Asian Journal of Chemistry;   Vol. 33, No. 12 (2021), 2885-2895

ASIAN JOURNAL OF CHEMISTRY

https://doi.org/10.14233/ajchem.2021.23450

REVIEW

Castor Oil-Based Nanolubricants: An Overview

JYOTI SRIVASTAVA[1,2,*], TANDRA NANDI[1] and RAKESH K. TRIVEDI[2]

[1]Defence Materials and Stores Research and Development Establishment, Kanpur-208013, India
[2]Department of Oil Technology, Harcourt Butler Technical University, Kanpur-208002, India

*Corresponding author: E-mail: jyotisri69@rediffmail.com

Received: 30 July 2021;   *Accepted*: 15 September 2021;   *Published online*: 6 December 2021;   AJC-20578

Vegetable oils are very effective, economic and appealing option as compared to conventional lubricants due to their environment-friendly nature, sustainable behaviour and biodegradability. Castor oil, one of the promising non-edible vegetable oils with nanoparticle additives has the potential to serve as base lubricating oil. The benefit of using nanoparticles in base oils is their small size, which works as a roller on contacting surfaces and results in reducing the wear and friction more efficiently. The present review paper has been structured as follows. The first part of this technical article is designed to give a brief about vegetable oils as a lubricant with special reference to castor oil. The second part of the review paper describes the effects of nanoparticles especially molybdenum disulfide (MoS_2) in different lubricating oils, especially in castor oil. Finally, the applications of nanolubricants and their future prospects are also discussed.

Keywords: Castor oil, Vegetable oil, Nanolubricant.

INTRODUCTION

Vegetable oils are the mixtures of triglyceride. Its origin lies in trees. Oilseeds, nuts, grains, cereals, fruits are the source of it. Our country has great potential for producing edible and non-edible tree-borne oils that can serve both purposes, environment friendliness and technological performance. Vegetable oils have low volatility, high viscosity index, good lubricity and an environmentally friendly nature. So much importance has been given to the use of vegetable oil-based lubricants because they have a perspective to replace mineral oil in various industrial and transportation applications [1,2]. It is a renewable resource and can be opted as a base oil [3-7]. The polar groups and long-chain fatty acids present in vegetable oil make it amphiphilic and provide a better film/force interconnection [8-10] that helps in minimizing friction and wear. Plant oils biodegrade more easily than mineral oils because of their glyceride fatty acids. Vegetable oil-based lubricants are efficient in both boundary and hydrodynamic regimes [2,9,11]. Table-1 shows different types of vegetable oils, their origin and application as different types of lubricants. These oils are found almost in every field of technological activity and are used for multiple purposes.

TABLE-1
TYPES OF VEGETABLE OILS AND
THEIR APPLICATION AS LUBRICANTS

Vegetable oil	Origin	Application	Ref.
Canola	Seed	Hydraulic oil,	[12]
Coconut	Kernel	Gas Engine oil	[13]
Palm	Fruit pulp	Engine oil	[14]
Rapeseed	Seed	Transmission/Hydraulic	[15]
Olive oil	Ripen fruit	Automotive lubricant	[16]
Sunflower	Seed	Diesel fuel substitute	[17]
Castor	Seed	Gear lubricants	[10]
Cottonseed	Seed	Hydraulic fluid	[18]
Soybean oil	Seed	Hydraulic fluid	[19]
Jatropha	Seed	Hydraulic oil	[20]

The objective is to reduce the environmental damage along with meeting the requirements of the market and governmental laws. Amongst vegetable oils, castor oil is unique due to the hydroxyl group of ricinoleic acid, which makes it a natural polyol. It also provides oxidative stability to the oil with enhanced shelf life compared to other vegetable oils by preventing peroxide formation.

Being a non-edible oil, it is more suitable for industrial applications as compared to other competent vegetable oils. Nanotechnology can be effectively used for enhancing the performance of lubricant oils by the use of nano-additives. These additives in lubricant oils can increase the antifriction, anti-wear and extreme pressure properties to fulfill the industry needs. Common lubricant additives are generally micron-sized layered compounds like graphite, MoS_2 and WS_2 [21]. Their layers slide over each other to reduce friction, but these layered compounds have several drawbacks. The extremity of these layered compounds is chemically responsive causing them to slowly disintegrate. This may result in breaking a portion of it and binding it to the metal surface. Another aspect is their relative larger size, which prevents them from entering the pores of metal parts. They accumulate and stick on the surface where they were meant to lubricate. These aspects ultimately reduce their lubricating ability causing the metal components to grind against each other and wear down. Thus, there is a need for smaller more stable nano solid lubricants and the phenomena for applying these nanoparticles into nanolubrication. The thermal, optical, mechanical, electric and magnetic properties of the nanomaterials are far superior to those of micron-sized materials therefore nanoparticles have drawn considerable attention from material scientists and engineers alike. Nanoparticle dispersion in the liquid may cause huge enhancement or a total change in the existing properties of the base fluid.

Choi was the first to introduce the concept of nanofluids in the year 1995 [22]. A typical nanofluid is formed with a very low concentration (< 1% by volume) of nanoparticles and may or may not contain surfactants or other dispersing chemicals. There are several terminologies used like heat transfer fluids, ferrofluids and nanolubricating fluids, *etc*. The criticality in the field of nanofluids is not only to produce nanoparticles of small enough size but also to make uniform dispersion for longer periods without agglomeration. In the era of miniaturization nanotechnology, nanolubricants can play an important role. It is evident from the literature that tribological properties of various nanoparticle-based vegetable oils showed a reduction in friction and wear property [23,24]. This review, therefore, highlights the potential of castor oil in nanolubricant formulation. It also gives the basic information of castor oil, its properties and uses as nanolubricants with different nano additives especially molybdenum disulfide (MoS_2) nanoparticle and their application in the field of lubricant industry.

Base oil: All lubricant formulations comprise base oil and additives. Normally, lubricants consist of 90% base oil and 10% additives. Mineral oil and synthetic oils from petrochemicals are mainly used as a base oil in the present lubricant industry. As discussed previously vegetable oils have several advantages like availability in abundance, economical, biodegradable and less toxic. Castor oil is a strong candidate for its utilization as a bio lubricant because of its biological root and is non-edible. Another advantage of castor is that its growing period is much shorter than that of Jatropha and Pongamia. Being an annual crop gives the farmers the ability to shift away easily depending on market conditions.

Castor oil: It is a natural oil obtained from the seeds of the castor beans by two methods cold pressing and hot pressing. Cold pressing is employed for medicinal use and hot pressing for industrial applications. It is pale yellowish oil. Ricinoileic acid is a major acid (90%) present in castor oil, which differentiates it from other vegetable oils. Castor (*Ricinus cummunis*) is also acknowledged as the "Palm of Christ". Being a member of the Euphorbiaceae family it is mainly found in India, Eastern Africa and the south-eastern Mediterranean basin. Castor oil has already been practiced in carts and Persian wheels as a lubricant. Castor is known for its long shelf-life and assured good returns due to multiple industrial applications.

Castor seed cultivation and production: An important non-edible castor oil is extracted from castor beans, which contain about 44-48% of oil [25]. The global production of castor oil is about 1.8 million tons per annum [26]. India, Brazil and China have been the main producing countries, fulfilling global demand. Thirty different countries cultivated castor on a commercial scale, of which the USSR, Thailand, Ethiopia and The Philippines are other major countries. Crop of this non-edible oilseed is cultivated around the world. Although the crop is perennial but grown as annual taking economic considerations. Arid and semi-arid regions of the world are suitable places for its cultivation. The cropping period is 4-5 months. In India, July-August is the best time for seed sowing and harvesting starts around December-January. According to the latest Agriwatch survey, in 2018-19 India produced 1.082 million tonnes of castor seed but in 2019-20 there was an 88% hike and castor seed production increased to 2.036 million tonnes. Agriwatch survey estimates castor acreage to stand at 770,150 hectares in 2019-20. Further, using remote sensing techniques, the castor acreage for the state is estimated at 753,660 hectares for 2019-20. This is despite the locust attack in December 2019, which caused serious damage to the crop. The major reasons for the increase in acreage this year are higher returns to the farmers in the seed last season and good seasonal rainfall this year in all growing districts, Agriwatch stated [27].

