A Study on the Tribological Performance of Nanolubricants

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Abstract: In recent years, the tribology field has expanded with the advent of nanolubrication. Nanolubricants are the name given to the dispersion of nanoparticles in a base oil, and has attracted researchers due to its potential application. In addition to being used in the tribology field, nanoparticles are also used for medical, space, and composites purposes. The addition of nanoparticles in base oils is promising because it enhances specific tribological characteristics including wear-resistance and friction, and the most important reason is that the majority of them are environmentally friendly. This paper reviews the tribological effect of various nanoparticles as lubricant additives. Parameters of nanoparticles that affect tribological performance, the technique to enhance stability, and lubrication mechanism that is currently believed to function will be delineated in detail. Moreover, this review facilitates an understanding of the role of various nanoparticles, which helps in developing and designing suitable nanolubricants for various applications.

Keywords: nanoparticles; nanolubricants; tribological performance; lubrication mechanism; dispersion stability

1. Introduction

Tribology is the study of science related to friction, wear, and lubrication [1]. Lubrication is the process or technique to reduce the friction and wear for two relative moving surfaces by using lubricant. The benefits provided by lubrication include rust, water, and dust prevention and as an insulator in transformer [2]. Wear and friction can cause machinery failure (for example in the engine, shaft, bearings, gears) and energy losses. Hence, it is essential to have sufficient lubrication to overcome these issues. Hence, it is essential to have sufficient lubrication to overcome these issues. An analysis by Holmberg et al. [3] conclude that friction in the engine and other moving parts can result in the waste of one third of all the fuel energy used. They also analyze new technology that can reduce friction by 18% over 5–10 years and a 61% reduction over 15–25 years for automobiles. Additionally, the potential techniques for friction reduction such as coatings and surface texturing on automobile parts, novel additives, reducing the width of tires had been suggested.

Moreover, lubricant is an indispensable tool which is used to lubricate machinery to protect operating mechanical parts from wear and reduce friction. Mineral oil as a lubricant has already been in use for a long time. However, pollution in aquatic and terrestrial ecosystems caused by the disposal of mineral oil directly affected the environment [4]. An alternative source such as biolubricant oil is a promising replacement to mineral oil because it is biodegradable and nontoxic. Further, biolubricants
evidence several advantages compared to mineral oil including excellent lubricity, obtaining high flash point, viscosity, and low volatility.

To further minimize wear and friction in the system, small amounts of weight percentage of additives are added to the lubricant base stock to improve and enhance the oil properties. Those additives can be anti-wear (AW), extreme pressure (EP), anti-corrosion, dispersant, and AW and EP additives are especially used to lubricate mechanical parts. One should note that the traditional EP and AW additives are chlorine and phosphorus compounds, which have been restricted in terms of use due to the purpose of environment protection. To overcome this problem and most of the existing lubricants which have reached performance bottlenecks, researchers are currently investigating nanoparticles (NPs) design as a new class of lubricant additives. Most NPs are environmentally friendly and exhibit tribological properties improvement in lubricants since it does not require triboactive elements such as chlorine, phosphorus, and sulphur, which are harmful to the environment [5,6]. Moreover, the nanometer size range of NPs are able to fill contact asperities. They function as AW and EP additives and friction modifiers, obtain high thermal stability, and react with the friction surface without an induction period [7].

To date, various type of NPs used as lubricant additives have been documented in many studies. Metal [8], metal sulphides [9], metal oxide [10], boron nitrides [11], carbon materials [12,13], nanocomposites [14], and rare earth compounds [15] exhibit excellent wear and friction reduction. In this present study, NPs as lubricant additives will be reviewed. This review including the experiment test condition (speed, time, temperature, tested stock), NP information (size, concentration), the optimum concentration of NPs, the dispersion method, the method to evaluate dispersion stability, the lubrication mechanism of NPs, and the parameters of NPs that affect tribological properties in the lubricant. The relevant tribology information regarding the lubricants will also be discussed.

