Indian Journal of Chemical Technology
Vol. 32, July 2025, pp. 441-453
DOI: 10.56042/ijct.v32i4.17546

Experimental investigation on thermophysical and tribological characteristics of conventional and biolubricating oil blended with nanoparticles

A Thirumalaikumaran[1]*, G Senthilkumar[2] & C Sowmya Dhanalakshmi[3]

[1]Department of Mechanical Engineering, Kangeyam Institute of Technology, Kangeyam 638108, Tamil Nadu, India

[2]Department of Mechanical Engineering, Bannari Amman Institute of Technology, Sathyamangalam 638401, Tamil Nadu, India

[3]Department of Mechanical Engineering, SNS College of Technology, Coimbatore 641035, Tamil Nadu, India

*E-mail: malaibemech@gmail.com

Received 1 March 2025; accepted 16 May 2025

In this study, 1.0 wt% copper oxide (CuO) nanoparticles were added to conventional mineral oil (B20W-40), synthetic oil (S20W-40), and a transesterified castor oil methyl ester (CME). This study examined the properties of B20W-40+CuO (addition of 1.0 wt% CuO), S20W-40+CuO, and CME+CuO oils and compared them with their raw versions (B20W-40, S20W-40, and CME). All investigation in this study was conducted in accordance with American Society for Testing and Materials (ASTM) standards. The resulting variations in thermal, tribological, and corrosive properties were assessed. The addition of CuO enhanced the thermo-physical and tribological properties of nanofluids. The tribological effect of CuO nanoparticles increased the frictional coefficient of B20W-40, S20W-40, and CME by 6.44%, 39.20%, and 17.84%, respectively. Among the tested oils, B20W-40+CuO shows good thermophysical properties, and S20W-40+CuO shows better tribological effects due to the easy dispersion of CuO nanoparticles.

Keywords: Biodegradable, Castor oil methyl ester, Nanolubricant, Four-ball tribometer, Thermophysical properties, Tribological properties

Introduction

The study of friction, lubrication, and wear processes for interacting surfaces in relative motion is known as tribology[1]. Lubricity is the foundation for performance-related metrics of tribological characteristics. It is the capacity of an object to lubricate surfaces that contact with a thin layer of high-viscous lubricant[2]. The lubricants are generally categorized as mineral, vegetable, and synthetic oils. The synthetic oils are called artificial oils, which are produced by chemically reforming petroleum. The mineral oils are likewise derived from crude oil and are commonly used in motor and engine applications[3,4], but the detrimental effects and non-renewability associated with the usage of mineral and synthetic lubricants have emerged as the world's biggest concerns. The use of vegetable-based biodegradable lubricants for industrial applications has become more popular worldwide due to its safe disposal. Compared to the other two types, the vegetable oils are primarily a non-toxic, readily biodegradable, and environmentally friendly one[5]. In many mechanical and industrial applications, lubricants are essential because they lower friction, dissipate heat, and prolong component life. They work by creating a barrier between surfaces that come into touch, reducing wear and increasing effectiveness. The composition, viscosity, and particular lubrication regime of lubricants all affect their effectiveness[6]. Attrition is a result of any moving part reduced in its size or thickness due to high friction caused by uneven or rough surfaces. Attrition can be understood in terms of the cost-effectiveness of machine parts, such as the short lifespan and servicing cost, which result in the parts needing to be replaced entirely if not maintained. Friction and attrition properties are downplayed by adding toxic minerals like chlorine and phosphorous to the conventional lubricating oil in a perception to enhance the performance of mechanical parts[7]. These minerals are non-biodegradable and toxic to the users, posing an unprotected environment[8]. The problem of additive toxicity is substantially alleviated when biolubricating oils and nanoparticles are substituted for traditional lubricants.

Combining nanoparticles with lubricating oil helps the hybrid lubricant reach its best tribological effect and thermophysical qualities by promoting the formation of protective films, rolling effects, mending effects, and polishing effects[9,10]. Previously various nanoparticles, such as cerium oxide (CeO_2), zinc oxide (ZnO), titanium oxide (TiO_2), zirconium oxide (ZrO_2), and silicon oxide (SiO_2), were studied and received positive results[11,12]. The tribological properties of both conventional and biolubricating oils that have been combined with nanoparticles show notable improvements in performance, especially when it comes to lowering wear and friction[13]. The addition of nanoparticles like CeO_2, TiO_2, and Al_2O_3 to biolubricant has produced positive results, suggesting an effort toward more environmentally friendly lubrication options. Previously the friction coefficient was reduced by 26%, and the wear rate was significantly reduced when 0.15 wt% CeO_2 nanoparticles were blended into lubricating oil[14]. When compared to standard oils, canola oil with 0.25 to 0.5 wt% TiO_2 nanoparticles showed excellent tribological performance, reducing the coefficient of friction by 73.32%[15]. In contrast to standard SAE20W40 oil, canola oil mixed with 0.5% and 0.25% TiO_2 nanoparticles showed significantly superior tribological properties, reducing the coefficient of friction by 66.76% and 73.32%, respectively[15]. According to Uppar *et al.*[16] biolubricants made from a blend of jojoba and jatropha oils and nanoparticles show notable improvements in tribological properties, resulting in wear reductions of 94.68% and 79.85%, respectively, with coefficients of friction of 0.061 and 0.059, respectively. From the results of the previous studies, the usage of nanoparticles less than 100 nm in size holds excellent mechanical properties, resulting in the improvement of tribological and thermo-physical properties of lubricating oils[17].

Numerous studies have tried to combine mineral lubricants with a specific ratio of pure vegetable oils to enhance their lubricating qualities and accelerate their natural disintegration. These studies demonstrate the importance of different oil blends and their performance in machining operations. It was clear that combining the mineral oils with pure vegetable oils is the way to improve their lubricating performance. The vegetable based oils often have long carbon atom chains joined by open-ended fatty acid chains, which serve as effective additions to reduce friction[18]. In comparison to pure oils, a blend ratio of 1:2 (palm to sunflower oil) was found to be ideal, producing notable decreases in surface roughness (16.79%), specific cutting energy (11.82%), and tool wear (10.19%)[19]. According to Edla *et al.* the best coefficient of friction and oxidative stability were discovered in a 1:1 ratio of transesterified rice bran oil to jatropha oil. This suggests that this blend may provide biolubricants with maximum effectiveness and the least amount of environmental damage[20]. According to Yuan *et al.* a combination of 31% castor oil and 69% ethanol is the ideal ratio. Compared to conventional fluids, this environmentally friendly combination minimizes environmental impact while improving lubrication performance characteristics[21]. In another study, a two-step ultrasonographic method was used to synthesize stable CuO-coconut oil nanofluids without the surfactants. The study primarily focused on investigating viscosity variations across different shear rates, temperatures, and concentrations of CuO nanoparticles[22]. With oleic acid as a surfactant, Kole and Dey combined varying concentrations of CuO nanoparticles with IBP Haulic-68 gear oil to create stable CuO nanofluids. Here, with a CuO volume fraction of 0.025, the viscosity of the fluid was increased by around three times that of the base fluid, but it sharply declined with increased temperature. As the CuO percentage increases, the Newtonian behaviour of oil transforms into a non-Newtonian one, and when the volume percentage of CuO exceeds 0.005, shear thinning was observed[23]. Katpatal *et al.* developed new lubricants by mixing ISO VG46 mineral oil with jatropha non-edible vegetable oil in ratios of 90:10 and 80:20. The findings suggest that the lubricant composed of 90% base oil and 10% nanoparticles, with a CuO content of 1.5 wt%, might potentially be used as a replacement for ISO VG46 oil[24]. CuO nanoparticles modified with surfactant sodium dodecyl sulfate (S-CuO) were evaluated by Sharma *et al.* as additives in conventional castor oil and palm oil. Through the SEM analysis of S-CuO nanoparticles of ~80 nm in size and spherical in shape, significant improvements in anti-wear, antifriction, and extreme pressure behaviour[25]. There is a lot of evidence from the past that edible and non-edible oils can be used in place of traditional cutting fluids when carrying out different machining tasks. However, because of the extraordinary need for edible oils as a food source, there is growing interest in using non-edible vegetable oils for energy and machining operations[26].

