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REVIEW OF VEGETABLE NANOLUBRICANTS FOR TRIBOLOGICAL APPLICATIONS

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Abstract: About 40 million tons of lubricants are used every year for various industry purposes and applications, where most of them are petroleum based oils. These oils are difficult and expensive to dispose of, have low biodegradability and are contamination risks. Recent efforts have been focused on reducing the environmental impact of petroleum based lubricants through the use of vegetable oils since they are biodegradable and have good lubricity. A drawback of vegetable oils is their poor thermal stability and oxidation, which causes them to decrease their properties at higher loads. Nanoparticle (NP) additives have been explored for improving the tribological performance of vegetable. This literature review seeks to compare and analise the impact of the different NP types, concentrations and vegetable oil type on the coefficient of friction. The vegetable oils that have shown to provide the best tribological behaviour were coconut oil, sunflower oil, palm sesame oil, canola oil, among others. The NP with the best performance were SiO_2 and CuO and the concentration with the highest improvement was between 0.01-3.0 wt.%. The results of this study provide an insight on the areas of opportunity for developing new lubricant formulations with vegetable oils and NP additives for industrial applications.

Key words: vegetable oils, nanoparticles, coefficient of friction, tribology, nanolubricants

1. INTRODUCTION

Lubricants and cutting fluids are widely used for various industries to reduce contact, friction and wear between moving surfaces. In the past decades, mineral oils and synthetic lubricants employed for these purposes have shown to cause health and environmental issues [1,2]. For these reasons, vegetable lubricants have been explored as substitutes for petroleum-based lubricants [3].

Vegetable lubricants are environmentally friendly, have low toxicity and are renewable. They consist of triglycerides, which are glycerol molecules that have three long chain fatty acid attached to hydroxyl groups and interact with metallic surfaces. These fatty acids may have different chain lengths and number of double bonds [4] and can be saturated (lauric acid, palmitic acid, stearic acid), mono-unsaturated (oleic acid) and poly-unsaturated (linoleic acid, linolenic acid) [5].

Some disadvantages of vegetable lubricants are their low thermal and oxidative stability [6] which are dependent on the content of the unsaturated fatty acids. Furthermore, oxidative stability is reduced under high loads. Nanoparticles (NPs) of various types and geometries have been explored as additives for vegetable lubricants to improve these properties. **Error! Reference source not found.** shows a chart of number of publications with the search topics "vegetable oil" "nanoparticle" and "tribology" over the last 15 years. It can be observed that there is an increased interest in the scientific community regarding the development of nanolubricants of vegetable oils for tribological purposes.

2. VEGETABLE OILS

Commonly used vegetable lubricants reinforced with NPs found in the literature (**Error! Reference source not found.**) are coconut and sunflower oil. This is due to the high content of saturated acids in coconut oil which makes it more resistance to oxidation [7] and in the case of sunflower oil is due to high proportion of oleic acid, a mono-unsaturated fatty acid [5]. Fewer studies can be found with soy bean, rapeseed, palm, sesame, pongamia, jojoba, canola, olive, jatropha, neem, desert date and avocado oil.

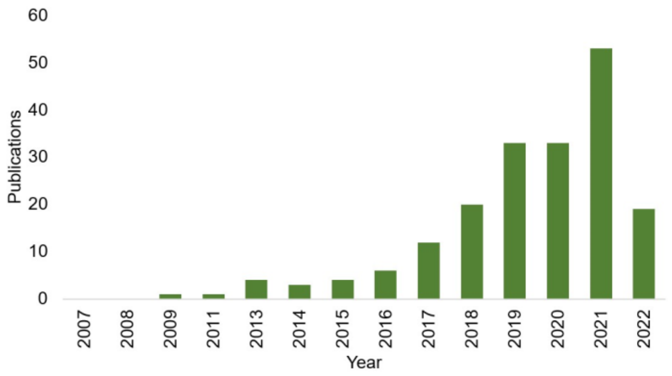

Fig. 1. Number of publications with "vegetable oil" "nanoparticle" and "tribology" as search topics from 2007-2022, according to Sciencedirect.com