2. Tribology

Tribology is the study of the science of interacting surfaces or two moving bodies in relative motion. It is related to friction, wear, lubrication, degradation of metal surfaces, corrosion, engine life, and energy losses. Since there are incredibly high energy losses due to this phenomenon, such losses caused by friction and wear should be minimized [16]. To satisfy the lubrication requirements of the particular application, specifically in tribological aspects, the most important way is selecting a suitable lubricant. Lubrication, friction, and wear are related to tribological performance. Lubricity is concerned with the formation of a protective layer or tribofilm on the contact surfaces. High lubricity reduces direct surface contact, thereby reducing friction and energy losses [17]. However, having a high lubricity is not always accompanied by better wear protection, because the formation of a protective layer on the rubbing surfaces happens through the absorption of the surface-active substance of lubricants such as base stocks or additives. When surface asperity contacts each other, three types of mechanical wear are possible resulting in the following: adhesion, abrasion, and fatigue [18]. Adhesive wear occurs when high loads, high temperature, or inadequate lubrication cause two relatively moving surfaces asperity welds and then immediately tear apart. Abrasive wear happens when surface rubbing occurs between contact surfaces of relative hardness. Fatigue wear is the progressive and localized structural damage of material in repeated loading [19]. Prior to discussing the tribological performance of the nanolubricants, it is necessary to understand the three basic tribology parameters, which are the mechanical properties of a tribological system, lubrication, and the physicochemical properties of the lubricant [19].

2.1. Energy Losses

Energy losses due to friction are incredibly high. Energy losses in the engine due to friction result in heating and promote the wear on the surfaces of moving part. It has been reported that 75–82% total energy losses in the vehicle, engine losses is between 68% and 72%, 12–30% energy from fuel used to move the vehicle and energy losses due to friction are around 3%, as shown in Figure 1 [20,21].
The combined effect of friction and wear caused 30% total energy losses [22]. Energy losses due to the friction can be reduced by a few technologies such as the design of tires and bearings, tribology, and additives. Further, in order to overcome the energy losses, the lubricant which imparts the best lubrication is essential.

2.2. Mechanical Properties of a Tribological System

The mechanical properties of a tribological system are related to material hardness and its surface roughness, contact geometry, and the sliding mechanism of the rubbing part, as shown in Figure 2. Discussion of those properties are limited to the laboratory tribometer. Usually, the material used for the test has a hardness of around 30-64 Hardness Rockwell C (HRC) and 0.01–1.0 µm surface roughness. For example, the hardness and surface roughness of steel ball used in a four-ball tribometer is 62 HRC and 0.040 µm [23]. However, it still depends on the type of material, hardening process, and coating. Basically, the higher the hardness of materials, the more significant the wear resistance, while the lower surface roughness of materials evidences better lubricity [24]. It seems impossible to compare the tribological results between different types of tribometers, such as four-ball tribotester, pin-on-disk, ball-on-disk. This is because of varying sliding geometries and their sliding mechanism, for example, sliding and rolling. Some commonly used tribological test geometry configurations are shown in Figure 3. Valid comparisons can be achieved when conducted using a similar type of tribometer and method/parameter, for example, ASTM D2266, ASTM D2783, ASTM G99 [19].
According to the Stribeck curve, there are three well-known lubrication regimes. The first regime is boundary lubrication (BL), second regime is mixed and elastohydrodynamic lubrication (EHL), and the third regime is hydrodynamic lubrication (HL) [25], as shown in Figure 4. BL happens when repeated loading/high load or low sliding speed generates heat and causes high wear and energy losses because of the unstable and thin tribofilm that forms on the rubbing surfaces. Thus, lubricant additives are important to protect the friction surface(s) [26]. Shock loading is also a factor that results in BL. Again, by further decreasing the load or increasing sliding speed, the lubrication regimes will shift to a mixed/EHL regime and then to a hydrodynamic regime. Through this transition, friction and wear will decrease due to hydrodynamic lift since a thicker tribofilm will separate the contacting surfaces. HL will occur when two interacting surfaces are separated by a tribofilm. In this regime, no significant mechanical wear occurs except fatigue due to the contacts being fully lubricated and the friction dominated by viscous dragging forces [26]. EHL is similar to hydrodynamic lubrication, but this lubrication is involved in the rolling motion. Mixed lubrication is a combination of BL and HL. When under a mixed/EHL regime, the tribofilm had around 1–3 times greater film thickness than surface roughness. Under the hydrodynamic regime, the tribofilm had three times greater film thickness than surface roughness [27]. Besides, the tribofilm in EHL lubrication is much thinner and the pressure exerted is greater than hydrodynamic lubrication. Typically, the coefficient of friction (COF) value of BL will greater than 0.1, while for mixed/EHL lubrication has a range of 0.01–0.10 COF and HL has a COF less than 0.01 [18].