Chemical composition of castor oil: Oil has 90% ricinoleic acid, which is monounsaturated, 18-carbons fatty acid, Fig. 1 shows the castor seed, castor oil and the structure of this unique acid. In its structure, the acid group at first carbon, the double bond between nine and tenth carbon followed by a hydroxyl functional group at twelfth carbon are present. This hydroxyl group makes the oil functional and valuable as a chemical feedstock [9]. The fatty acid composition of the oil showed that ricinoleic acid comprised almost 90% of the total fatty acid composition. Other fatty acids present are linoleic acid (4.0%), stearic acid (1.0%), palmitic acid (1.0%), dihydrostearic acid (0.6%), oleic acid (3.0%) and linolenic acid (0.2%) and eicosanoic acid (0.2). Sometimes the difference in climatic conditions might affect the ricinoleic acid of castor accessions. It is the only commercially available source of a hydroxylated fatty acid, due to, which it has global importance in chemical industries. The presence of the hydroxyl group in castor oil provides a functional group location for performing a variety of chemical reactions including halogenation, dehydration,

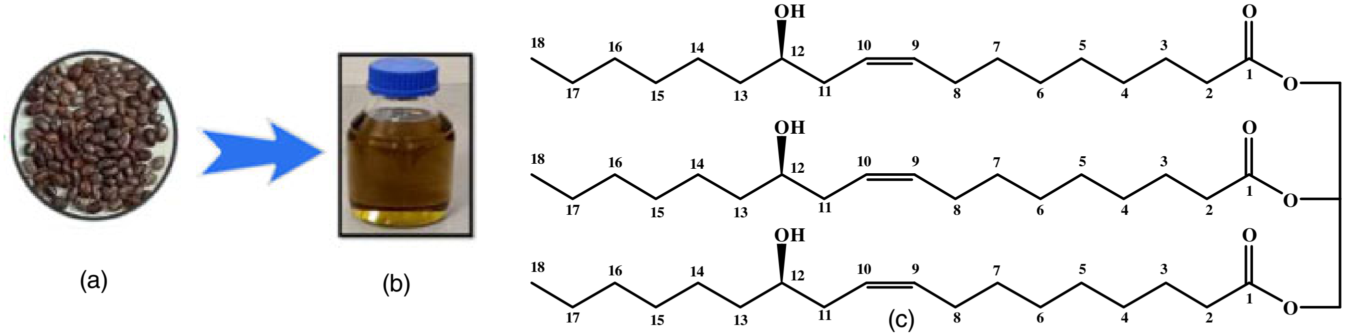


Fig. 1. (a) Castor seed, (b) castor oil and (c) ricinoleic acid, the main fatty acid of castor oil

alkoxylation, esterification and sulfation. As a result, this unique functionality allows castor oil and its derivatives in manifold applications in lubricants, paints, inks and additives, textile chemicals, agriculture, rubber and plastic, cosmetics, food, paper and pharmaceutical and electronics and telecommunications sectors. The physico-chemical characteristics of castor oil and its advantages as a lubricant have been shown in Table-2.

Density plays an essential role in lubricant functioning and performance. From Table-2, it is evident that the castor oil density range is advantageous in high bearing load. The higher viscosity of oil is owing to the hydroxyl group in hydrogen bonding. Moisture content estimates the quantity of water in the oil and it mainly affects the shelf life of the oil. The increase in moisture content is due to poor storage conditions and relative humidity that's why sometimes its value in castor oil may be higher side. The difference in the acid value of castor oil can be attributed to the quality of the oil and factors such as immature seeds and poor storage conditions. The iodine value calculates the unsaturation of the oil indicator of better thermo-oxidative stability. The high percentage of ricinoleic acid (unsaturated fatty acid) in castor oil keeps it liquid even at low temperatures and the higher value of flash point means that the oil is less flammable, safer to handle or transport at temperatures below 250 ºC and makes it beneficial in the high-temperature application, which will be useful in the vehicle engine and gearbox lubricant [10]. Its industrial application and comparison with other oils have been published from time to time. It has been found that some important properties like viscosity, thermal conductivity and pour point for castor oil were higher than the values of a standard lubricant (SAE 40 engine oil) [36]. Castor oil is superior to mineral oil in many aspects, especially lower volatility, higher viscosity index, better lubricity and fire resistance. Hence, a good option to use as a base oil in biodegradable lubricants [11]. Besides, its application as a base stock for environmentally friendly lubricants in grinding [37], high-speed turning [38] and precision turning [39] has also been reported. It has higher specific gravity and a viscosity of a magnitude far greater than that of any other known untreated oil. These remarkable properties have pointed to its use as a lubricant successfully, mainly in bearings carrying heavy loads. Castor oil is pale yellow, viscous, nonvolatile and nondrying [40]. Naranpanawe *et al.* [41] studied mineral oil replacement with castor along with coconut and sesame oil for transformer liquid insulation. Suhane *et al.* [42] investigated castor oil-based lubricant for automotive applications in comparison to available commercial servo gear oil. Talkit *et al.* [43] found in their work that higher viscosity and a lower acid value of castor

TABLE-2
PHYSICO-CHEMICAL CHARACTERISTICS OF CASTOR OIL

Properties (units)	Values	Advantageous as lubricant	Ref.
Density (Kg/m^3)	964-993	A higher density is beneficial to use lubricant successfully, mainly in bearings carrying heavy loads.	[25,28]
Kinematic viscosity (cst)		These remarkable properties have pointed to its use as a lubricant successfully, mainly in bearings carrying heavy loads	[29,30]
@ 40 °C	220.6-225.7		
@100 °C	18.5-19.72		
Viscosity index	102	The optimum viscosity index refers to more stable oil viscosity over a broad temperature range.	[29]
Moisture content (%)	0.2-3.9	Low moisture content is an indication of good shelf-life characteristics of the lubricant.	[31,32]
Acid value (mg KOH g^{-1})	0.03-4.9	Lower values of acid value are favourable regarding the storage and quality of the oil.	[31,32]
Iodine value (mg g^{-1})	87-93.5	Lower iodine value referred to good oxidative stability.	[29,33]
Hydroxyl value (mg KOH g^{-1})	164.5	Higher additive solubility power, due to polarity and the hydroxyl groups	[34]
Thermal conductivity (W/m °C)	4.72	Good heat transfer characteristics	[35]
Flash point (°C)	205-250	High flash point ensures more safety in the handling and storage.	[28,29]
Pour point (°C)	<-27	Low pour point characteristics help easier handling of lubricant in cold weather conditions and by structural modification of castor oil, it can be decreased further up to –40 °C	[29]

oil blends in soybean oil found direct use as an alter-native lubricant for mineral oil-based lubricants and Delgado *et al.* [44] used ethyl cellulose additives in it and observed a significant increase in anti-wear property. Pathmasiri *et al.* [45] used it in enhancing the viscosity of palm oil. Castor oil along with palm oil is used as a biolubricant for applications in industry. Singh [46] found that the castor oil pertaining lubricant as a smoke pollution reducer. He has taken a biodegradable two-stroke (2T) lubricating oil used generally in the engines of scooters and motorcycles. He developed lubricant, having tolyl monoesters and additives. Their performance results showed a smoke reduction by 50-70% at a 1% oil-fuel ratio. Shrirame *et al.* [47] analyzed the benefits of this as compared to non-edible Jatropha and Pongamia oils regarding the growing period. This growing time is shortest with castor, making conditions favourable to farmers about its cultivation and market condition. García *et al.* [48] stated that castor oil as a valuable non-edible source for lubricants due to easy derivatization. Karupannasamy & Ruthuraraj [49] concluded that castor oil emulsion gave better lubrication properties as compared to palm, mahua and mineral oil emulsions in machining. The study has also been conducted to evaluate the performance of 60NiTi bearings with castor oil lubrication in comparison to mineral oils [50]. It showed castor oil-lubricated NiTi-steel contacts exhibited superlubricity, the lesser value of friction coefficient, 0.01 has been obtained under similar conditions. The purpose behind this is to explore castor oil as a "green" lubricant. Castor oil exhibits better antifriction, load-carrying capacity and similar wear performance than commer-cial oil with suitable anti-wear agents [51].