The gap in previous research for environmentally friendly lubricant has been bridged in this study by bringing together non-edible vegetable oils as biolubricating oil for the reduction of toxic value and biodegradability of the lubricating oil. In this study, raw castor oil was transesterified to produce castor oil methyl ester (CME) and used as a biolubricant along with conventional mineral (B20W-40) and synthetic oils (S20W-40). In this study, the produced CME, B20W-40, and S20W-40 oils were blended with 1 wt% CuO nanoparticles, and their various thermophysical and tribological properties were tested. Thermophysical properties like thermal conductivity, kinematic viscosity, flash point, fire point, pour point, and copper strip corrosion test are investigated. To investigate the tribological characteristics, four ball wear experiments were performed. Additionally, the material surfaces of the balls are examined using energy dispersive X-ray spectroscopy (EDX) in conjunction with field emission scanning electron microscopy (FE-SEM). All the test results were reported and compared with the base oils.

Experimental Section

Selection of oil

For the selection of lubricating oils, viscosity is thought to be the most important characteristic among all the chosen characteristics. Comparing many vegetable oils like mahua (*Madhuca Indica*), jatropha (*Jatropha* curcas), neem (*Azadirachtaindica*), tobacco (*Nicotianatabacum*), and castor (*Ricinus communis*), castor oil is more viscous due to its high polarity value forming an adhered film on the boundary layer of the contacting surfaces, which effectively provides good lubrication resulting in reduced attrition and increased sustainability of the lubricant in the machine parts. Compared to conventional oil sources, castor oil offers a number of advantages as a sustainable energy source, mostly because of its unique characteristics and benefits in production. It is appropriate for biodiesel and biolubricants due to its high ricinoleic acid concentration, which improves lubricity. Furthermore, unlike other vegetable oils, which pose a serious threat to food supplies, castor oil is made from non-edible seeds[27].The castor plant and seeds, which are shown in Fig. S1 (Supplementary Information), display the castor plant, which they grow mainly in tropical climates of countries like India, Brazil, and China. India ranks third in the production of castor oil in the world, supporting a world demand of 86%.

Extraction of biolubricant oil

The castor seeds are harvested directly from the fields of Anthiyur (latitude of 11° 34' 30.22" N), a village in the northern parts of Tamil Nadu, India. The harvested seeds were dried by sun irradiation and made dust-free to produce pure and high-performing biolubricant oil. The oil was extracted by the cold-pressing wooden oil extraction technique. Once the extraction was completed, the process of esterification was carried out as per the flowchart in Fig. S2 (Supplementary Information). Since the production of biolubricant is difficult with a high free fatty acids (FFA) value, an esterification process is used, and the level of FFA is controlled by a neutralization process[28].

The different biofuel conversion processes play a vital role in transforming biomass into sustainable energy, each utilizing distinct methods and serving specific applications. Gaining a clear understanding of these processes is key to improving biofuel production and advancing energy sustainability. Pyrolysis, gasification, and transesterification are the most important processes that convert biomass or bio-based materials into energy-rich biofuels. Transesterification is a fundamental process in the production of bio-lubricants, where alkyl groups are exchanged between an ester and an alcohol to form a new ester[29]. This process, often catalyzed by acids or bases, transfers triglycerides into fatty acid methyl esters, which could be further changed into biolubricants with improved properties. In this work,the extracted castor oil is then subject to a transesterification process by adding a mixture of NaOH and methanol at a temperature of 65°C. To remove the moisture from the esterified castor oil, and a magnetic stirrer is used to stir for 90 min. The stirred substance is left for 24 h to settle down glycerin by gravity using separating funnel. At the bottom, glycerin settles down, whereas CME is formed as top layer. The produced CME is subjected to warm water washing for around 6 to 8 times till the purest form of CME are achieved. The commercially available standard oils, such as B20W-40 (API SL JASO MA2) and synthetic oil B20W-40 (API SN JASO MA2) were purchased locally from Maruthi Agencies, Erode, and tested. Table 1 shows various characteristics of the oils used for this work and Fig. S3 (Supplementary Information) shows the various processes involved in the production of CME.

Table 1 — Specification of the mineral synthetic and vegetable oils

Properties	ASTM Standard	B20W-40 4T	S20W-40 4T	Castor oil
Density (g/mL)	D4052	0.88	0.870	0.873
Kinematic viscosity, cSt @ 40 °C	D445	161.10	172.3	271
Kinematic viscosity, cSt @ 100 °C	D445	19.26	20.8	26.7
Flash point (°C)	D93	220	214	208
Pour point (°C)	D97	- 30	- 36	-16
Viscosity index	D2270-10	136	142	163

Table 2 — Properties of CuO nanomaterial at room temperature

Properties	Value
Purity	>99.0%
Average particle size	30–50 nm
Colour	Black
Morphology	Spherical
Density	0.80 g/cm^3
Atomic weight	79.50 g/mol
Thermal conductivity	29 W/mK

Preparation of CuO Nanoparticles

To prepare CuO nanoparticles, an aqueous solution of copper acetate monohydrate is prepared with demineralized water. Glacial acetic acid weighing 1 mL and 0.1 mol of NaOH is added to the prepared solution and heated to 65°C with steady stirring. The process was repeated until the solution reached the pH value of 6-7. After that, the solution was allowed to settle at room temperature, and the black precipitate was detected. The obtained CuO precipitate was centrifuged and cleaned three to four times using deionized water. Further, the same was heated in a hot air oven for 24 h and dried. Table 2 shows the properties of the CuO nanomaterial.

Preparation of nanolubricant

For both practical and scientific uses, a stable and uniform suspension of nanofluid is essential. The preparation of nanofluids depends on stability since it influences the thermophysical properties and heat-carrying capabilities. The selected CuO nanoparticles also have a dispersion problem due to their unstableness and their intermolecular forces[30]. Numerous methods, such as surface modification, pH management, surfactant addition, and ultrasonication, have been documented in the literature to increase the stability of nanoparticles in a base fluid[31]. In this study, surface modification is adopted by adding oleic acid surfactant with nanoparticles in a beaker containing ethanol and stirred using a magnetic stirrer. In order to maintain homogeneity, the solution is heated till the ethanol becomes completely volatile.

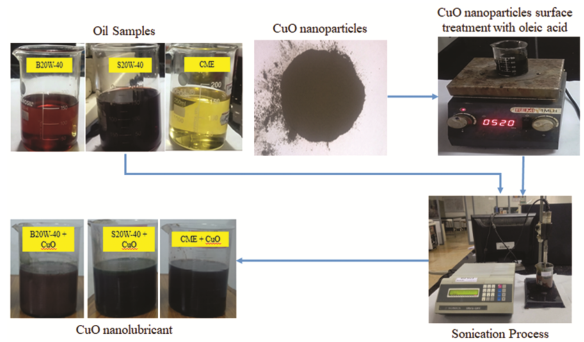

Fig. 1 — Dispersion of CuO nanoparticles in lubricating oil

The infused CuO is then added to the CME samples and exposed to sonication in an ultrasonic probe for 30 minutes. Finally, the homogenized CME biolubricant (CME+CuO) was obtained. The same method was also adapted to prepare B20W-40+CuO and S20W-40+CuO lubricants. The nanolubricant was prepared with as lubricant 98.84%, and additive solution 1.16% (1.0 wt% CuO + 0.16 wt% oleic acid). Fig. S4 (Supplementary Information) shows produced base and nanolubricant and Fig. 1 shows the dispersion of CuO nanoparticles in lubricating oil samples.

Copper strip corrosion test

The SYP1017-II copper strip corrosion tester was used to determine the corrosion adherence of the tested lubricants in accordance with ASTM D 130. In this test, a polished standard copper strip of size 75 x 12.5 x 3 mm is submerged in the oil sample and kept for 3 h at 150°C in an oven. The copper strip was taken out after 3 h, cleaned, and its color and degree of tarnish were evaluated using the ASTM copper strip corrosion stand. All laboratory tests in this study were performed three times, and the average of the results was taken and recorded for further analysis.