![Figure 3. Commonly used tribological test geometry configuration: (a) four-ball tribometer, (b) pin-on-disc, (c) block-on-ring, (d) pin-on-flat, and (e) ball-on-flat.](image)

2.3. Lubrication

Lubrication is essential to overcome and reduce friction between two interacting parts. According to the Strubeck curve, there are three well-known lubrication regimes. The first regime is boundary lubrication (BL), second regime is mixed and elastohydrodynamic lubrication (EHL), and the third regime is hydrodynamic lubrication (HL) [25], as shown in Figure 4. BL happens when repeated loading/high load or low sliding speed generates heat and causes high wear and energy losses because of the unstable and thin tribofilm that forms on the rubbing surfaces. Thus, lubricant additives are important to protect the friction surface(s) [26]. Shock loading is also a factor that results in BL. Again, by further decreasing the load or increasing sliding speed, the lubrication regimes will shift to a mixed/EHL regime and then to a hydrodynamic regime. Through this transition, friction and wear will decrease due to hydrodynamic lift since a thicker tribofilm will separate the contacting surfaces. HL will occur when two interacting surfaces are separated by a tribofilm. In this regime, no significant mechanical wear occurs except fatigue due to the contacts being fully lubricated and the friction dominated by viscous dragging forces [26]. EHL is similar to hydrodynamic lubrication, but this lubrication is involved in the rolling motion. Mixed lubrication is a combination of BL and HL. When under a mixed/EHL regime, the tribofilm had around 1–3 times greater film thickness than surface roughness. Under the hydrodynamic regime, the tribofilm had three times greater film thickness than surface roughness [27]. Besides, the tribofilm in EHL lubrication is much thinner and the pressure exerted is greater than hydrodynamic lubrication. Typically, the coefficient of friction (COF) value of BL will greater than 0.1, while for mixed/EHL lubrication has a range of 0.01–0.10 COF and HL has a COF less than 0.01 [18].

![Figure 4. Graphical illustration of various types of lubrication regimes and conditions [19].](image)
2.4. Physicochemical Properties of the Lubricant

One of the critical parameters for tribological performance is the physicochemical properties of the lubricant. Different types of oil have their properties, such as different viscosity, density, and flash point since they are made from different feedstocks. Viscosity indicates resistance to flow due to internal friction, and it is the most important property in lubricant oil. Furthermore, it is related to temperature, pressure, and the form of tribofilm, and ultimately decides the tribological performance [2]. Higher viscosity indicates higher flow resistance; increasing the viscosity of the lubricant creates a thicker tribofilm but provides lower efficiency due to higher viscosity results in more poor fuel atomization [28]. Considering the condition of temperature elevation and high loading, a lubricant that has a high pressure-viscosity coefficient and high viscosity index will be preferred, to ensure the tribofilm is stable. Other physical properties including pour point, flash and fire point, oxidative stability, and thermal stability will affect the strength and stability of the tribofilm [28].

Furthermore, the tribochemical characteristics of lubricants concern so-called surface active materials exhibit lubricity, load carrying capacity, and wear resistance. They primarily act as an anti-wear additive (AW), an extreme pressure additive (EP), and a friction modifier (FM) [19]. AW and EP additive are categorized into two main types, active and non-active. Active additives through the tribochemical reaction with the contact surface form a sacrificial protective film to reduce wear. In contrast, non-active additives form a protective film by becoming deposited via by-product to minimize wear. AW and EP additive have a similar function in terms of application. However, the difference between them is the rate of reaction of EP to form the protective film is higher, the film is more robust and thicker and suitable for high-speed operation. FM provides a softer, easily sheared protective film which minimizes light surface contacts (sliding and rolling friction), and thus less energy is consumed. Typically, the COF of FM film is 0.01–0.05, which is lower than COF of EP and AW film (0.06–0.15), but higher than the COF of EP and AW (0.001–0.009) under hydrodynamic regime [29]. Those additives mostly operate in BL and mixed/EHL lubrication regime, which result in protecting material surfaces and enhancing lubricity [19].