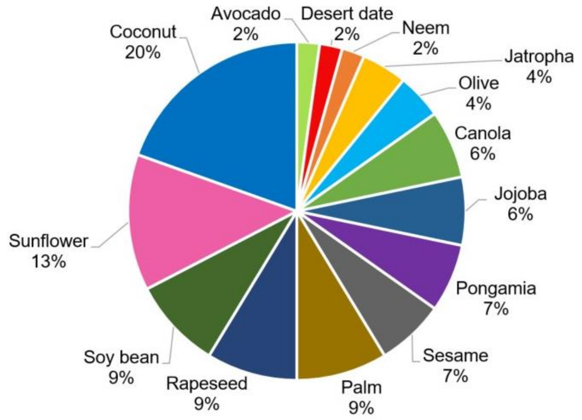

Fig. 1. Common vegetable lubricants used for preparing nanolubricants

2.1 Importance of fatty acids on the tribological performance of vegetable oils

Table 1 shows the fatty acid concentration in common vegetable lubricants. The lipid number of each fatty acid, which indicates the number of carbon atoms followed by the number of double bonds in the fatty acid chain is shown in parenthesis. For each vegetable oil the percentage of saturated, mono-unsaturated and poly-unsaturated fatty acid is presentaed.

The performance of vegetable lubricants is highly dependent on the fatty acid concentrations. Fatty acids adhere to metallic surfaces forming a monolayer that reduces friction between moving surfaces [8]. However, the presence of double bonds in the carbon chains of the triglycerides decrease their thermal-oxidative properties and as explained by Reeves et al. [8], double bonds decrease the density of the fatty acid monolayer.

Also, the monolayer that reduces contact between metallic surfaces is produced by saturated and mono-unsaturated fatty acids. The drawback of the presence of saturated fatty acids in vegetable oils such as stearic acid, lauric acid and palmitic acid is that they are solid at room temperature, whereas oleic mono-unsaturated fatty acids such as oleic acid, and poly-unsaturated fatty acids like linoleic acid are liquid at room temperatures. For example, coconut oil has better thermal and oxidative stability compared to other vegetable oils due to the high concentration of saturated fatty acids (lauric acid) and therefore has a high pour point, limiting its use for low temperature conditions [9,10].

For vegetable oils with unsaturated fatty acids it has been determined that high concentrations of oleic acid (with one double bond]) and low concentrations of linoleic acid (with two double bonds) aid in reducing coefficient of friction (COF).

In a study by Reeves et al. [8] avocado, olive and canola oil have shown the lowest COF values due to the high oleic acid content, whereas sesame oil with lower oleic acid concentration had higher COF values [8].

Table 1. Fatty acid content in vegetable lubricants

	Fatty acids						
	Saturated fatty acids			**Mono-unsaturated fatty acids**	**Poly-unsaturated fatty acids**		
Vegetable oil	**palmitic acid (16:0) (%)**	**lauric acid (12:0) (%)**	**stearic acid (18:0) (%)**	**oleic acid (18:1) (%)**	**linoleic acid (18:2) (%)**	**linolenic acid (18:3) (%)**	**Ref.**
Avocado	14.00-16.00	-	0.80	61.00-67.00	14.00	-	[11]
Canola	4.00	-	1.00	60.00-65.00	20.00	10.00	[12]
Coconut	7.50	51.00	3.00	5.00	1.00	-	[7]
Desert date	13.74	-	13.34	34.35	37.58	0.04	[13]
Jatropha	15.4	-	5.00	24.00	63.00	0.30	[14]
Jojoba	1.59	-	4.14	42.84	31.52	-	[15]
Neem	13.00	-	24.00	62.00	10.00	-	[16]
Olive	13.00		1.50	70.00	15.00	-	[17]
Palm	45.00		8.00	38.00	10.00	0.50	[14]

Pongamia	3.70-14.10	0.10	2.40-10.90	44.50-71.30	10.80-27.10	3.60-6.30	[18]
Rapeseed	4.50		1.5.00	56.00	21.00	10.00	[14]
Sesame	7.9-12.0		4.5-6.7	34.40-45.50	36.9-47.9	-	[19]
Soy bean	10.00		4.00	21.00	56.00	8.00	[14]
Sunflower	6.50		5.00	24.00	63.00	0.30	[14]
High oleic sunflower oil	5.31		3.36	70.83	6.85	-	[20]