Thermophysical properties measurements

The thermophysical properties such as thermal conductivity, kinematic viscosity, flash point, fire point, and pour point of B20W-40, S20W-40, CME, B20W-40+CuO, S20W-40+CuO, and CME+CuO were measured as specified by ASTM standards. The measurement standard, accuracy and instruments used for the analysis are shown in Table S1 (Supplementary Information). The thermal conductivity of the samples was measured using a KD2 Pro thermal conductivity analyzer (Brand: METER, Model: TEMPOS). The kinematic viscosity was determined with a Redwood Viscometer (Smap Tech Enterprises, Coimbatore), while the flash and fire points of the oil were assessed using a Cleveland open cup apparatus (SubiTek, Coimbatore, India).

Measurement of tribological properties

A device called a four-ball wear tester (Fig. S5) offers many standards for evaluating the properties of fluids under various testing circumstances. The tests in this work were carried out using the four-ball tribometer in accordance with the ASTM D4172-B standard. For the analysis, four new chrome alloy steel balls are used in the tests. In the apparatus, three of the four balls (Diameter 12.7 mm, Extra polish grade 25 and hardness 64-66 HRC) were set at the bottom, and a final one was positioned at the top. The three balls, fastened in the bottom, are securely held in a container with 10 mL of the lubricant. The three balls are then forced up towards the ball positioned at the top. A top ball is locked in place using a steel clutch to ensure that it can rotate at the necessary fixed speed. On the other hand, the top ball is simultaneously forced up against the bottom three balls. The device has additional required components, such as the oil cup assembly and loads in kg[32,33]. Before the experimental run, the surface was cleaned with acetone. The testing of behaviour characteristics was conducted under a fixed load of 40 kg. Additionally, the rotational speed of the top ball was set to 1200 rpm, and the sample was kept at 75°C. The experiments were carried out with 40 kg load, 1200 rpm for 30 min at 75ºC. The diameter of the wear area (WSD) for every one of the three balls that were used in the study was calculated from the photomicrograph taken with a SEM microscope. The procedure was ascertained for all other balls, and the average value was recorded.

Results and Discussion

Characterization of CuO Nanoparticles

The CuO nanoparticle formation is validated using diffraction peak matching with patterns (JCPDF Card no. 05-661) at 2θ values of 35.5°, 38.7°, 48.9°, and 67.9° as shown in Fig. 2. The average crystallite size is determined to be between 9-12 nm using Debye Scherrer's relation shown in Eq. (1). The XRD pattern showed no impurity peaks[17].

$$D = \frac{0.9\lambda}{\beta\ cos\theta} \quad \dots (1)$$

Where, $\lambda - wavelength\ of\ Cu\ k\alpha_1 = 1.54060\ \AA$, $\beta - experimental\ peak\ width$ and $\theta - Bragg\ angles\ of\ the\ main\ planes$.

Fig. 3 displays the SEM micrograph of CuO nanoparticles. A look at the morphology of the CuO

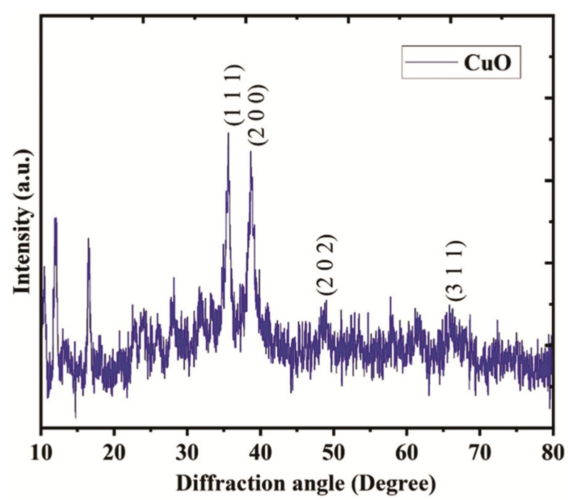

Fig. 2 — XRD Pattern of CuOnanoparticles

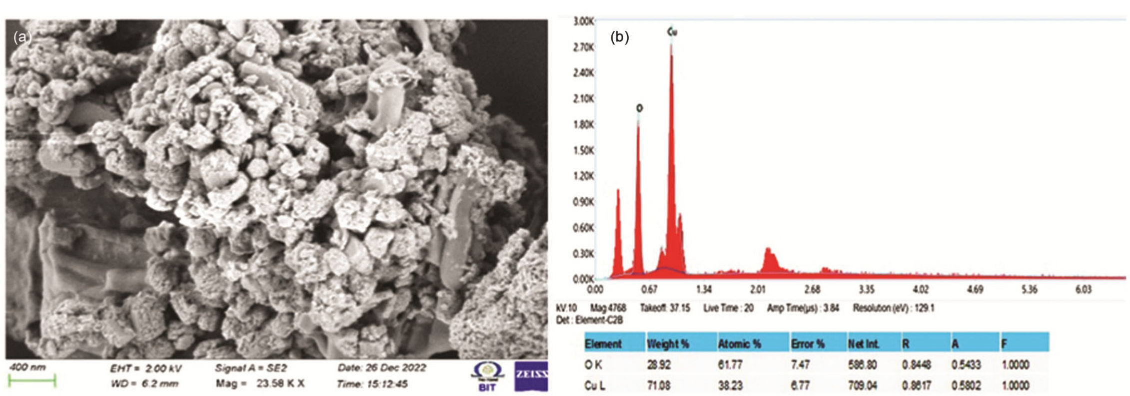

Fig. 3 — (a) SEM image and (b) EDX spectrum of CuO nanoparticles

reveals that most of them have nearly spherical shape, while a small percentage have irregular morphologies. As can be observed, the average size of CuO particles is between 50 and 70 nm. The small number of aggregates noticed in the image was due to the resulted agglomeration during the washing process. The XRD data and the particle size predicted by the SEM examination are in good agreement. The slight variation in the analysis can be explained by the local features shown by the SEM study and the overall picture depicted by the XRD[32]. The elemental composition and weight percentage of Cu and O are detected by EDX spectrum with two unique peak values for Cu and O separately as spotted in the figure. The CuO spherical nanoparticles act as an artificial ball bearing in the concept of the third body mechanism. In asperities, spherical nanoparticles will roll without difficulty with less consumption of energy, and that provides a rolling friction among the surface and lubricating oil. Due to this effect, the abrasion rate as well as the coefficient of friction can be minimized.

Stability analysis of the nanolubricant

The steric stabilization test was used to observe the dispersion and sedimentation of the lubricant blended with nanoparticles over a 30-day period, and it was conducted in transparent vials for ease of visualization. The sedimentation process following the sonication of CuO nanoparticles with three tested oils is depicted in Figs 4 a–c. The full dispersion of nanoparticles in all three oils is depicted in day one (Fig. 4a). The nanoparticles are beginning to settle in CME on day three, but the other oils stay the same. As seen in (Fig. 4b), CuO nanoparticles are fully settled at the end of the first week in CME. The blended nanoparticles were fully dispersed in S20W-40 oil during the course of 30 days. But the particles were partly sedimented in B20W-40 oil (Fig. 4c).

Corrosion resistance property

A copper-strip corrosion tester was used to examine the corrosion behaviour of raw CME, B20W-40+CuO, S20W-40+CuO, and CME+CuO. The Fourball wear tester is shown in Fig. S5 (Supplementary Information). All four oils subjected to the corrosion test exhibited mild corrosion (1a) on the copper strip as shown in Fig. 5. Higher level of FFA in the CME and CME+CuO may be the cause of the corrosion of copper strips[34]. The higher concentration of FFA ultimately raised the overall acidity of the lubricating oil. The chemically altered B20W-40+CuO and S20W-40+CuO also exhibited mild corrosion (1a). Higher acidity lubricants can cause rust and corrode metal surfaces, as well as create adverse effects on rubber seals and coatings[35]. As seen in the figure, the copper strip that had been corroded by all four oils had a minor tarnish.