Nanoparticles: These are the particles with a range between 1 and 100 nm in size and also called ultrafine particles. Nanoparticles are of significant importance as they emerged as novel functional material between bulk materials and atomic or molecular level materials [52]. Nanoparticles are often of varied shapes and sizes like spherical, cylindrical, triangles, diagonal, round, cubic, pyramid, *etc*. They are often classified as 1D, 2D or 3D based on dimensions [53]. Spherical particles with the lowest surface for a given volume are thermodynamically more stable than other geometrical shapes. Spherical nanosphere can roll one over another, like miniature ball bearings. These nanomaterials have shown some potentiality in reducing friction and enhancing protection against wear when incorporated fully lubricant formulations. The main problem with micron-sized particles is the rapid settling of particles, in contrast, nanoparticles remain in suspension almost indefinitely and act uniformly in solution, dramatically reducing erosion and clogging. These nanoparticles-based lubricants are attractive for several applications like that of coolant [54,55] and magnetic dampers [56]. A variety of nanomaterials, like molybdenum disulfide, tungsten disulfide, boron nitride, copper nanoparticles, *etc*. has been used as suspension fluids for vibration damping while graphene is utilized in car fluids. Dai *et al*. [57] reviewed the effects of nanoparticles on oil lubrication using statistical methods. It is also stated that the morphology of nanoparticles plays an important role in lubrication.

Molybdenum disulfide (MoS_2): Molybdenum disulfides have drawn attention among researchers due to their extensive applications as catalysts and lubricants [58]. Molybdenum disulfide (MoS_2) is a transition metal dichalcogenide layered compound, having hexagonal arranged structure having S-Mo-S sheets arranged one above the other by weak van der Waals interactions. The layered structure shows smooth sliding contact resulting in low wear and coefficient of friction property for its use as a lubricant [59]. The applicability of MoS_2 can further be exploited by decreasing the size of MoS_2 crystals, which will also improve the lubrication properties in bearing and other heavy-wear applications and will promote the further development of nanolubricants [60]. Table-3 shows the literature summary of the majorly reported synthesis methods for MoS_2 nanoparticles, which can be used in nanolubricant formulations. Using these methods different morphologies of nanoparticles in range (4-150 nm) can be obtained.

Characteristics of nanoparticles: Being tiniest, nanoparticle results in more effective lubrication as it goes into pores of mechanical parts. The spherical structure of nanoparticles facilitates friction reduction more due to the rolling mechanism than the sliding mechanism of the common layered compound. Their nanometer scale enables them to find their way into minute places and reduces their agglomeration, resulting in increased coverage even on the surface. Many types of nanoparticles are available that can work as lubricant additives. They can be metal nanoparticles, carbon nanoparticles, polymer nanoparticles and metal chalcogenides. As nanoparticles have

TABLE-3
DIFFERENT METHODS FOR MoS_2 NANOPARTICLES (NP) SYNTHESIS

Method	Particle size (nm)	Type	Ref.
Sonochemical synthesis	15	Nanoparticle	[61]
Wet chemical synthesis	50	Nanoparticle	[62]
Solvothermal synthesis	10-50	Nanosheets and nanoflowers	[63]
Hydrothermal	40-70	Spherical and lamellar hollow multilayer (7-9 layers) nanoparticle	[64]
Chemical vapour deposition method	632	NP with fullerene-like (IF-MoS_2)	[65]
Ball milling (mechanical activation)	100	Nano flakes	[66]
Catalyzed thermal decomposition	10-25	Multi-walled MoS_2 nanotubes	[67]
Chemically synthetic method	Diameter: 20-40 length: 50-150	Nanorods	[68]
Hydrothermal	Diameter: 4 lengths of 50	Nanowire	[69]
Reverse microemulsion	20-60	Chain-like MoS_2 assemblies consisting of hexagonal MoS_2 nanoparticle	[70]
Wet chemical	< 5	Nanoparticle	[71]

a higher surface to volume ratio compared with bigger particles, their addition in base oils is expected to enhance tribological properties like antiwear, antifriction and load-carrying capacity between tribosystems.

Preparation of nanolubricant from nanoparticles: When nanoparticles are put in different base oils, they upgraded the tribological performance of base oils. The following techniques are generally employed for making stable nanolubricant.

One-step method: This single-step process involves the producing and dispersing particles altogether in a base oil. The idea is to make a stable formulation and minimize agglomeration of nanoparticles and avoid multistep processing of nanoparticles. The particles are uniformly and stably suspended in the base fluid. The drawback of the method is not scalable and cost-effective. Eastman *et al*. [72] used a single-step method for the preparation of Cu/ethylene glycol nanofluids.

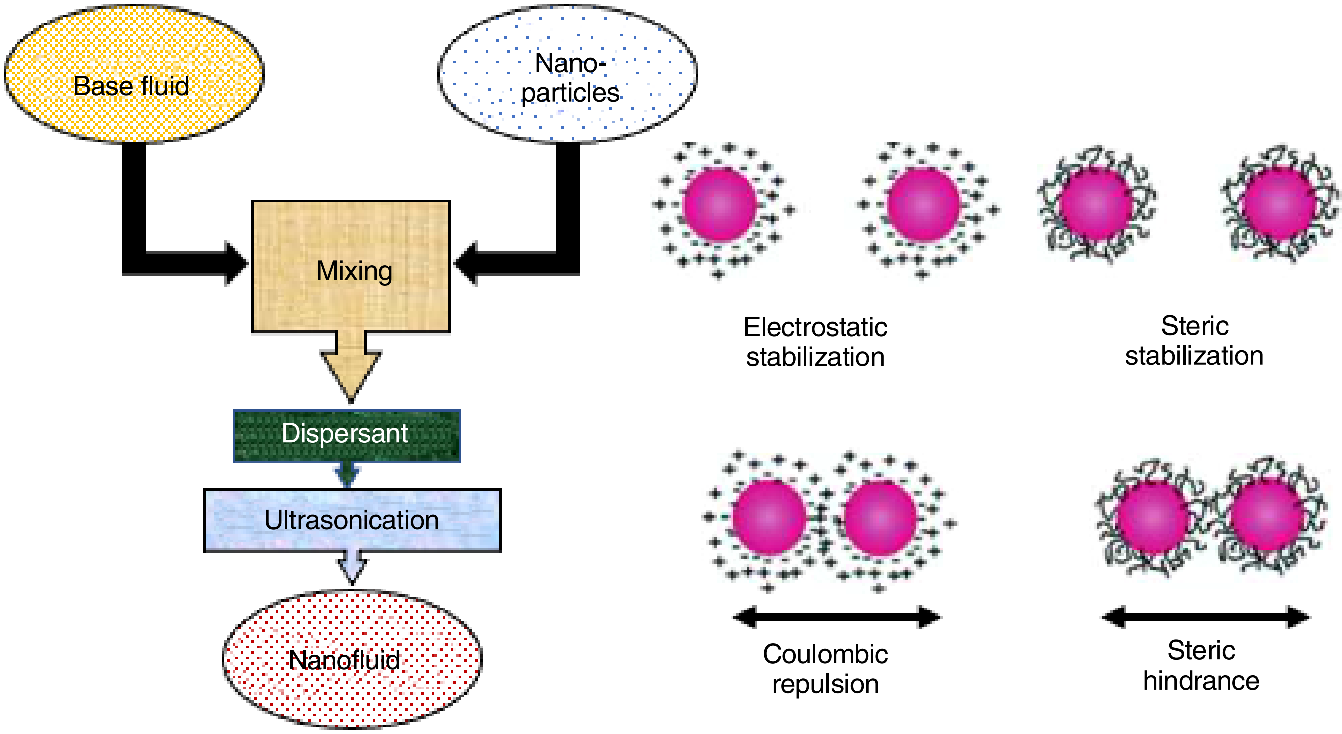
Two-step method: In this method, initially a nanoparticle is made afterward dispersed into a base fluid. The significant factor for making a stable dispersion is given by the Stokes-Einstein equation [73], which gives the rate of particle sedimentation as:

$$v = 2rp\left|\rho p - \rho f\right|\frac{g}{9\eta f}$$

This shows the way to stable particle dispersion is a small particle radius (rp) and a small density difference (ρp-ρf) between that of the particle and the base fluid and a high fluid viscosity (ηf). Other parameters like particle surface charge, energy input, the quantity of surfactants and the chemical or rheological properties of the base fluid also play a key role. A successful dispersing technique should be able to prevent primary particles from aggregating into larger ones or to make larger particles disintegrate into smaller ones. Researchers use, either physical or chemical methods to disperse nanoparticles into a fluid [74]. Fig. 2a describes the flow diagram with the steps involved in its formulation.

Physical methods: Two types of commonly used physical methods are generally adopted: Mechanical and ultrasonic dispersion. There are several techniques for mechanical dispersion like high shear mixing using a high-speed mixer, homogenizer, microfluidizer and colloid mill. Ultrasonication is also used for making stable dispersions. Ultrasonic is mechanical energy that propagates through a liquid medium in the form of elastic waves. These vibrations generate cavitation, which agitates the dispersion and breaks the agglomerates. Chemical methods are used as an aid to physical methods. To control this, the energy barrier around the particle should be more than the thermal energy kT, for the particles to repel each other and remain dispersed.