3. TRIBOLOGICAL TESTING OF VEGETABLE OILS AND THEIR NANOLUBRICANTS

Table 2 shows the tribological testing conditions for vegetable oils and their nanolubricants. Fig. 2 shows the schematic representation of the most common contatc pairs for determining the tribological performane of vegetable lubricants and their nanolubricants. In order to further stress the lubricant and obtain tribological properties from them, it is observed that researchers prefer to use the 4-ball method or the pin on disk method, together they are more than 50% of the tests reported in the literature, for example Reeves et al. [8] and Shafi et al. [11] both investigated avocado oil with similar pin on disk equipment, Shafi et al. [11] reported abrasive wear traits but primarily scuffing wear, on the other hand Reeves et al. [8] reported a wear mechanism very similar to that reported by Shafi et al. [11], this tells us that the reproducibility in tribological equipment can be reliable if standard methods of measurement of tribological characteristics are followed. As can be seen in Table 3, important reductions in COF and wear are obtained thanks to the action of NPs with very low concentrations of weight % (less than 1.5%), for example, for canola oil Omrani et al. [21] and Sikdar et al. [22] achieved important reductions in the coefficient of friction of up to 84% and both report a scuffing type wear using NPs of GNP which coincides with the ball milled shape. Both used a tribotester with rotary sliding motion such as ball on disk and pin on disk.

Similarly, in efforts to reduce wear, Thottackkad et al. [10] and Cortes et al. [23] achieved significant reductions of up to almost 21% using as oil and CuO NPs with weight percentages of 0.5% and less. In this case, the wear presented abrasive traces (grooves) as a consequence of the hardness and shape of the NPs and the friction pair used, which is block on ring. Although different contact pressures were used, the tribological wear behaviour was similar.

Finally, we can observe in Table 2 that with similar contact pressures in the multiple four ball tests used under the ASTM D4172 method, all the NPs studied significantly reduced the COF and wear, regardless of the type of oil and the type of NP used, which demonstrates the importance of further researching the development of vegetable nanolubricants.

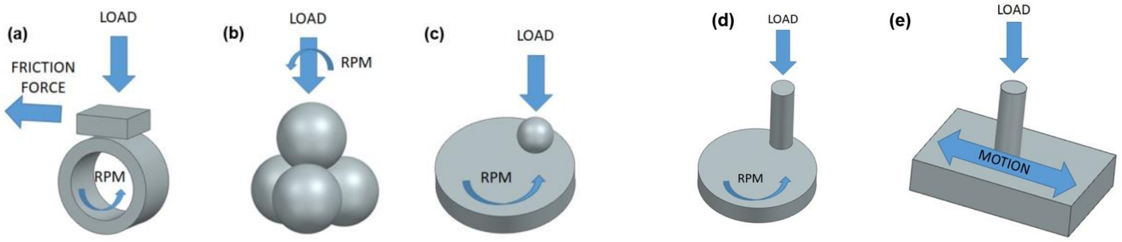

Fig. 2. Contact pairs employed for determining the tribological properties of vegetable oils and their nanolubricants

Table 2. Tribological testing conditions for vegetable lubricants

Contact Pair	Contact Pressure (MPa)/Test	Load (N)	RPM	Vegetable oil	NPs	Materials	Ref.
Ball on disk	134	30	21.5	Canola	GNP, hBN	Al 6061 alloy	[22]
Block on ring	335	400	172	Sunflower	SiO_2, TiO_2	Block: AISI 304 Steel Rings AISI 52100 Steel	[24]
Block on ring	106	40	300	Coconut	SiO_2, CuO	AISI 304 steel	[23]
Disk on Disk	N.A.	Up to 400	570	Mineral base oil	CuO	Zinc plated steel	[25]