Thermal conductivity measurement

Different samples of conventional and nanolubricants were prepared to measure thermal conductivity. The thermal conductivity analyzer measured the thermal conductivity of the samples using the transient hot wire method with an accuracy of ±5%. This device is helpful for measuring the value in the range of 0.2–2 W/mK. The device includes a conventional glass container, a display unit, and a probe having 1.3 mm diameter and a 60 mm length sensor. For the analysis, the glass container is first filled with roughly 50 mL of sample. Then, the probe is placed inside the container. After 90 s, the instrument showed the thermal conductivity value of the samples. For each sample, three readings were taken, and an average was considered and recorded. In the previous work, Katpatal *et al.* documented the use of this device[35].

Thermophysical testing apparatus and standards used are shown in Table S1 (Supplementary

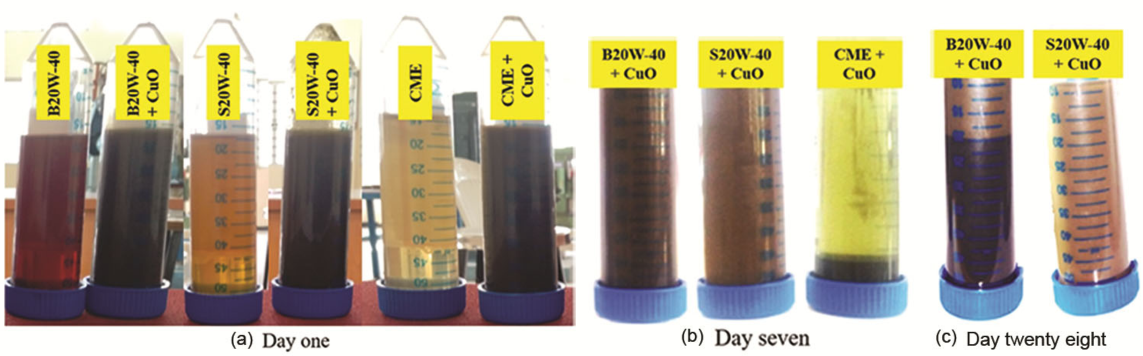

Fig. 4 — Agglomeration of the lubricant at different durations

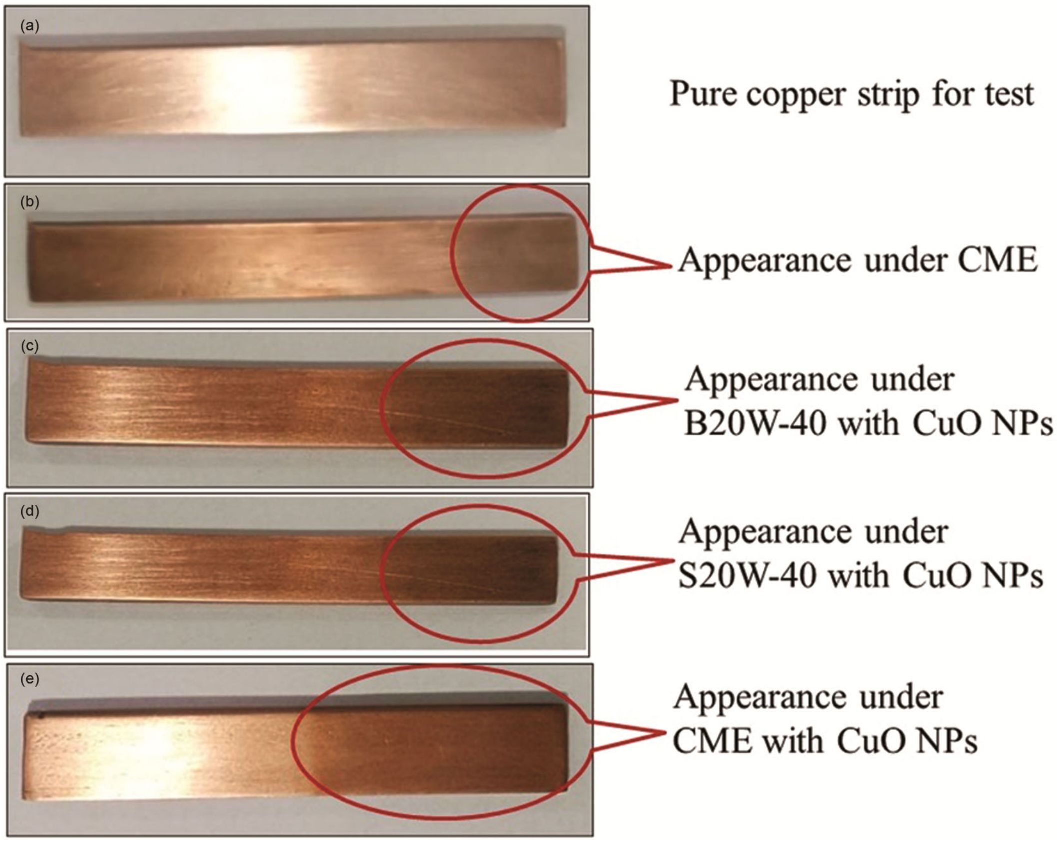

Fig. 5 — Corrosion resistance testspecimen (a) Raw strip (b) CME (c) B20W-40+CuO (d) S20W-40+CuO and (e) CME+CuO

Information). Thermal conductivity for B20W-40, S20W-40, and CME mixed with and without CuO nanoparticles is shown in Fig. 6. The thermal conductivity increased to 1.44%, 4.34%, and 1.86% due to addition of CuO nanoparticles with B20W-40, S20W-40 and CME, respectively. The result of the other researchers who have explored this analysis is used to strengthen the current investigation. Kole and Day discovered that adding 0.025% volume of CuO to gear oil increased thermal conductivity by 10.4%[36]. In a different investigation, Kole and Day found that adding 0.02% volume of Cu to gear oil increased thermal conductivity by 24%. By adding 0.075% volume of Cu to transformer oil[37], Xuan and Li observed an increase in nanofluid thermal conductivity by 43%[38]. Katpatal *et al.* showed the addition of 5 wt% CuO with jatropha nanolubricant showed an increment of 9.61%[35]. The reason for increased thermal conductivity is evidenced by the high thermal conduction of CuO nanoparticles. When the temperature increase, the thermal conductivity of the nano-oil increases by which the oil acts as a cleaner and removes dust particles. The Brownian

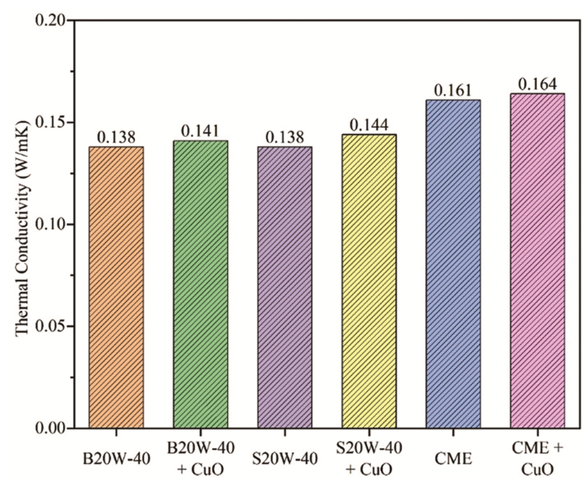

Fig. 6 — Comparison chart on thermal conductivity of the lubricating oil

motion of suspended nanoparticles transfers the heat energy from colloidal energy packets, which improves the thermal conductivity of the nanofluids[39,40]. In suspended nanoparticles, Brownian motion transfers heat energy through a number of interconnected processes that improve thermal conductivity. The

Table 3 — Rheological properties of various oils

Lubricating oil	Kinematic viscosity (10^{-6} m^2/s) without nanoparticle		Kinematic viscosity (10^{-6} m^2/s) with 1.0 wt% nanoparticle	
	at 40 °C	at 100 °C	at 40 °C	at 100 °C
B20W-40	187.3	40.1	223.4	55.0
S20W-40	180.2	38.2	197.2	44.4
CME	38.1	13.2	46.5	14.4

random movement of particles suspended in a fluid, known as Brownian motion, is essential for heat transfer because it influences the suspension's thermal characteristics and encourages localized convection. In general, Brownian motion can have a notable impact on fluid flow and heat transfer behaviour. It enhances thermal conductivity, decreases particle concentration near surfaces, and can also affect the fluid's velocity. The lower enhancement of the thermal conductivity in the selected samples may be due to the higher enhancement of the viscosity with the addition of the nanoparticles[36].