Stabilization methods: Two methods for nanolubricant stabilization are generally practiced, namely electrostatic and steric. In electrostatic stabilization, static charges of ample magnitude are spread over the surface of suspended particles so that they repel one another and remain in dispersed conditions. The electrostatic stabilization is based on the DLVO theory [75,76]. The concentration for stabilization should be optimum, the uncontrolled electrolyte may cause agglomeration. The pH value may also affect electrostatic repulsion. The addition of acid or alkali may also cause the formation of finely dispersed nanoparticles. Steric repulsion checks the nanoparticles from



(a) (b)

Fig. 2. (a) Flow chart of nanofluid formulation, (b) Nanolubricants stabilization method

coming close enough to coalesce and precipitate. Dispersants such as surfactants, polymers, *etc*. are employed for this. The stability due to steric depends on polymer temperature, concentration, solubility and average chain length of the polymer. The two-step process is used widely for the preparation of nanofluids. Various researchers have used dispersed copper and aluminum oxide (Al_2O_3) nanoparticles in base fluids like water, ethylene glycol, *etc.* with or without ultrasonication [77-79]. Nanotube based emulsions were produced by the two-step method [80]. Fig. 2b represents these two methods of stabilization.

Different nanoparticles in different base oils: Many workers studied on the effect of different types of nanoparticles in different types of base oils from time to time. Some used single nanoparticles while others added a combination of different nanoparticles in base oils. Table-4 shows the nanolubricant compositions using various types of base oils like mineral, synthetic and vegetable oils with various nanoparticles like tungsten di sulfide (WS_2), iron, copper oxide, boron nitride (h-BN) and Al_2O_3, *etc*.

Enhancement in tribological properties was reported by many researchers [83-85]. Some cases showed an increase in thermal properties [89,100,103] and some reported improve-

TABLE-4
NANOLUBRICANTS COMPOSITIONS USING DIFFERENT BASE OILS AND NANOPARTICLES

	Base oils	Nano additives	Inference	Ref.
Mineral-based oils	Mineral oil	MWCNT	The nanolubricant containing MWCNT dispersed with surfactant caused the minimum wear and lowest frictional force.	[81]
	Shell helix ultra motor oil and Great wall motor oil.	WS_2	Tungsten disulfide motor oil has better antiwear, antifriction and extreme pressure properties than base motor oils.	[82]
	Mineral oil	Fe, Cu and Co	A significant reduction in COF and wear is achieved in all three nanoparticles with the best result with Cu nanoparticles.	[83]
	SAE 30 (LB51151) and SAE 30 (LB 511 63-11)	CuO, TiO_2 and diamond	The tribological properties of the mentioned lubricating oils with CuO, TiO_2 and Nano-Diamond nanoparticles were examined. The experimental results exhibit CuO based nanolubricants that perform good antifriction and anti-wear properties.	[84]
	SAE 15W-40 diesel engine oil	h-BN and Al_2O_3	Inspected the effect of nanoparticles in base oil and concluded that friction Co-efficient and wear were reduced significantly.	[85]
	Engine oil (SAE15W40)	Ag	The results showed a considerable reduction in wear and friction and improvement in load-carrying capacity in comparison to the base oil.	[86]
	Ensis PQ144 oil	Nano graphite	The graphite mixed oil clearly shows a favourable effect of reducing the frictional force.	[87]
Synthetic Oil	Hexadecane oil	MoS_2	The friction in wet condition was found to decrease with increasing temperature	[88]
	Silicone oil	PDMS-modified Fe_3O_4@graphene	Stable suspension of silicone oil with nanoparticle is obtained Working as thermal fluid.	[89]
	Poly α-olefin	Al_2O_3 and TiO_2	Nanoparticles addition to base oil reduced the coefficient of friction and wear.	[90]
	Poly α-olefin	CuO	Reduction in the friction coefficient and wear using tiny nanoparticles has been achieved.	[91]
	Poly α-olefin-6	CuO, ZnO and ZrO_2	All nanoparticle suspensions showed a decrement in friction and wear compared to the base oil	[92]
Vegetable oil	Rapeseed oil	CuO, CeO_2 and PTFE	Nano additives have shown a remarkable reduction in the wear scar diameter.	[93]
	Rice bran oil	Al_2O_3, CuO and Fe_2O_3	CuO based lubricant showed the best results regarding machinability, suitable for Minimum quantity lubrication (MQL).	[94]
	Chemically modifying olive oil	Cu and hBN	A significant reduction in COF was observed was achieved at the optimum concentration.	[95]
	Sunflower oil	SiO_2 and TiO_2	Sunflower oil with nanoparticles has the potential as a good biodegradable lubricant.	[96]
	Epoxied soybean and sunflower oil	ZnO and CuO	The developed bio-lubricants showed good tribological properties with improved abrasion resistance.	[97]
	Rapeseed oil	Graphene oxide derivatives	Two types of graphene oxide-based additives namely 1-dodecanethiol (GO-D) and tert-dodecyl mercaptan (GO-T) were added in base oil and found that dispersion stability and tribological properties of GO-D in rapeseed oil are better to GO-T and both additives are better than that of neat GO.	[98]
	Coconut oil	Cu and Ag blended	Copper-based nanolubricants exhibited better as compared to silver-based regarding friction reduction.	[99]
	Groundnut oil	Cu and Zn hybrid	Better enhancement in thermal conductivity is reported in base vegetable oil.	[100]
	Canola oil	CuO	Canola oil CuO nano additives showed minimum friction coefficient and lowest specific wear rate.	[101]
	Neem oil	Graphene	The addition of GNPs in neem oil showed a decrease in coefficient of friction, make the surface smoother and improved seizure load.	[102]
	RBD palm olein oil	Polyaniline (PANI) nanotubes	Thermal properties get enhanced by the addition of PANI nanotubes dispersed in the base oil.	[103]

ment in machinability using nanolubricants [94]. Several mechanisms have been proposed about how nanoparticles reduce friction and wear.

The ball-bearing or rolling effect is one of them [104], the formation and elimination of layered-structure protective tribofilms is another [105]. The mending effect, *i.e.* penetration into the rubbing surfaces is also one of the mechanisms [106] and finally the polishing effect [104]. Table-5 summarizes specifically MoS_2 nanoparticles and their combination with other nanoparticles in various vegetable oils while Table-6 specifically illustrates the castor oil-based nanolubricants and their tribological outcomes.

In Table-5 tribology property improvement in base vegetable oils was reported by many researchers [107,108,110,

TABLE-5
DIFFERENT VEGETABLE OILS WITH MoS_2 NANOPARTICLES

Base-oil	Nanoparticles/size (nm) & Optimum Concentration (wt %)	Remarks	Ref.
Chemically modified palm oil (CMPO)	CuO/50-300 and MoS_2/50-2000 & 1	CuO and MoS_2 nanoparticles showed good results in CMPO, antiwear and extreme pressure properties increased by 1.5 times.	[107]
Rapeseed	MoS_2/14 & 1	The tribological properties of rapeseed oil were improved by MoS_2 nano-vesicles.	[108]
Coconut	MoS_2/90 & 0.53-0.58	Nanoparticles incorporation at an optimum concentration level in base oil made the surface smoother.	[109]
Soyabean (SO)	MoS_2 (Nanospheres)/100 & 1	MoS_2 hollow nanospheres improve the tribological properties of SO.	[110]
Sunflower oil	CuO and MoS_2 & 1	Reduction in wear rate and coefficient of friction was achieved by adding the mentioned nanoparticles in sunflower oil.	[111]
Sesame and coconut oil	Boric acid and MoS_2 & 0.25	A reduction in cutting force 44%–48% of nanosuspensions of molybdenum disulphide in sesame oil. Good results were obtained in dry machining also.	[112]
Coconut, Sesame and Canola	MoS_2 & 0.5	Nanoparticle addition exhibits better machining performance. Tool wear and surface roughness are also reduced.	[113]
Coconut, Soyabean, Ricebran oil	MoS_2, Graphite and hybrid mixture & 0.5	The value of Surface roughness decreases with an increase in the weight percentage of nanoparticle inclusions. (*i.e.* for graphite, MoS_2 and hybrid mixture). MoS_2 nanoparticle inclusions in soya bean oil exhibit the best surface finish.	[114]
Jatropha curcas oil	Cu/20-50, Graphite, MoS_2/20-50 nanoparticle Graphite Powder 400 & 0.5-1.5	JCO with 0.5 % MoS_2 showed the best results with maximum reduction in wear scar dia. *Jatropha curcas* oil with 1.5% Cu exhibited a maximum reduction in COF.	[115]