Four ball	ASTM D4172	40 kgf	1200	Jatropha oil	hBN	Steel balls, AISI 52-100, 12.7 mm	[26]
Four ball	ASTM D4172	40 kgf	1200	Desert date oil	Cu	Steel balls, AISI 52-100, 12.7 mm	[27]
Four ball	ASTM D4172	40kgf	1200	Palm	TiO_2	Steel balls, AISI 52-100, 12.7 mm	[28]
Four ball	ASTM D4172	40 kgf	1200	Paraffin oil and biolubricant	TiO_2	Steel balls, AISI 52-100, 12.7 mm	[29]
Four ball	ASTM D4172	40 kgf	1200	Pongamia	HNTs	Steel balls, AISI 52-100, 12.7 mm	[30]
Four ball	ASTM D4172	40 kgf	1200	Rapeseed	CuO, CeO_2 nano-PTFE	Steel balls, AISI 52-100, 12.7 mm	[31]
Four ball	ASTM D4172	40 kgf	1200	Sesame oil	CuO, Al_2O_3	Steel balls, AISI 52-100, 12.7 mm	[32]
Four ball	ASTM D4172	40 kgf	1200	Sunflower	Cu	Steel balls, AISI 52-100, 12.7 mm	[33]
Four ball	ASTM 2783	40 kgf (gradual increase)	1770	Palm	CuO, MoS_2	Balls: AISI 52100	[34]
Four ball	ASTM D4172	40 kgf	1200	Sunflower	$B_2O_6Zn_3$	Balls: AISI 52100	[35]
Pin on disk	No data	10	21.5	Avocado, rapeseed, corn, olive, peanut, safflower, sesame, soybean	NA	Disks: 2024 aluminum alloy	[8]
Pin on disk	No data	50	100	Olive	Cu, hBN	EN 31 steel	[17]
Pin on disk	No data	15	1.4 m/s	Coconut	Cu, Ag	EN 31-b, 60 HRC	[36]
Pin on disk	No data			Avocado Oil	Cu	Aluminum alloy 6061	[11]
Pin on disk	No data	40	800	Pongamia	Cu	Al-7%Si alloy and EN31 steel	[37]
Pin on disk	No data	160	600	Jojoba	Al_2O_3	No data	[38]
Pin on disk	No data	20	25 mm/s	Canola	GNP	Disk: Al 2024 Pin: 440C stainless steel	[21]
Pin on disk	No data	40	140	Pongamia	TiO_2	EN31 steel	[39]
Pin on flat (reciprocant)	No data	20	200mm/s	Soybean	MoS_2	Pin: Al_2O_3 Samples: cast iron	[40]
Reciprocating Ring	No data	10	High Frequency	Soybean and Sunflower	ZnO, CuO	Hard steel ball (570-750 HV) in reciprocating movement on a softer steel disk (190–210HV)	[41]
Ring compression test	No data	150 KN	N.A.	Soybean and rapeseed oils	CuO, SiO_2	Ring: hot-rolled AA 1100 Bars: pure copper	[42]
Rolling-sliding	No data	4		Sunflower and Castor	NA	Ball: AISI 52100 Disk: 52100	[3]
Steel–steel ball-on-plates	No data	3	1,000	Vegetable	NA	Steel plates C45E-1.1191, hardness 25–30 HRC	[20]

5. NANOPARTICLE ADDITIVES FOR VEGETABLE OILS

5.1 Nanoparticle types

NP additives can have an important impact in the tribological performance of lubricants. Due to their small size they can infiltrate contacting surfaces and provide a rolling bearing effect, a mending effect, a protective film, among others depending on their shape, size and chemistry [23,43].

Fig. 3 presents the NP types most widely used for preparing vegetable nanolubricants. Ceramic or clay based NPs are the most common, specifically CuO, SiO_2, TiO_2, Al_2O_3, halloysite clay nanotubes (HNTs). Metallic NPs are Ag and Cu, and Carbon-based NPs of multi-walled carbon nanotubes (MWNTs), graphene nanoplatelets (GNPs) have demonstrated promising results. Most of these NPs have a sphere-like geometry with the exception of GNPs with a laminar or flake-like shape, and MWNTs and HNTs, with a tubular shape.