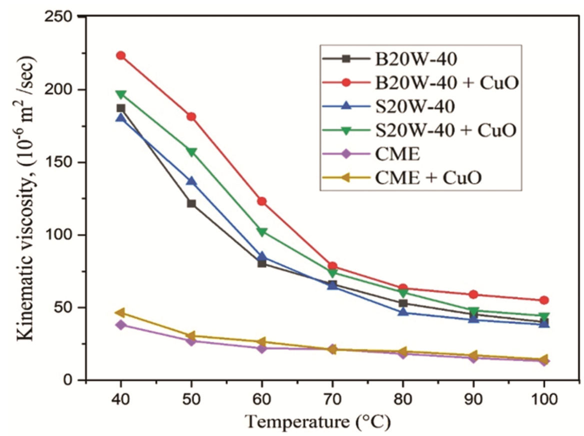

Fig. 7 — Viscosity analysis of the oils at different temperature

Effect of nanoparticle on viscosity measurement

The change in viscosity with 1.0 wt% addition of CuO nanoparticle at two different temperatures is shown in Table 3. The variations of kinematic viscosity at standard operating temperature ranging from 40°C to 100°C are displayed in the table. Viscosity is a crucial property of any oil that is used for lubrication. The temperature of the system has a significant impact on the viscosity of lubricant. The triglycerides of the vegetable oil have a narrow viscosity range, which limits their industrial use[42]. According to all suggested viscosity models, it has been found that the viscosity of the lubricant increases when the nanoparticles are loaded within it[43]. When the nanomaterial blended with the fluid, it agglomerated, increasing the shear stress. As a result, more effort is needed to disperse the nanolubricant[44]. As the concentration of nanoparticles increases, the fluid's rheological properties undergo notable changes, often resulting in shear thickening or shear thinning behaviour. Higher nanoparticle concentrations typically lead to increased viscosity and elevated critical shear rates, intensifying the shear thickening effect—especially in suspensions containing smaller nanoparticles. In general, the lubricant should adhere to safety standards when used for high-temperature applications. As the temperature gets increased, the viscosity gets decreased in all the samples of lubricating oil significantly, as shown in Fig. 7. As the temperature increases, the interparticle and intermolecular bonding forces weaken, which reduces the viscosity of the fluid. The higher temperature of the fluid, increase the average speed of the molecules hence the contact time between each molecule decreased. Consequently, the mean forces between molecules decrease with increasing temperature, resulting in a decrease in viscosity[45]. The kinematic viscosity of B20W-40, S20W-40, and CME lubricants increased by 19.27%, 9.43%, 22.04%, and 37.15%, 16.23%, and 9.09% at 40 °C and 100 °C for 1.0 wt.% concentration of CuO nanoparticles, respectively. The kinematic viscosity of the nanolubricant shows better results compared to base oils. The result of this study is also consistent with the available literature[30,31].

Flash and fire point measurement

The flashpoint is increased with the addition of CuO nanoparticles, which enhance the thermal stability of the lubricant oil relative to the basic fluids. The displayed result in Fig. 8 shows that flash and fire point values comparatively increased by adding 1.0 wt% concentration of CuO nanoparticles with B20W-40, S20W-40, and CME. Addition of CuO nanoparticles with B20W-40, S20W-40 and CME increased their flash point value up to 13.0%, 5.26% and 16.66%, respectively. Similarly, the fire point is increased to 5.66%, 3.17%, and 11.0% for B20W-40, S20W-40, and CME oil, respectively. Additionally,

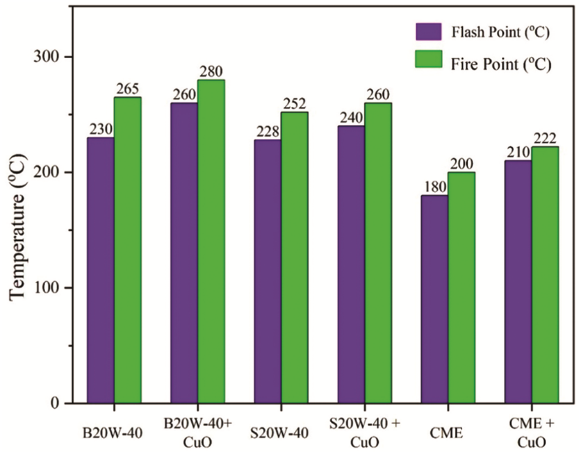

Fig. 8 — Flash and fire point analysis of the oils

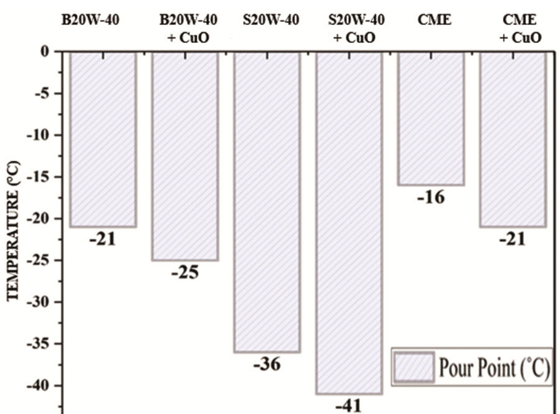

Fig. 9 — Comparison of pour point of the lubricating oil

the lowest temperature at which the oil can still flow was determined by analyzing the pour point. A low pour point ensures that the oil can still circulate and reach critical engine components during start-up, preventing wear and damage. From Fig. 9, it is observed that compared to all tested lubricating oils, S20W-40+CuO shows a better pour point. Since the engines are often subjected to a wide range of temperatures, oils with a low pour point maintain their lubricating properties in cold conditions, enhancing the reliability and longevity of the engine.

Tribology properties

The tribological properties of the lubricants B20W-40, S20W-40, and CME with and without CuO are evaluated by a four-ball wear tester. The obtained WSD and mean coefficient of friction (CoF) were illustrated in Fig. 10. The mean value of CoF is low for S20W-40 mixed with CuO additive. The value of CoF and WSD for S20W-40+CuO is 0.05934 and

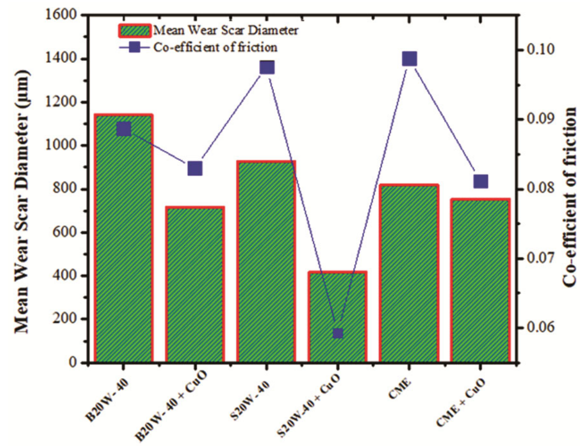

Fig. 10 — WSD and CoF analysis of the lubricating oils

415.6 µm, respectively. The CoF achieved medium value of 0.08114 for CME+CuO, for that oil the value of WSD is 753.9 µm. In this study, raw CME shows a higher CoF of 0.09877 with WSD of 817.4 µm. The value of CoF and WSD for B20W-40 is 1141.0 µm and 0.08861, respectively. Raw vegetable oil (CME) has a lower coefficient of friction (CoF) than raw mineral and synthetic oils because its fatty acids assist the lubricant molecules in adhering firmly to the steel ball's surface and preserving the lubricant layer[45]. The WSD is reduced by 37.3%, 55.16%, and 7.76% for B20W-40, S20W40, and CME when CuO nanoparticles were added with them. On the other side, the CoF reduced by 6.44%, 39.20%, and 17.84%, respectively. The friction behaviour was reduced by the inclusion of CuO nanoparticles in the lubricant. The sliding resistance and abrasion reduction can be qualified by the anti-wear characteristics of CuO nanoparticles; therefore, the sliding surface is protected by a filmy layer to avoid hard rubbing by nanoparticles.

