindle speed, feed rate and depth of cut with four different CFs formulated from sunflower and canola oils (including 8% and 12% of EP additives) and two commercial cutting fluids in the turning process. Results indicated that sunflower-based CF with 8% of EP and commercial semi-synthetic cutting fluid performed better than the rest of the cutting fluids for reducing surface roughness and forces.

Kuram et al. [44] investigated the effects of EP additives including VBCFs in terms of reduced cutting force, increased tool life, and improved surface finish during end milling of AISI 304 stainless steel. The experiments were conducted with three different VBCFs developed from sunflower with 8% EP, canola oil with 8% EP, and a commercial type of semi-synthetic cutting fluid. Results indicated that canola oil with 8% EP additive showed better performance than others. Many more nonedible vegetable oils are available across the globe. The utility of applying them as lubricants for various applications may be explored.

Amylum additive is dispersed in vegetable oil at varying percentages. Machining performance is assessed by comparing dry, synthetic cutting fluid, and pure oil for fixed cutting conditions [45]. When compared to dry machining, synthetic fluid, and pure oil-assisted machining, amylum-assisted cutting fluids have resulted in improved machining performance owing to the reduction in cutting temperatures and better lubricity. Hence, it can be comprehended that amylum additive has the potential to be used as an additive in biodegradable oils in view of eco-friendly and user compatible machining operations.

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Del et al. [46] found that the addition of 1 wt% of one of the halogen-free (chlorine) ionic liquid reduces friction and wear of both aluminum disks and ceramic balls with respect to dry or water-lubricated conditions in pin-on-disk tribometer. Many more nonedible vegetable oils are available across the globe. The utility of applying them as lubricants for various applications may be explored.

CONCLUSION

This paper presents the investigations of various researchers with respect to the performance of nonedible oils with the incorporation of nano additives and EP additives. Nonedible oil-based cutting fluids are established to be favorable alternates to mineral oil-based CFs, because of their excellent lubricating properties. The oxidative stability of nonedible oil is limited and has been overcome using various additives and chemical modification processes. Vegetable-based cutting fluids' competitive performance improves product quality by providing better cooling and lubrication by reducing cutting force and thrust force, increasing surface quality, reducing tool wear, and having good heat dissipating ability. Non-edible oils offer a better future in the formulation of lubricants and contribute to sustainable manufacturing processes.

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