5.2 Tribological mechanisms of nanoparticles for vegetable oils

As stated in the previous sections, the addition of NPs into vegetable oils and lubricating oils in general results in a considerable reduction of the coefficient of friction and an increase in the load-bearing capacity of the tribological systems. Different lubrication mechanisms have been proposed to explain the lubrication improvement of the different vegetable oil-based nanolubricants, including the rolling effect, protective film, mending, polishing effects, and exfoliation as shown in Fig. 5 [43].

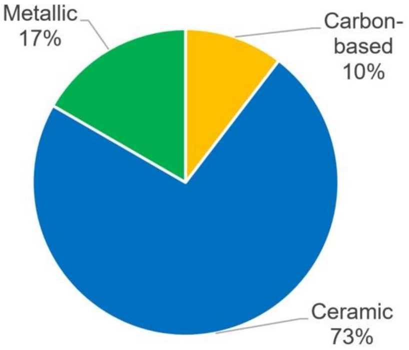

Fig. 3. Nanoparticle types used additives for vegetable lubricants

These mechanisms can be classified into two main categories. The first category is related to the direct effect of the NPs on lubrication improvement, including the rolling and the protective film effects. In the rolling effect (Fig. 5a), also known as the ball-bearing effect, the NPs suspended in the oil act as balls or rollers in rolling-element bearings between the friction surfaces, causing the pure sliding friction changes to sliding-rolling friction [23,24,42,44,45]. On the other hand, in the protective film effect, Fig. 5b, the NPs form a thin protective layer between the friction surfaces, reducing friction and wear. Several authors have reported this lubrication mechanism in vegetable oils modified by the addition of different NPs [11,17,38–41,46,47,21,22,24,26,27,29,33,37]. The other main category is related to the presence of NPs on surface enhancement, including the mending and polishing effects. In the mending effect, Fig. 5c, the NPs will accommodate into the surface cavities or imperfections to compensate for the mass loss [17,36,47]. In the polishing effect, Fig. 5d, the hard NPs act as an abrasive reducing the roughness of the rubbing surfaces, resulting in a decrease in friction [10,21–24,42]. Finally, Laminar-shape NPs such as GNPs and hBN are weakly held together by van de Waals bond, therefore, they exfoliate during friction and the layers are transferred to asperities providing a tribofilm [48] (Fig. 5e).

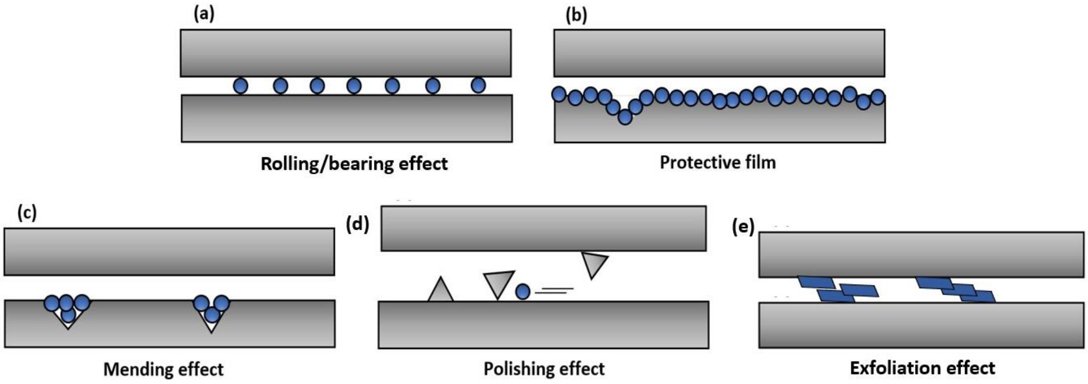

Fig. 4. Commonly reports tribological mechanisms of nanoparticles for reducing friction and wear

6. TRIBOLOGICAL PERFORMANCE OF VEGETABLE NANOLUBRICANTS

NPs have shown to increase the lubricating properties of vegetable oils particularly for boundary lubrication conditions, where thermal oxidation may occur. Table 3 presents various studies found in the literature of vegetable lubricants filled with NP additives and their impact in COF and wear.