SEM and EDX analysis

SEM photography analysis is used to understand the micro-level wear behaviour of tested ball surfaces. EDX is equipped with FESEM to identify the elemental composition of Cu and O in the worn surfaces. The worn surface of a steel ball lubricated with B20W-40, S20W-40, and CME with and without the addition of CuO concentration is displayed in Figs 11–13 at magnifications of 100x and 2000x. As seen in Fig. 11(a), the worn surface of B20W-40 oil without nanoparticles exhibits a slight exfoliation in the sliding direction. Fig. 12 (a) illustrates the small abrasive wear in the sliding direction of S20W-40 oil

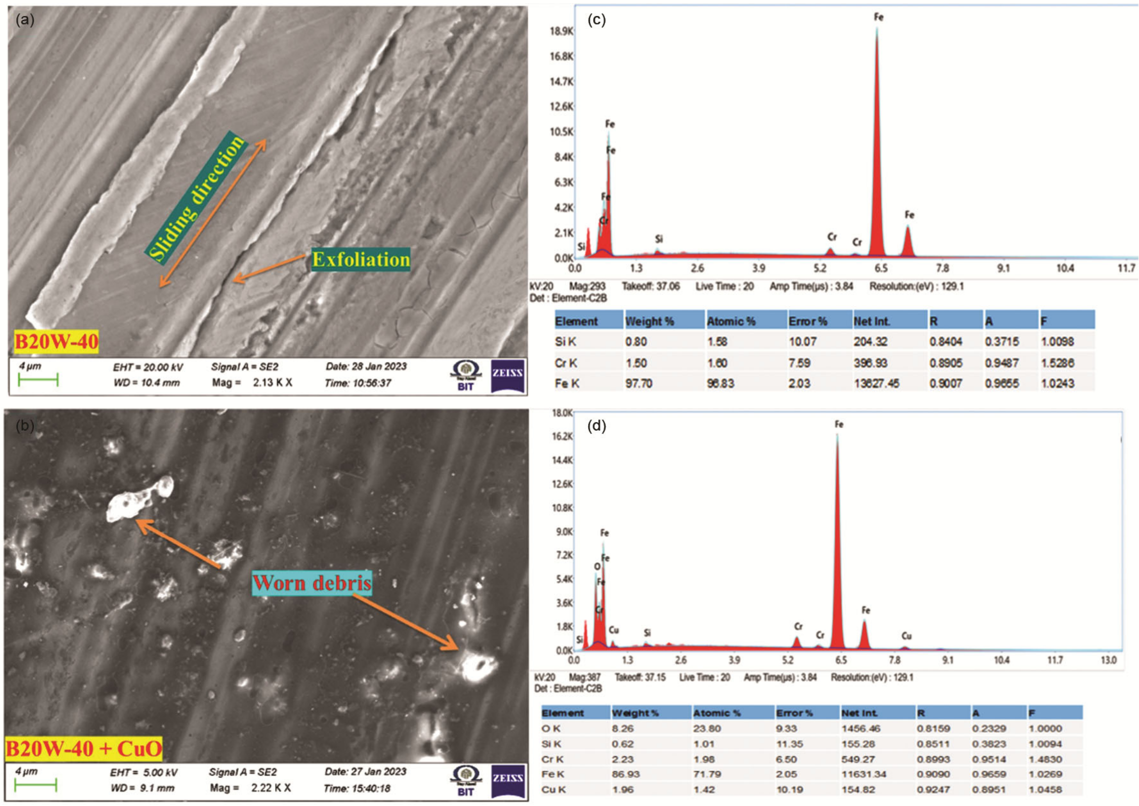

Fig. 11 — SEM and EDX analysis of B20W-40 and B20W-40+CuO

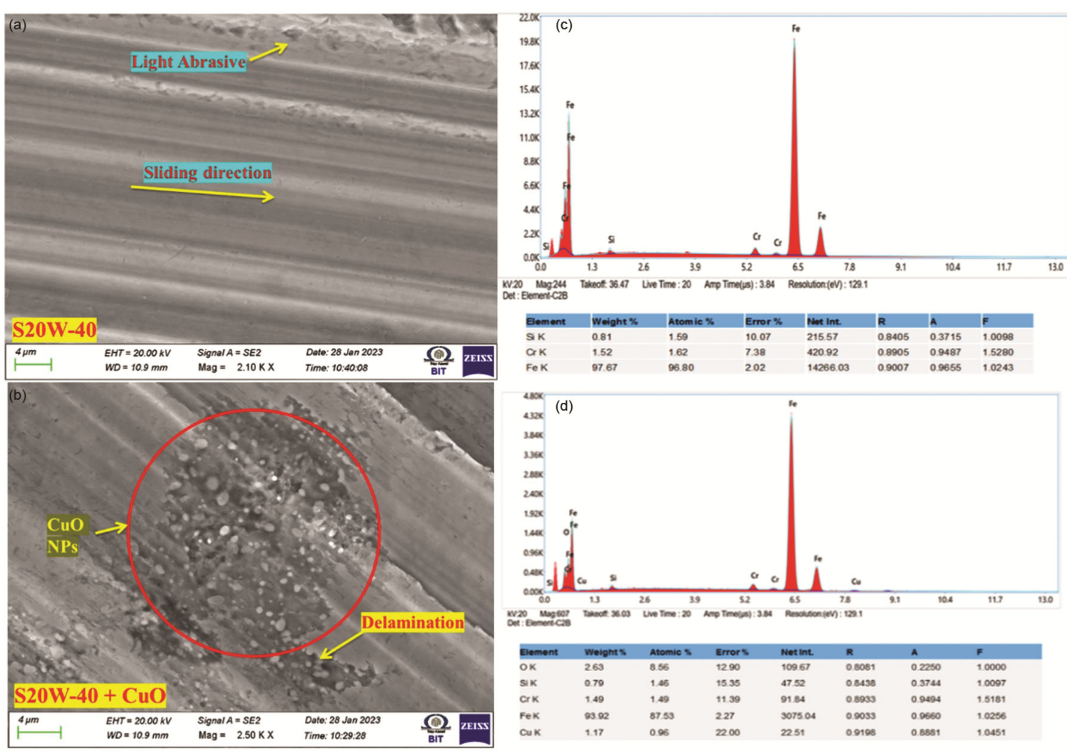

Fig. 12 — SEM and EDX analysis of S20W-40 and S20W-40+CuO

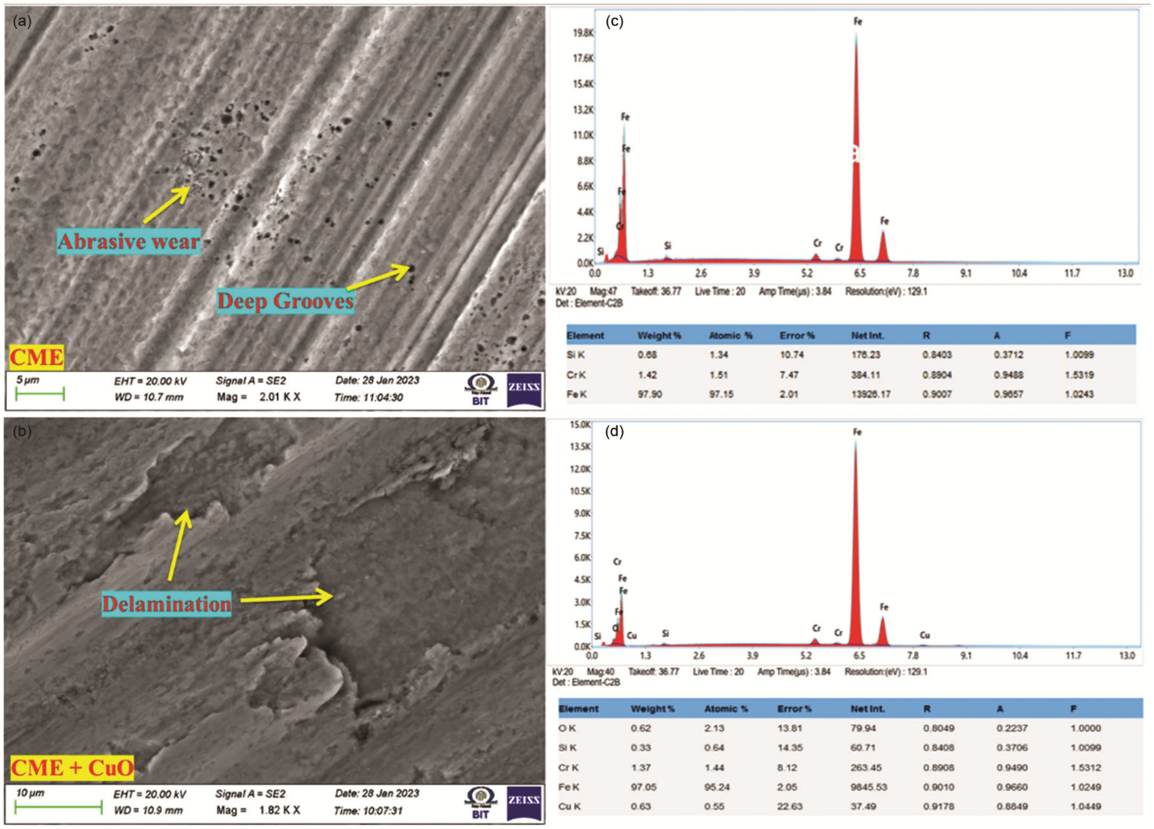

Fig. 13 — SEM and EDX analysis of CME and CME+CuO

without nanoparticles, while Fig. 13 (a) depicts the mild abrasive wear in CME oil. When CuO is added to B20W-40 oil, a slight wear is observed on the image and B20W-40 oil CuO is used to lubricate the worn surface (Fig. 11(b)). When S20W-40 oil mixed with CuO, it reduces the abrasion by uniform distribution on worn surface exhibiting lower WSD Fig. 12(b). From Fig. 13(b), it can be understood that CuO with CME functions as a better protective layer compared to source oil. As a result, the inclusion of CuO nanoparticles with all base oils reduces abrasion and sliding resistance through two lubrication mechanisms, such as protective film generation and polishing action.

EDX analysis provides additional information by analyzing the nanoparticle deposition on the worn surface. The elemental impact on the worn scar electron image and the associated elemental data for the nanolubricants are shown in Fig. 11. In addition, it shows the elementary analysis of the contact regions lubricated with sample oils with and without CuO nanoparticles. Through this analysis, the impact of CuO on wear reduction can be assessed and reported. The EDX spectrum demonstrates that the B20W-40+CuO contain 1.96 wt% of Cu and 8.26 wt% of O. Similarly, B20W-40+CuO and CME+CuO contain 1.17 wt% and 0.63 wt% of Cu and 2.63 wt% and 0.62 wt% of O, respectively. When combined with CuO, B20W-40 oil shows a larger CuO portion, whereas S20W-40 oil shows lower CuO portions (Figs 12 c & d). Finally, CuO added CME oil shows fewer amounts of CuO nanoparticles depicted from Fig 13 (c & d). A large amount of nanoparticles is occupied in a larger abrasive area and a smaller amount in a smaller abrasive area.

Conclusion

In this research work, thermophysical and tribology properties were investigated for B20W-40, S20W-40, and CME lubricating oil mixed with 1.0 wt.% CuO nanoparticle addition. Thermal conductivity is increased with the addition of CuO by 1.44%, 4.34%, and 1.86% for B20W-40, S20W-40, and CME oil, respectively. The kinematic viscosity with addition of CuO nanoparticles at 40°C increased by 19.27%, 9.43% and 22.04% and at 100°C, it increased by 37.15%, 16.23% and 9.09% for B20W-40, S20W-40 and CME oils, respectively. Besides that, CME oil is preferable for normal operating temperature. The tribological effects of the oils with CuO were