TABLE-6
CASTOR OIL WITH DIFFERENT VARIETIES OF NANOPARTICLES

Nanoparticles	Size (nm)/Optimum concentration (wt %)	Remarks	Ref.
Hexagonal boron nitride nanoparticles	171.2/5	Wear quantity was improved by 55.05% and 51.74% at low and high load respectively. At high load, a 30.2% decrease in the friction coefficient is obtained.	[116]
Surface modified CuO nanoparticles	< 50/1	The utmost reductions in WSD were 28.3% and COF was reduced by 17.3% at the optimum value of nanoparticle concentrations. A remarkable improvement in the weld load was seen in nanolubricants.	[117]
Graphite, multi-walled carbon nanotube and multilayered graphene	Graphite (1 µm-2 µm), (MWCNT) (Avg dia: 20) Multi-layered graphene (3-6)/0.1-2	All three carbon-based nanoparticles in castor oil have exhibited better wear reduction and extreme pressure properties at an optimum value of concentration, beyond, which the anti-wear properties declined.	[118]
MoS_2 and CuO	CuO 55 MoS_2 60/1	In a Hybrid combination of nanoparticles, COF was reduced in the range of 76.03-81.7%, while the wear value was reduced to 93.1-92.23% compared to castor and molding oil respectively as base oil.	[119]
ZnO	(35-45)/0.1	The COF in castor oil exhibited a lesser value than mineral oil at the optimum concentration. The wear rate also found lesser value similarly.	[120]
CeO_2 and Polytetrafluroethylene	CeO_2 (90) and Polytetra fluroethylene (150)/0.25% for CeO_2 and 0.1% PTFE.	The maximum reduction in wear scar diameter was achieved 37.4% withCeO_2 and 35.3% with Polytetrafluroethylene nanoparticle. Significant improvement in the antifriction and load-carrying properties of castor oil was also achieved with the mentioned nanoparticles.	[121]
Alumina (Al_2O_3) nanoparticles in castor oil methyl ester (CME20)	Size not mentioned	The Brake thermal efficiency and brake specific fuel consumption of blend B20 increased with the addition ofAl_2O_3 nanoparticles as compared with diesel. The NO_X and HC emissions are less for alumina added biodiesel blends.	[122]

111,115]. The comparative tribological performance of three nanoparticles namely Cu, graphite and MoS_2 has been done and MoS_2 nanoparticles performed the best [115]. In some studies MoS_2 incorporation in different vegetable oils made surface smoother [109,113,114]. In Table-6, MoS_2 combination with CuO nanoparticles in castor oil showed the best results regarding antiwear and antifriction property [119].

Applications: The encouraging results and remarkable properties are shown by vegetable oil-based nanolubricants in terms of reduction in friction and resistance to wear and in machining, open new areas in the field of tribology and lubrication. They can decrease frictional resistance, shield an engine from wear during surface contact, eliminate wear fragments, reduce heating, provide more cooling and lessen emissions. Biolubricants can be the right choice in long-term usage. A significant decrease in fuel consumption and environmental pollution can be achievable. The following are the application areas in which its usage as a replacement for conventional oils has been discussed.

Nanolubricants in IC engines: For precise and effective lubrication, the use of common engine lubricants results in the environmental pollution. It is due to evaporation and engine exhaust emissions that happen during engine operation. Remains from these engine oils slowly decompose and are toxic to humans and environmental vegetation. Properties like biodegradability, renewability and low toxicity in materials will be the future of engine lubrication technology [123,124]. In this regard, nanoparticle technology comes out as new prospects because of wear and friction-reducing nature. Many reasons for the adoption of nanoparticles as lubricant additives as discussed earlier also, the most important is their small size, which allows nanoparticles to enter a contact area easily and providing adequate lubrication affect. Vegetable oil-based products can also have the potential for reducing carbon dioxide and hydrocarbon emission when used in such applications as a lubricant in internal combustion engines and industrial processes.

Nanolubricants in minimum quantity lubrication grinding: In material removal operations, especially in finishing operations grinding is very important. The grinding process is abrasive. During grinding most of the input energy is converted into heat such high temperature can cause thermal damage to the workpiece. It has been reported that MoS_2 nanoparticle addition in paraffin oil, canmist oil and soybean oil improves the performance of grinding fluids [125]. Although castor oil is competent base oil for lubrication performance but due to poor mobility, its application is limited especially in precision grinding [126]. It is found that soybean/castor mixed oil shows a better lubricating effect compared with castor oil and other mixed base oils. The lubricating capability of soybean/castor mixed oil is further enhanced by MoS_2 nanoparticles. They added an 8% mass fraction of the oil mixture and get good machining results. They achieved the lowest force ratio (0.329), specific energy (58.60 J/mm^3) and average grinding temperature (182.6 ºC). Additionally, better surface microtopography and debris morphology of ground parts were also obtained.

Nanolubricants in refrigeration system: Performance upgradation of heating, ventilation, air conditioning and refrigeration (HVAC&R) systems are a basic need in the industry. Nanofluids can be possible materials in maximizing the efficiency of these systems. So many researchers studied different particles based nanolubricants in (HVAC & R) systems to enhance the antifriction and antiwear property, improve thermal dissipation and system efficiency. Lee *et al*. [127] reported improvement in the antifriction property when nanoparticles are used in base oils. Wang *et al*. [128] incorporation of titanium oxide (TiO_2) nanoparticles in mineral oil to improve the solubility of HFC. Bi *et al*. [129] used TiO_2 and aluminum oxide (Al_2O_3) nanoparticles-based nanolubricants for the domestic refrigerator. Subramani & Prakash [130] employed Al_2O_3 nanoparticles based lubricants and found 25% lesser power consumption. Kumar & Elansezhian [131] used Al_2O_3 nanoparticles in polyalkylenglycol (PAG) oil in a refrigeration system in, place of pure PAG and reported about 10% lesser energy consumption.

Conclusion

Vegetable oils can be the right choice in place of conventional oils as lubricants in mechanical systems. Edible oils like soybean, sunflower, coconut, *etc.* usage as fuel and lubricant are difficult as these have to fulfill the domestic requirements of a big population. Non-edible oils like castor oil due to their abundance and excellent physical and chemical properties can serve the purpose. Castor oil is very good for lubricity, low volatility, high viscosity index and environmental friendly but has limited widespread application due to high viscosity, hydrolytic instability and low-temperature properties. These demerits can be minimized by using additives. Nanoparticles lighten fascinating prospects in the area of tribology and lubrication. They have significant potential as lubrication additives and performance. The addition of nanoparticles in castor oil will be 'cherry on nut'. These demerits can be overcome either by chemical modification of the castor oil as it has different functional groups such as the hydroxyl, vinyl and the ester group, by using appropriate additives [132] or by blending. Besides this more procedural and systematic study is required for the addition of nanoparticles in castor oil, as many authors [111-114] have not mentioned particle size, which is the most important factor in lubrication.

ACKNOWLEDGEMENTS

The authors thanks Dr. N. Eswara Prasad, OS & Director, DMSRDE, Kanpur, India for his constant motivation and encouragement.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

REFERENCES

1. Y. Gerbig, S.I.U. Ahmed, F.A. Gerbig and H. Haefke, *J. Synth. Lubrication*, **21**, 177 (2004); https://doi.org/10.1002/jsl.3000210302
2. S. Boyde, *Green Chem.*, **4**, 293 (2002); https://doi.org/10.1039/b202272a
3. G. Geethanjali, K.V. Padmaja and R.B.N. Prasad, *Ind. Eng. Chem. Res.*, **55**, 9109 (2016); https://doi.org/10.1021/acs.iecr.6b01550