For canola oil, GNPs and hBN were able to lower COF by 52% and 40%, respectively [22]. NPs of hBN in jatropha oil also reduced wear by 20.28% [26], whereas in olive oil the enhancement in wear was of 13% [17]. Finally, Danish et al. [46] performed milling experiments on Inconel 718 with a sunflower oil reinforced with graphene which reduced surface roughness by 49% and tool wear by 20%.

Coconut oil, one of the vegetable lubricants with the highest number of studies in the literature has been reinforced with NPs such as CeO_2, Cu, CuO, MoS_2, SiO_2 and MWNTs [10,23,36,47,49–51] with COF and wear reductions of up to ~93% and ~42%, respectively. Interestingly, different studies where CuO NPs were used as an additive obtained similar optimal NP concentrations (0.34 wt.% and 0.5 wt.%) [10,23].

Shafi et al. [11] studied the tribological performance of avocado oil mixed with 0.5 wt.% Cu NPs and found that these NPs formed a physical film between sliding surfaces leading to a decrease in COF by up to 33%. Singh et al. [27] proposed the use of a Cu/desert date oil nanolubricants as an alternative to mineral oil. In this study, nanolubricants with Cu were also able to form a protective film between surfaces which reduced friction and wear.

Jojoba oil with NPs of Al_2O_3 and TiO_2 reduced COF by 14% and 33%, respectively, wear was lowered by 15% and 25%, respectively. In neem oil, SiO_2 NPs provided enhancements of up to 94% in COF. Rapeseed oil reinforced with CuO NPs lowered COF by 26.8% at 0.5 wt.% in a ring compression test, which is a commonly used test for estimating friction in metal-forming processes [42]. However, in another study performed in close contact sliding conditions the optimal content of CuO in rapeseed oil was 0.1 wt.% which reduced COF by ~70%. Therefore, the testing conditions also play an important role in the tribological mechanism that NPs may provide.

Various types of NPs have been explored as additives for sunflower oil, as observed in Table 3. Cortes et al. [24] evaluated the tribological characteristics of this vegetable lubricant with TiO_2 and SiO_2 at different concentrations under sliding conditions. Results showed that COF decreased with SiO_2 and TiO_2 by 77.7% and 93.7%, respectively, and wear volume loss was lowered by 74.1% and 70.1%, respectively. These improvements were attributed to a polishing effect and a protective film effect provided by the NPs. In other studies, NPs may be detrimental for the tribological performance of vegetable lubricants. Trajano et al. [41] synthesized biolubricants of soybean and sunflower by epoxidation reaction and added oxide NPs of ZnO and CuO. Results showed than the addition of NPs did not exhibit wear and friction reductions due to the high affinity of the biolubricant to be adsorbed onto the surfaces which limited the deposition of NPs and instead caused third-body wear.

The concentrations of NPs in vegetable lubricants where the best tribological improvements have been obtained according to the literature range between 0.01-3.0%, being 0.1%, 0.5% and 1.0% the most common. Optimizing the NP concentration in a lubricant is crucial for obtaining enhancements in tribological properties. Furthermore, excessive amounts of NPs may cause agglomeration and therefore these large clusters cannot infiltrate the contact area between surfaces to effectively reduce friction and wear [25]. However, the optimal concentration of NPs depends on the typo of NPs being use, chemistry, shape, size, compatibility and type of vegetable oil, testing conditions, among others. Therefore, these parameters should be taken into account when designing the experiments.

Table 3. Vegetable lubricants with nanoparticle additives and the impact on COF and wear reductions