investigated by the four-ball wear test. The CuO nanoparticles in the oil acted as third-body nanoball bearings and filled the asperities by tribo-sintering mechanisms. Hence, the co-efficient of friction improved by a reduction value of 6.44%, 39.20% and 17.84%. Tested ball surfaces were examined by SEM, which confirmed the surface enrichment is attained by the action of protective film and polishing effect of nanoparticles. The elemental presence of Cu and O on the worn surface was evidenced by EDX results, which show a higher presence of Cu in B20W-40, comparatively lower in S20W-40, and very less in CME oil when the oils were blended with CuO. From the results obtained it is concluded that the base oils with nanoparticles gives better thermophysical and tribological behaviour. Further biolubricating castor oil methyl ester can be a suitable option to replace conventional lubricants.

Acknowledgment

The authors are grateful to acknowledge the support rendered by the Research Center, Bannari Amman Institute of Technology, Sathyamangalam, Erode, Tamil Nadu, India; the Center for Research, SCSVMV University, Kanchipuram, Tamil Nadu, India; the Sophisticated Instrumentation Facility (SIF), NIT-Thiruchirappalli, Tamil Nadu, India; and Bombay Test House Pvt Ltd, Navi Mumbai, Maharashtra, India.

Supplementary Information

Supplementary information is available on the website http://nopr.niscpr.res.in/handle/123456789.

Conflict of interest

The authors declare no conflict of interest.

References

1 Dang R K, Chauhan A & Dhami S S, Static thermal performance evaluation of elliptical journal bearings with nanolubricants, *Proc Inst Mech Eng Part: J J Eng Tribol*, 235 (2021) 1627.

2 Uniyal P, Gaur P, Yadav J, Khan T & Ahmed O S, A review on the effect of metal oxide nanoparticles on tribological properties of biolubricants, *ACS Omega*, 9 (2024) 12436.

3 Kumaravel S, Saravanan C G, Vikneswaran M, Raman V, Sasikala J, Josephin J S F & Allasi H L, Exploration of flame characteristics of gasoline engine fuelled by gasoline-pentanol blends using combustion endoscopy, *Sci Rep*, 14 (2024) 31692.

4 Rajesh S P, Retnam B S J, Dhas J E R, Lenin A H & Manjunathan A, Specific fuel consumption and exhaust emission test on single cylinder four-stroke diesel engine using polyethylene extract biodiesel as fuel, *Int J Veh Struct Syst*, 14 (2022) 339.

5 Shankar S, Manikandan M, Raja G & Pramanik A, Experimental investigations of vibration and acoustics signals in milling process using kapok oil as cutting fluid, *Mech Ind*, 21 (2020) 521.

6 Devlin M T, Common properties of lubricants that affect vehicle fuel efficiency: A North American historical perspective, *Lubricants*, 6 (2018) 68.

7 Dhanola A & Garg H C, Experimental analysis of the efficacy of vegetable oil-based nanolubricants for improving journal-bearing performance, *Proc Inst Mech Eng Part: J J Eng Tribol*, 235 (2021) 1974.

8 Alves S M, Mello V S, Faria E A & Camargo A P P, Nanolubricants developed from tiny CuO nanoparticles, *Tribol Int*, 100 (2016) 263.

9 Peña-Parás L, Taha-Tijerina J, Garza L, Maldonado-Cortés D, Michalczewski R & Lapray C, Effect of CuO and Al_2O_3 nanoparticle additives on the tribological behavior of fully formulated oils, *Wear*, 332 (2015) 1256.