4. K.M. Talkit, D.T. Mahajan and V.H. Masand, *Arch. Appl. Sci. Res.*, **7**, 22 (2015).
5. S.Z. Erhan and S. Asadauskas, *Ind. Crops Prod.*, **11**, 277 (2000); https://doi.org/10.1016/S0926-6690(99)00061-8
6. T.Y. Woma, S.A. Lawal, A.S. Abdulrahman, M.A. Olutoye and M.M. Ojapah, *Tribology Online*, **14**, 60 (2019); https://doi.org/10.2474/trol.14.60
7. S. Syahrullail, S. Kamitani and A. Shakirin, *Procedia Eng.*, **68**, 172 (2013); https://doi.org/10.1016/j.proeng.2013.12.164
8. L.A. Quinchia, M.A. Delgado, T. Reddyhoff, C. Gallegos and H.A. Spikes, *Tribol. Int.*, **69**, 110 (2014); https://doi.org/10.1016/j.triboint.2013.08.016
9. A. Nakarmi and A. Joshi, *Nepal J. Sci. Technol.*, **15**, 45 (2015); https://doi.org/10.3126/njst.v15i1.12009
10. D.S. Chinchkar, S.T. Satpute and N.R. Kumbhar, *Int. J. Eng. Res. Technol.*, **1**, 2 (2012).
11. X. Wu, G. Zhao, X. Wang and X. Liu, *Tribol. Lett.*, **65**, 51 (2017); https://doi.org/10.1007/s11249-017-0833-9
12. H.A. Elemsimit and D. Grecov, *Proc. Inst. Mech. Eng., Part J J. Eng. Tribol.*, **230**, 257 (2016); https://doi.org/10.1177/1350650115599013
13. K.J. Mannekote and S.V. Kailas, *Tribology Online*, **6**, 76 (2011); https://doi.org/10.2474/trol.6.76
14. K.S.V.K. Reddy, N. Kabra, U. Kunchum and T. Vijayakumar, *Chinese J. Eng.*, **2014**, Article ID 643521 (2014); https://doi.org/10.1155/2014/643521
15. A. Arnšek and J. Vi•intin, *J. Synth. Lubrication*, **16**, 281 (2006); https://doi.org/10.1002/jsl.3000160402
16. C.D. Rakopoulos, *Energy*, **17**, 787 (1992); https://doi.org/10.1016/0360-5442(92)90122-G
17. R. Radu and Z. Mircea, The Use of Sunflower Oil in Diesel Engines, SAE Technical Paper 972979, Event: International Fuels & Lubricants Meeting & Exposition (1997).
18. N.L. Gunjal, D.S. Bajaj and A.K. Mishra, International Advanced Research Journal in Science, Engineering and Technology, 2nd International Conference on Advances in Mechanical Engineering Amrutvahini College of Engineering, Sangamner, India, vol. 3, Special Issue 1, March (2016).
19. L.A.T. Honary, *Bioresour. Technol.*, **56**, 41 (1996); https://doi.org/10.1016/0960-8524(95)00184-0
20. A. Imran, H.H. Masjuki, M.A. Kalam, M. Varman, M. Hasmelidin, K.A.H.A. Mahmud, S.A. Shahir and M. Habibullah, *Procedia Eng.*, **68**, 178 (2013); https://doi.org/10.1016/j.proeng.2013.12.165
21. A. Savan, A. Pflüger, P. Voumard, A. Schröer and M. Simmonds, *Lubr. Sci.*, **12**, 185 (2000); https://doi.org/10.1002/ls.3010120206
22. S.U.S. Choi and J.A. Eastman, Enhancing Thermal Conductivity of Fluids with Nanoparticles, Paper presented at ASME International Mechanical Engineering Congress & Exposition, San Francisco, CA, November 12-17 (1995).
23. S. Baskar, G. Sriram and S. Arumugam, *Tribol. Ind.*, **37**, 449 (2015).
24. Y. Su, L. Gong and D. Chan, *J. Nanomater.*, **2015**, 276753 (2015); https://doi.org/10.1155/2015/276753
25. T. Panhwar, S.A. Mahesar, A.A. Kandhro, S.T.H. Sheerazi, A.H. Kori, Z.H. Laghari and J.-R. Memon, *Ukr. Food J.*, **8**, 778 (2019); https://doi.org/10.24263/2304-974X-2019-8-4-9
26. B. Chidambaranathan, S. Gopinath, R. Aravindraj, A. Devaraj, S.Gokula Krishnan and J.K.S. Jeevananthan, *Mater. Today: Proc.*, **33**, 84 (2020); https://doi.org/10.1016/j.matpr.2020.03.205
27. V. Umarji, Castor Seed Production Estimated to Grow by 88% in 2019-20: Agriwatch Business standards February 22 (2020); https://www.business-standard.com/article/economy-policy/castor-seed-production.
28. O. Gokdogan, T. Eryilmaz and M.K. Yesilyurt, *Cienc., Tecnol. Futuro*, **6**, 95 (2015); https://doi.org/10.29047/01225383.29
29. P.V. Joseph, D. Saxena and D.K. Sharma, *J. Synth. Lubrication*, **24**, 181 (2007); https://doi.org/10.1002/jsl.39
30. P. Ghosh, M. Hoque and G. Karmakar, *Polym. Bull.*, **75**, 501 (2018); https://doi.org/10.1007/s00289-017-2047-6
31. M.B. Mensah, J.A.M. Awudza and P. O'Brien, *R. Soc. Open Sci.*, **5**, 180824 (2018); https://doi.org/10.1098/rsos.180824
32. A.S. Abdulkareem, A. Jimoh, A.S. Afolabi, J.O. Odigure and D. Patience, Production and Characterization of Biofuel from Non-Edible Oils: An Alternative Energy Sources to Petrol Diesel, Energy Conservation (2012); https://doi.org/10.5772/51341
33. O.J. Omohu and A.C. Omale, *Eur. J. Biophysics*, **5**, 62 (2017); https://doi.org/10.11648/j.ejb.20170504.11
34. M.A. Saied, S.H. Mansour, M. Eweis, M.Z. El-Sabee, A.L.G. Saad and K.N.A. Nour, *Eur. J. Lipid Sci. Technol.*, **110**, 926 (2008); https://doi.org/10.1002/ejlt.200800001
35. V.R. Patel, G.G. Dumancas, L.C.K. Viswanath, R. Maples and B.J.J. Subong, *Lipid Insights*, **9**, (2016); https://doi.org/10.4137/LPI.S40233
36. O. Kazeem, O. Taiwo and A. Kazeem, *Int. J. Sci. Eng. Technol.*, **3**, 1503 (2017).
37. S. Guo, C. Li, Y. Zhang, Y. Wang, B. Li, M. Yang, X. Zhang and G. Liu, *J. Clean. Prod.*, **140**, 1060 (2017); https://doi.org/10.1016/j.jclepro.2016.10.073
38. H.J. Pei, W.J. Zheng, G.C. Wang and H.Q. Wang, *Adv. Mater. Res.*, **381**, 20 (2012); https://doi.org/10.4028/www.scientific.net/AMR.381.20
39. H.J. Pei, Y.J. Shen, C.G. Shen and G.C. Wang, *Appl. Mech. Mater.*, **130-134**, 3830 (2011); https://doi.org/10.4028/www.scientific.net/AMM.130-134.3830
40. J. Salimon, D.A.M. Noor, A.T. Nazrizawati, M.Y.M. Firdaus and A. Noraishah, *Sains Malays.*, **39**, 761 (2010).
41. W.M.L.B. Naranpanawe, M.A.R.M. Fernando, J.R.S.S. Kumara and E.M.S.N. Naramapanawa, Performance Analysis of Natural Esters as Transformer Liquid Insulation Coconut, Castor and Sesame Oils, Paper Presented at IEEE 8th International Conference on Industrial and Information Systems, Dec 17-20 (2013); https://doi.org/10.1109/ICIInfS.2013.6731694
42. A. Suhane, R.M. Sarviya, A. Rehman and H.K. Khaira, *Int. J. Eng. Res. Appl.*, **4**, 104 (2014).
43. K.M. Talkit, D.T. Mahajan and V.H. Masand, *J. Chem. Pharm. Res.*, **4**, 5139 (2012).
44. M.A. Delgado, L.A. Quinchia, H.A. Spikes and C. Gallegos, *J. Clean. Prod.*, **151**, 1 (2017); https://doi.org/10.1016/j.jclepro.2017.03.023
45. T.K.K.S. Pathmasiri, G.I.P. Perera and R. Gallage, *Energy Sources A*, (2019); https://doi.org/10.1080/15567036.2019.1643425
46. A.K. Singh, *Ind. Crops Prod.*, **33**, 287 (2011); https://doi.org/10.1016/j.indcrop.2010.12.014
47. H.Y. Shrirame, N.L. Panwar and B.R. Bamniya, *Low Carbon Econ.*, **2**, 1 (2011); https://doi.org/10.4236/lce.2011.21001
48. Z.L.A. García, J.M. Franco, C. Valencia, M.A. Delgado, C. Gallegos and M.V. Ruiz-Méndez, *Eur. J. Lipid Sci. Technol.*, **115**, 1173 (2013); https://doi.org/10.1002/ejlt.201300066
49. D.K. Karupannasamy and R. Ruthuraraj, *Int. J. Recent Technol. Eng.*, **8**, 1902 (2013).
50. Q.F. Zeng and G.N. Dong, *Trans. Nonferrous Met. Soc. China*, **24**, 354 (2014); https://doi.org/10.1016/S1003-6326(14)63068-5
51. B. Bongfa, P.A. Atabor, A. Barnabas and M.O. Adeoti, *J. Tribologi*, **5**, 1 (2015).
52. S.M. Nasri, S.A. Nama and M.T. Mezher, *J. Mechan. Eng. Res. Develop.*, **42**, 30 (2019); https://doi.org/10.26480/jmerd.03.2019.30.34
53. R. Padmini, P.V. Krishna and G.K. Mohana Rao, *Proc. Inst. Mech. Eng., B*, **229**, 2196 (2015); https://doi.org/10.1177/0954405414548465
54. R. Padmini, P. Vamsi Krishna and G.K. Mohana Rao, *Tribol. Int.*, **94**, 490 (2016); https://doi.org/10.1016/j.triboint.2015.10.006