Lubricant	**NP**	**Concentration (%)**	**COF reduction (%)**	**Wear reduction (%)**	**Ref.**
Avocado	Cu	0.50	33.00	40.00	[11]
Canola	GNPs	0.30	84.00	-	[21]
Canola	GNPs	1.50	52.00	85.00	[22]
Canola	hBN	1.00	40.00	40.00	[22]
Coconut	Ag	0.25	20.00	-	[36]
Coconut	CeO_2	0.51	-	17.00	[49]
Coconut	CeO_2-ZrO_2	0.50	34.69	7.98	[50]
Coconut	Cu	0.25	50.00	-	[36]
Coconut	CuO	0.34	7.70	13.00	[10]
Coconut	CuO	0.50	93.25	26.00	[23]
Coconut	MoS_2	0.50	52.17	12.75	[47]
Coconut	MWNTs	3.00	33.33	41.82	[51]
Coconut	SiO_2	1.25	93.75	37.03	[23]
Desert date	Cu	0.90	18.75	17.98	[27]
Jatropha	hBN	0.05	-	20.28	[26]
Jojoba	Al_2O_3	0.10	13.83	15.39	[38]
Jojoba	TiO_2	0.30	33.00	25.00	[44]
Neem	SiO_2	0.30	24.00	25.00	[45]
Olive	Cu	0.50	20.77	3.97	[17]
Olive	h-BN	0.50	16.02	13.23	[17]
Palm	CuO	1.00	-	6.00	[34]
Palm	MoS_2	1.00	-	55.00	[34]
Palm	TiO_2	0.10	9.09	11.11	[28]
Palm	TiO_2	0.10	15.00	-	[29]
Pongamia	Cu	0.075	26.19	42.11	[37]
Pongamia	HNTs	1.50	14.30	10.64	[30]
Pongamia	TiO_2	0.10	71.40	28.60	[39]

Rapeseed	CeO_2	0.10	74.24	16.72	[31]
Rapeseed	CuO	0.10	69.70	9.84	[31]
Rapeseed	CuO	0.50	26.80	-	[42]
Rapeseed	SiO_2	0.50	21.57	-	[42]
Sesame	Al_2O_3	0.20	-	20.00	[32]
Sesame	Cu	0.20	-	25.00	[32]
Sesame	SiO_2	0.85	18.76	18.14	[52]
Soy bean	CuO	0.70	26.71	-	[42]
Soy bean	MoS_2	20.0	22.00	-	[40]
Soy bean	SiO_2	0.50	23.60	-	[42]
Soy bean	ZnO	0.50	-10.00	-16.67	[41]
Sunflower	$B_2O_6Zn_3$	0.5	13.00		[35]
Sunflower	Cu	0.01	0.067	30.40	[33]
Sunflower	CuO	0.50	-26.00	-14.28	[41]
Sunflower	Graphene	0.70	-	20.00	[46]
Sunflower	SiO_2	1.25	77.70	74.10	[24]
Sunflower	TiO_2	1.00	93.70	70.10	[24]
Sunflower	ZnO	0.50	-20.00	-25.00	[41]

7. VEGETABLE NANOLUBRICANTS FOR MANUFACTURING PROCESSES

Several approaches can be found in the literature done to move from the laboratory experiments with standardized tribotesters to actual manufacturing processes. Table 4 shows some manufacturing processes where vegetable oil nanolubricants have employed and the impact of cutting forces, feed forces, surface finish, tool life, among others. It can be observed that MoS_2 [53–57] and graphene [46,58] NPs have been explored by several groups due to their tribological enhancements.

Foro machining processes, for example, Gajrani et al. [55] prepared minimum quantity lubrication (MQL) with hybrid nano-green cutting fluids with 0.3% of CaF2 and MoS_2 NPs for hard machining of hardened AISI H13 tool steel with tungsten carbide inserts. Lower cutting and feed forces, as well as reductions in COF and improved surface finish were obtained with MoS_2. Similarly, Danish et al. [46] performed hard machining of Inconel 718 with MQL graphene/sunflower lubricants with important reductions in surface roughness, cutting forces, cutting temperature and tool wear compared to dry machining experiments. Also, lower tool wear was observed for milling of Inconel 625 and 304 stainless steel with a MWNT/soybean nanolubricants [59].

With respect to grinding operations, Dambatta et al. [60] analysed the effect on the specific normal force, specific tangential force and surface quality for grinding Al6061-T6 with a canola oil reinforced with SiO_2 NPs, through MQL [46]. Jia, et al. [53] lowered specific energy and surface roughness of a Ni-based alloy with MoS_2/soybean-castor oil nanofluids.

Turning of AISI 1040 through MQL with MoS_2 dispersed into coconut oil lowered cutting forces, temperature, tool wear and surface roughness, compared to dry machining [56], and in another study by this group [59] with the same nanolubricants improvements in cutting force, cutting temperatures, tool flank wear and surface roughness were obtained.