10 Gosai D C, Modi A J & Gillawat A K, Impact of nano-fuel additives and nano-lubricant oil additives on diesel engine performance and emission characteristics, *Int J Heat Mass Transfer Res*, 12 (2025) 103.

11 Abd-Elhaseeb D M, Ali M K A, Ezzat M F & Mourad M A, Review of the tribological properties of nanoparticles dispersed in bio-lubricants, *Proc Inst Mech Eng Part J: J Eng Tribol*, 237 (2023) 27.

12 Allasi H L, Rajalingam A A, Jani S P & Uppalapati S, Influence of synthesized (green) cerium oxide nanoparticle with neem (Azadirachtaindica) oil biofuel, *Bull Chem Soc Ethiop*, 37 (2023) 477.

13 Azam S & Park S S, Impact of biosynthesized CeO_2 nanoparticle concentration on the tribological, rheological, and thermal performance of lubricating oil, *Lubricants*, 12 (2024) 400.

14 Nugroho A, Kozin M, Mamat R, Bo Z, Ghazali M F, Kamil M P & Daud S, Enhancing tribological performance of electric vehicle lubricants: Nanoparticle-enriched palm oil biolubricants for wear resistance, *Heliyon*, 10 (2024) e39742.

15 Prakash K R, Lathika A S, Ramanna M, Bandadka S & Anand A, Experimental study on tribological, rheological and bio-degradability characteristics of canola oil with TiO_2 nanoparticles as bio-nanolubricants, *Tribol Ind*, 46 (2024) 458.

16 Uppar R, Dinesha P & Kumar S, Characterization of bio-lubricants with nanoparticles additives, *Energy Sources Part A*, 46 (2024) 3684.

17 Akbulut M, Nanoparticle-based lubrication systems, *J Powder Metall Min*, 1 (2012) 1.

18 Farfan-Cabrera L I, Gallardo-Hernández E A, Gómez-Guarneros M, Pérez-González J & Godínez-Salcedo J G, Alteration of lubricity of Jatropha oil used as bio-lubricant for engines due to thermal ageing, *Renew Energy*, 149 (2020) 1197.

19 Sen B, Kothapalli S K, Kumar R, Abdullah I, Singh G & Santhosh A J, Minimum quantity blended bio-lubricants for sustainable machining of superalloy: An MCDM model-based study, *AIP Adv*, 14 (2024) 075224

20 Edla S, Krishna A, Karthik G V S, Arif M M & Rani S, Potential use of transesterified vegetable oil blends as base stocks for metalworking fluids and cutting forces prediction using machine learning tool, *Biomass Convers Biorefin*, 13 (2021) 10665.
21 Yuan J, Liu N, Zou X, Wu L, Zhang Y, He T & Chen Y, Processing characteristics and lubrication performance of castor oil-ethanol blended coolant-based minimal quantity lubrication, *CIRP J Manuf Sci Technol*, 36 (2022) 78.
22 Rashin M N & Hemalatha J, Viscosity studies on novel copper oxide-coconut oil nanofluids, *Exp Therm Fluid Sci*, 48 (2013) 67.
23 Kole M & Dey T K, Effect of aggregation on the viscosity of copper oxide-gear oil nanofluids, *Int J Therm Sci*, 50 (2011) 1741.
24 Katpatal D C, Andhare A B & Padole P M, Viscosity behaviour and thermal conductivity prediction of CuO-blend oil based nano-blended lubricant, *Proc Inst Mech Eng Part: J J Eng Tribol*, 233 (2019) 1154.
25 Sharma V, Hossain A K, Duraisamy G & Vijay M, Transesterification of pyrolysed castor seed oil in the presence of CaCu $(OCH_3)_2$ catalyst, *Energies*, 14 (2021) 6064.
26 Saravanakumar K, Robinson Y, Dhanalakshmi C S & Madhu P, Improving the poor properties of methyl ester with pyrolysis oil and fossil diesel-An experimental investigation on PSZ ceramic coated engine with the addition of GO nanoparticles, *Indian J Chem Technol*, 31 (2024) 553.
27 Pradhan S, Saha C, Kumar M & Naik S N, Transesterification and reactive extraction of castor oil for synthesis of biodiesel/biolubricant, *IOP Conf Ser Earth Environ Sci*, 785 (2021) 012005.
28 Raj R S, Madhu P, Dhanalakshmi C S & Prakash M A, Application of CuO nanoparticles on performance and emission characteristics of ternary blends of diesel, waste cooking oil and pumpkin seed oil biodiesel in an IC engine, *Indian J Chem Technol*, 32 (2025) 33.
29 Saravanan C G, Varuvel E G, Vikneswaran M, Femilda-Josephin J S, Chinnathambi A, Pugazhendhi A & Allasi H L, The combustion of lemon peel oil/gasoline blends in spark ignition engine with high-insulation piston crown coating, *Sci Rep*, 14 (2024) 28740.
30 Gupta R N & Harsha A P, Tribological study of castor oil with surface-modified CuO nanoparticles in boundary lubrication, *Ind Lubr Tribol*, 70 (2018) 700.
31 Yusof S N A, Sidik N A C, Asako Y, Japar W M A A, Mohamed S B & Muhammad N M A, A comprehensive review of the influences of nanoparticles as a fuel additive in an internal combustion engine (ICE), *Nanotechnol Rev*, 9 (2020) 1326.
32 Jabal M H, Hassoun E O, Abdulmunem A R & Ani F N, Experimental investigation of the neat rubber seed oil as a hydraulic fluid using four-ball tribotester, *J Eng Sci Technol*, 14 (2019) 2670.
33 Hassan M, Ani F N & Syahrullail S, Tribological features of refined, deodorized, and bleached palm olein with mineral oil blend, *Tribol Trans*, 59 (2016) 671.
34 Li W & Wang X, Bio-lubricants derived from waste cooking oil with improved oxidation stability and low-temperature properties, *J Oleo Sci*, 64 (2015) 367.
35 Katpatal D C, Andhare A B, Padole P M & Khedkar R S, Study of dispersion stability and thermo-physical properties of CuO-Jatropha oil-based nanolubricants, *J Braz Soc Mech Sci Eng*, 39 (2017) 3657.
36 Kole M & Dey T K, Role of interfacial layer and clustering on the effective thermal conductivity of CuO-gear oil nanofluids, *Exp Therm Fluid Sci*, 35 (2011) 1490.
37 Kole M & Dey T K, Enhanced thermophysical properties of copper nanoparticles dispersed in gear oil, *Appl Therm Eng*, 56 (2013) 45.
38 Xuan Y & Li Q, Heat transfer enhancement of nanofluids, *Int J Heat Fluid Flow*, 21 (2000) 58.
39 Choi S U S, Zhang Z G, Yu W, Lockwood F E & Grulke E A, Anomalous thermal conductivity enhancement in nanotube suspensions, *Appl Phys Lett*, 79 (2001) 2252.
40 Hong T K & Yang H S, Nanoparticle-dispersion-dependent thermal conductivity in nanofluids, *J Korean Phys Soc*, 47 (2005) 321.
41 Li C H, Jiang P & Peterson G P, Dual role of nanoparticles in the thermal conductivity enhancement of nanoparticle suspensions, *J Nanofluids*, 2 (2013) 20.
42 Salimon J, Salih N & Yousif E, Biolubricants: Raw materials, chemical modifications and environmental benefits, *Eur J Lipid Sci Technol*, 112 (2010) 519.
43 Lee S W, Park S D, Kang S, Bang I C & Kim J H, Investigation of viscosity and thermal conductivity of SiC nanofluids for heat transfer applications, *Int J Heat Mass Transfer*, 54 (2011) 433.
44 Xie H, Chen L & Wu Q, Measurements of the viscosity of suspensions (nanofluids) containing nanosized Al_2O_3 particles, *High Temp High Pressures*, 37 (2008) 127.
45 Namburu P K, Kulkarni D P, Dandekar A & Das D K, Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids, *Micro Nano Lett*, 2 (2007) 67.