55. T. Chaitanya, N. Harsha and V.S.N. Venkata Ramana, *Int. J. Innov. Res. Sci., Eng. Technol.*, **3**, 30 (2018).
56. Sonali, D., Karandikar, P. M., *Int. J. Innov. Res. Sci., Eng. Technol.*, **7**, 6862 (2018).
57. W. Dai, B. Kheireddin, H. Gao and H. Liang, *Tribol. Int.*, **102**, 88 (2016); https://doi.org/10.1016/j.triboint.2016.05.020
58. D. Kim, D. Sun, W. Lu, Z. Cheng, Y. Zhu, D. Le, T.S. Rahman and L. Bartels, *Langmuir*, **27**, 11650 (2011); https://doi.org/10.1021/la201878f
59. X. Zhang, B. Luster, A. Church, C. Muratore, A.A. Voevodin, P. Kohli, S. Aouadi and S. Talapatra, *Appl. Mater. Interf.*, **1**, 735 (2009); https://doi.org/10.1021/am800240e
60. C.L. Stender, E.C. Greyson, Y. Babayan and T.W. Odom, *Adv. Mater.*, **17**, 2837 (2005); https://doi.org/10.1002/adma.200500856
61. M.M. Mdleleni, T. Hyeon and K.S. Suslick, *J. Am. Chem. Soc.*, **120**, 6189 (1998); https://doi.org/10.1021/ja9800333
62. F.A. Deorsola, N. Russo, G.A. Blengini and D. Fino, *Chem. Eng. J.*, **195-196**, 1 (2012); https://doi.org/10.1016/j.cej.2012.04.080
63. S.V.P. Vattikuti and C. Byon, *J. Nanomater.*, **2015**, 710462 (2015); https://doi.org/10.1155/2015/710462
64. L.O. Shyyko, V.O. Kotsyubynsky and I.M. Budzulyak, *J. Nanosci. Nanotechnol.*, **16**, 7792 (2016); https://doi.org/10.1166/jnn.2016.12559
65. B. Gao and X. Zhang, *S. Afr. J. Chem.*, **67**, 6 (2014).
66. Z. Wu, D. Wang and A. Sun, *J. Cryst. Growth*, **312**, 340 (2010); https://doi.org/10.1016/j.jcrysgro.2009.10.024
67. J. Chen, S.L. Li and Z.L. Tao, *J. Alloys Compd.*, **356-357**, 413 (2003); https://doi.org/10.1016/S0925-8388(03)00114-2
68. Y. Tian, J. Zhao, W. Fu, Y. Liu, Y. Zhu and Z. Wang, *Mater. Lett.*, **59**, 3452 (2005); https://doi.org/10.1016/j.matlet.2005.06.012
69. W.J. Li, E.W. Shi, J.M. Ko, Z. Chen, H. Ogino and T. Fukuda, *J. Cryst. Growth*, **250**, 418 (2003); https://doi.org/10.1016/S0022-0248(02)02412-0
70. M. Liu, X. Li, Z. Xu, B. Li, L.L. Chen and N.N. Shan, *Chin. Sci. Bull.*, **57**, 3862 (2012); https://doi.org/10.1007/s11434-012-5339-0
71. G. Santillo, F.A. Deorsola, S. Bensaid, N. Russo and D. Fino, *Chem. Eng. J.*, **207-208**, 322 (2012); https://doi.org/10.1016/j.cej.2012.06.127
72. J.A. Eastman, S.U.S. Choi, S. Li, W. Yu and L.J. Thompson, *Appl. Phys. Lett.*, **78**, 718 (2001); https://doi.org/10.1063/1.1341218
73. P.C. Hiemenz and R. Rajagopalan, Principles of Colloids and Surface Chemistry, CRC Press: New York, Edn. 3 (1997).
74. Y. Chen, P. Renner and H. Liang, *Lubricants*, **7**, 7 (2019); https://doi.org/10.3390/lubricants7010007
75. R. Akiyama, N. Fujino, K. Kaneda and M. Kinoshita, *Condens. Matter Phys.*, **10**, 587 (2007); https://doi.org/10.5488/CMP.10.4.587
76. H. Reerink and J.Th.G. Overbeek, *Discuss. Faraday Soc.*, **18**, 74 (1954); https://doi.org/10.1039/df9541800074
77. R. Choudhary, D. Khurana, A. Kumar and S. Subudhi, *J. Exp. Nanosci.*, **12**, 140 (2017); https://doi.org/10.1080/17458080.2017.1285445
78. S. Lee, S.U.S. Choi, S. Li and J.A. Eastman, *J. Heat Transfer*, **121**, 280 (1999); https://doi.org/10.1115/1.2825978
79. H. Xie, J. Wang, T. Xi, Y. Liu, F. Ai and Q. Wu, *J. Appl. Phys.*, **91**, 4568 (2002); https://doi.org/10.1063/1.1454184
80. S.U.S. Choi, Z.G. Zhang, W. Yu, F.E. Lockwood and E.A. Grulke, *Appl. Phys. Lett.*, **79**, 2252 (2001); https://doi.org/10.1063/1.1408272
81. S.M. Muzakkir, K.P. Lijesh and H. Hirani, *Int. J. Curr. Eng. Technol.*, **5**, 681 (2015).
82. C. Shi, D. Mao and H. Feng, *J. Cent. South Univ. Technol.*, **14**, 673 (2007); https://doi.org/10.1007/s11771-007-0129-6
83. J. Padgurskas, R. Rukuiza, I. Prosycevas and R. Kreivaitis, *Tribol. Int.*, **60**, 224 (2013); https://doi.org/10.1016/j.triboint.2012.10.024
84. Y.Y. Wu, W.C. Tsui and T.C. Liu, *Wear*, **262**, 819 (2007); https://doi.org/10.1016/j.wear.2006.08.021
85. M.I.H.C. Abdullah, N. Tamaldin, H. Amiruddin and N.R.M. Nuri, Ind. *Lubricat. Tribol.*, **68**, 441 (2016); https://doi.org/10.1108/ILT-10-2015-0157
86. C.P. Twist, I. Bassanetti, M. Snow, M. Delferro, H. Bazzi, Y.-W. Chung, L. Marchió, T.J. Marks and Q.J. Wang, *Tribol. Lett.*, **52**, 261 (2013); https://doi.org/10.1007/s11249-013-0211-1
87. K. Kirhorn, L.U. Lanny, G. Oleksandr and M. Oleksandr, Nano Graphite Flakes as Lubricant Additive, Paper presented at Proceedings of the 6th Swedish Production Symposium, The Swedish Production Academy (2014).
88. M. Praveena, V. Jayaram and S.K. Biswas, *Ind. Eng. Chem. Res.*, **51**, 12321 (2012); https://doi.org/10.1021/ie3011337
89. P. Tao, L. Shu, J. Zhang, C. Lee, Q. Ye, H. Guo and T. Deng, *Progr. Nat. Sci. Mater. Int.*, **28**, 554 (2018); https://doi.org/10.1016/j.pnsc.2018.09.003
90. N.G. Demas, R.A. Erck, C. Lorenzo-Martin, O.O. Ajayi and G.R. Fenske, *J. Nanomater.*, **2017**, 8425782 (2017); https://doi.org/10.1155/2017/8425782
91. S.M. Alves, V.S. Mello, E.A. Faria and A.P.P. Camargo, *Tribol. Int.*, **100**, 263 (2016); https://doi.org/10.1016/j.triboint.2016.01.050
92. A. Hernández Battez, R. González, J.L. Viesca, J.E. Fernández, J.M. Díaz-Fernández, A. Machado, R. Chou and J. Riba, *Wear*, **265**, 422 (2008); https://doi.org/10.1016/j.wear.2007.11.013
93. R.N. Gupta, A.P. Harsha and S. Singh, *Appl. Nanosci.*, **8**, 567 (2018); https://doi.org/10.1007/s13204-018-0670-7
94. A. Das, S.K. Patel and S.R. Das, *Mech. Ind.*, **20**, 506 (2019); https://doi.org/10.1051/meca/2019036
95. L. Kerni, A. Raina and M.I.U. Haq, *Wear*, **426-427**, 819 (2019); https://doi.org/10.1016/j.wear.2019.01.022
96. V. Cortes, K. Sanchez, R. Gonzalez, M. Alcoutlabi and J.A. Ortega, *Lubricants*, **8**, 10 (2020); https://doi.org/10.3390/lubricants8010010
97. M.F. Trajano, E.F. Moura, K.B. Ribeiro and S.M. Alves, *Mater. Res.*, **17**, 1124 (2014); https://doi.org/10.1590/1516-1439.228213
98. G. Zhang, Y. Xu, X. Xiang, G. Zheng, X. Zeng, Z. Li, T. Ren and Y. Zhang, *Tribol. Int.*, **126**, 39 (2018); https://doi.org/10.1016/j.triboint.2018.05.004
99. M.S. Khan, M. S. Sisodia, S. Gupta, M. Feroskhan, S. Kannan and K. Krishnasamy, *Eng. Sci. Technol. Int. J.*, **22**, 1187 (2019); https://doi.org/10.1016/j.jestch.2019.04.005
100. S.K. Mechiri, V. Vasu and A. Venu Gopal, *Exp. Heat Transf.*, **30**, 205 (2017); https://doi.org/10.1080/08916152.2016.1233147
101. V. Kumar, A. Dhanola, H.C. Garg and G. Kumar, *Mater. Today Proc.*, **28**, 1392 (2020); https://doi.org/10.1016/j.matpr.2020.04.807
102. B. Suresha, G. Hemanth, A. Rakesh and K.M. Adarsh, *Adv. Tribol.*, **2020**, 1 (2020); https://doi.org/10.1155/2020/1984931
103. A.G.N. Sofiah, M. Samykano, S. Shahabuddin, K. Kadirgama and A.K. Pandey, *J. Therm. Anal. Calorim.*, **145**, 2967 (2020); https://doi.org/10.1007/s10973-020-09891-6
104. X. Tao, Z. Jiazheng and X. Kang, *J. Phys. D Appl. Phys.*, **29**, 2932 (1996); https://doi.org/10.1088/0022-3727/29/11/029
105. R.B. Rastogi, M. Yadav and A. Bhattacharya, *Wear*, **252**, 686 (2002); https://doi.org/10.1016/S0043-1648(01)00878-X
106. G. Liu, X. Li, B. Qin, D. Xing, Y. Guo and R. Fan, *Tribol. Lett.*, **17**, 961 (2004); https://doi.org/10.1007/s11249-004-8109-6
107. A.A. Noori, H.A. Hussein and N.S.M. Namer, *IOP Conf. Ser.: Mater. Sci. Eng.*, **518**, 032040 (2019); https://doi.org/10.1088/1757-899X/518/3/032040