Drilling of Al6063 aluminium alloy with Al_2O_3/soybean through MQL improved tool wear and number and quality of the holes compared to a commercially available water soluble oil.

Most of the studies found in the literature provide lubrication through MQL, over wet machining. This approach can also help reduce the lubrication costs. Therefore, vegetable oil nanolubricants have a high potential to be used as green lubricants for large scale industrial processes.

Table 4. Vegetable nanolubricants in manufacturing processes

Manufacturing process	**Vegetable oil**	**NP**	**Concentration (%)**	**Workpiece material**	**Results**	**Ref.**
Ball milling	Vegetable oil	graphene	0.1	AISI 1045 steel	better performance for central wear and chipping at cutting edge	[61]
Drilling	Soybean	Al_2O_3	1.5	Al6063	Increased number of drilled holes and reduced the drilling torques and thrust forces, eliminated chips and burrs and increased tool life	[62]
Grinding	Canola	SiO_2	6.0	Al6061-T6	lower specific grinding forces, reduction in the surface roughness of	[60]

					the workpiece	
Grinding	Soybean/ castor	MoS_2	8.0	Ni-based alloy GH4169 with	Lower force ratio, specific energy and average grinding temperatures	[53]
Grinding	Soybean Palm Rapeseed	MoS_2	6.0	45 steel	Best lubrication and heat transfer performance with soybean and MoS_2	[54]
Grinding	Canola	GNPs	1.5	Ti6Al4V	-16.9% surface roughness -22.10% grinding force -33.83% specific grinding energy -15.10% coefficient-of-friction	[58]
Hard machining	Coconut	MoS_2	0.3	AISI H13 tool steel	-17% cutting force -28% feed force -11% tool-chip interface COF -37% surface roughness.	[55]
Hard machining	Sunflower	graphene	0.7	Inconel 718	-49% surface roughness -25% cutting forces -31% cutting temperature -20% tool wear	[46]
Milling	Soybean	MWNTs	1.0	Inconel 625 304 stainless steel	Lower tool flank wear	[59]
Turning	Coconut Sesame Canola	MoS_2	0.5	AISI 1040 steel	-39% surface roughness -37% cutting forces -21% cutting temperature -44% tool wear with coconut oil and MoS_2	[56]
Turning	Coconut Sesame Canola	MoS_2	0.5	AISI 1040 steel	Improvements in cutting force, cutting temperatures, tool flank wear and surface roughness with coconut oil and MoS_2	[57]
Turning	Coconut	50 % CuO and 50% Al_2O_3	0.1, 0.3, 0.5	AISI 1018 steel	Improved surface roughness	[63]

8. CONCLUSIONS

In this study, a literature review on vegetable nanolubricants was carried out with emphasis on the type of NPs, concentrations and vegetable oils most widely studied, as well as tribotesting, tribological mechanisms of NPs and the application in manufacturing processes. It was found that the number of publications on this topic has considerably increased on the last 15 years due to the higher interest on the development of environmentally friendly, biodegradable and renewable lubricants and cutting fluids for various industrial applications.

The most widely used NPs for vegetable lubricants in laboratory tests were oxides, particularly SiO_2 and CuO due to the enhancements obtained in tribocharacteristics. Commonly used contact pairs for determining the tribological properties of vegetable nanolubricants were block on ring, four ball and pin on disk.

Optimal NP concentration varied according to the type of NP, vegetable lubricant and testing conditions, with 0.1, 0.5 and 1.0 wt.% being the most commonly used for the highest improvement in tribocharacteristics. The vegetable lubricants with the most studies were coconut oil and sunflower oil because of the content of saturated and mono-unsaturated fatty acids, which can provide a monolayer that adheres to metallic surfaces. NPs may be detrimental to the tribological performance of vegetable lubricants depending on the chemical modification of the lubricants or due to high NP concentrations which tend to agglomerate so they are not able to infiltrate contacting surfaces.

Finally, many studies can be found were vegetable nanolubricants were employed for manufacturing processes such as milling, turning, grinding, drilling among others. The improvements found in these studies show the potential of replacing conventional petroleum based lubricants with greener options such as vegetable nanolubricants.

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