108. S. Bhaumik, R. Maggirwar, S. Datta and S.D. Pathak, *Appl. Surf. Sci.*, **449**, 277 (2018); https://doi.org/10.1016/j.apsusc.2017.12.131
109. R.N. Gupta and A.P. Harsha, *Proc. Inst. Mechan. Eng., Part J: J. Eng. Tribol.*, **232**, 1055 (2017); https://doi.org/10.1177/1350650117739159
110. V.S. Rao and M.V.S. Babu, *Int. Res. J. Eng. Technol.*, **5**, 827 (2018).
111. K.N. Thakkar, S.S. Mhatre and R.Y. Parikh, *Nanomedicine*, **6**, 257 (2010); https://doi.org/10.1016/j.nano.2009.07.002
112. J.N. Tiwari, R.N. Tiwari and K.S. Kim, *Prog. Mater. Sci.*, **57**, 724 (2012); https://doi.org/10.1016/j.pmatsci.2011.08.003
113. S.U.S. Choi, Eds.: D.A. Signer and H.P. Wang, Developments and Applications of Non-Newtonian Flows, ASME, New York, vol. 66, pp. 99-105 (1995).
114. J.S. Loveday, R.J. Nelmes, M. Guthrie, D.D. Klug and J.S. Tse, *Phys. Rev. Lett.*, **87**, 215501 (2001); https://doi.org/10.1103/PhysRevLett.87.215501
115. B.M. Berkovsky, V.F. Medvedef and M.S. Krakov, Magnetic Fluids in Engineering Applications, Oxford University Press: Oxford, New York (1993).
116. Y. Wang, Z. Wan, Z. Lu, Z. Zhang and Y. Tang, *Tribol. Int.*, **124**, 10 (2018); https://doi.org/10.1016/j.triboint.2018.03.035
117. R.N. Gupta and A.P. Harsha, *Ind. Lubr. Tribol.*, **70**, 700 (2018); https://doi.org/10.1108/ILT-02-2017-0030
118. S. Bhaumik, S. Datta and S.D. Pathak, *J. Tribol.*, **139**, 061802 (2017); https://doi.org/10.1115/1.4036379
119. M. Gulzar, H.H. Masjuki, M. Varman, M.A. Kalam, R.A. Mufti, N.W.M. Zulkifli, R. Yunus and R. Zahid, *Tribol. Int.*, **88**, 271 (2015); https://doi.org/10.1016/j.triboint.2015.03.035
120. Z.Y. Xu, K.H. Hu, C.L. Han, X.G. Hu and Y.F. Xu, *Tribol. Lett.*, **49**, 513 (2013); https://doi.org/10.1007/s11249-012-0092-8
121. C.P. Koshy, P.K. Rajendrakumar and M.V. Thottackkad, *Wear*, **330-331**, 288 (2015); https://doi.org/10.1016/j.wear.2014.12.044.
122. Z.Y. Xu, K.H. Hu, Y.K. Cai, F. Huang and C.L. Han, *Tribology- Mater. Surf. Interf.*, **8**, 179 (2014); https://doi.org/10.1179/1751584X14Y.0000000074
123. M. Lovell, C.F. Higgs, P. Deshmukh and A. Mobley, *J. Mater. Process. Technol.*, **177**, 87 (2006); https://doi.org/10.1016/j.jmatprotec.2006.04.045
124. N. Salih, J. Salimon, E. Yousif and B.M. Abdullah, *Chem. Cent. J.*, **7**, 128 (2013); https://doi.org/10.1186/1752-153X-7-128
125. B. Shen, P. Kalita, A.P. Malshe and A.J. Shih, Performance of Novel MoS_2 Nanoparticles-Based Grinding Fluids in Mini-Mum Quantity Lubrication Grinding, Transactions of NAMRI/SME, vol. 36, pp. 357-364 (2008).
126. D. Jia, C. Li, Y. Zhang, M. Yang, Y. Wang, S. Guo and H. Cao, *Precis. Eng.*, **50**, 248 (2017); https://doi.org/10.1016/j.precisioneng.2017.05.012
127. C.G. Lee, S.W. Cho, Y. Hwang and J.K. Lee, Effects of Nanolubricants on the Friction and Wear Characteristics at Thrust Slide Bearing of Scroll Compressor, International Proceeding of the 22nd International Congress of Refrigeration, Beijing (China) August 21-26 (2007).
128. R.X. Wang and H.B. Xie, A Refrigerating System Using HFC134a and Mineral Lubricant Appended with N-TiO_2 as Working Fluids, Proceedings of the 4thInternational Symposium on HAVC, Beijing, China: Tsinghua University Press (2003).
129. S.S. Bi, S. Shi and L.L. Zhang, *Appl. Therm. Eng.*, **28**, 1834 (2008); https://doi.org/10.1016/j.applthermaleng.2007.11.018
130. N. Subramani and M.J. Prakash, *Int. J. Eng. Sci. Technol.*, **3**, 95 (2011); https://doi.org/10.4314/ijest.v3i9.8
131. D.S. Kumar and R. Elansezhian, *Int. J. Modern Eng. Res.*, **2**, 3927 (2012).
132. N.J. Fox and G.W. Stachowiak, *Tribol. Int.*, **40**, 1035 (2007); https://doi.org/10.1016/j.triboint.2006.10.001