3. Nanolubricants and Base Oils

3.1. Nanolubricants

From here the use of nanoparticles/nanomaterials as lubricant additives are known as nanolubricants. Typically, their diameter particle size is between 1 and 100 nm. In laboratory tests, the use of nanolubricants in base oils or coatings promotes a significant reduction of friction and wear, which exhibits interesting tribological properties. Nanolubricants can be synthesized by the one-step method or two-step method. For the one-step method, the nanolubricants directly formulate through a chemical process. In the two-step method, the first procedure is the nanomaterials are synthesized in dry powder form by either physical or chemical methods, and the second procedure is to disperse them into base oil by mixing techniques with or without dispersants or surfactants [30]. An illustration of nanolubricants synthesis is shown in Figure 5.

![Figure 5. Synthesis of nanolubricants.](image-url)
3.2. Base Oils

Lubricants are classified into three physical appearances: solid, semisolid, and liquid form. Generally, lubricants are synthesized from three different types of base oils. They are mineral oil, synthetic oil, and biolubricant. The American Petroleum Institute (API) classified lubricant base oil quality and the necessary information of different groups of base oils under API 1509, as shown in Table 1 [31]. Groups I–III base oils are refined from crude oil. Group IV base oils are fully synthetic oils made by polyalphaolefins (PAO). Group V base oils are those oils not found in groups I–IV categories. This group includes other base oils such as silicone, organophosphates, polyalkylene glycol (PAG), polyolester, and biolubricants.

| Base Oil Category                  | Properties                                                                 |
|-----------------------------------|-----------------------------------------------------------------------------|
| Group I (solvent refined) *       | Properties                                                                 |
| Group II (hydrodetered) *         | <0.03 and/or <90 Saturates (%) <90 Viscosity Index <120                     |
| Group III (hydrocracked) *        | <0.03 and >90 Saturates (%) <120                                             |
| Group IV ** Polyalphaolefins (PAO) synthetic lubricants |                                                              |
| Group V All other base oils not included in Group I to IV |                                                             |

Based on the chemical composition, nanoparticles consist of metal, metal oxide, sulphide, nanocomposites, carbon nanoparticle, and rare earth compounds. According to Dai et al. [38], metal-containing nanoparticles are the subject of most of the studies carried out, and they occupy 72% of the reviews. In contrast, studies that focused on carbon nanoparticles, nanocomposites, and rare earth compounds accounted for just 7%, 6%, and 7%, respectively.
4.1. Metal

Form here the metallic NPs have a small particle size, high surface area, low melting point, and low shear strength. They provide excellent tribological performance and self-repairing function as lubricant additives [39], including Cu, Bi, Sn, Fe, Ni, Al, Pd, Co, Zn. The lubrication mechanism of metallic NPs can be categorized into (a) the surface properties will be changed and separate two friction surfaces with the formation of tribofilms, hence provide promising tribological performance; (b) NPs roll between two friction surface leading to the reduction of friction and wear; (c) heat and pressure generated during operation, leading to the compaction of NPs on the wear track, with this phenomenon considered as a repair or sintering effect [38].

Padgurskas et al. [40] investigated the tribological properties of Fe, Cu, and Co NPs and their mixture as lubricant additives on SAE 10 mineral oil. They reported that the use of nanoCu is the most effective NPs to reduce friction and wear both alone or as a mixture, and the mixture of NPs is more effective than pure NPs. Asadauskas et al. [41] conducted a comparative study of tribological properties of Cu, Fe, and Zn NPs between vegetable oil (rapeseed oil, soy oil, canola oil, and olive oil), mineral oil, and synthetic oil. They reported that without NPs, synthetic oil obtained the lowest wear, and with the addition of NPs, nanoFe evidenced better dispersion stability than nanoCu and nanoZn. NanoFe improved the wear resistance of rapeseed oil, while nanoZn reduced wear and smoothened scars in mineral oil.

The addition of nano-bismuth in light and heavy base oil resulted in wear reduction from 535 to 454 µm and 651 to 563 µm, friction reduction from 0.091 to 0.052 and 0.074 to 0.047 [42]. The addition of nanoCu in paraffin oil resulted in a reduction of friction (23%) and wear (26%) [39]. An investigation of the tribological properties of nanoNi in PAO6 reported a reduction of 7–30% in wear and 5–45% in friction [43]. Furthermore, the addition of nanoAl increased load carrying capacity and improved friction and wear [44]. The summary of literature for metallic NPs as lubricant additives is shown in Table 2.
### Table 2. Summary of literature for metallic nanoparticles as lubricant additives.

| Nanoparticle | Base Oil | Particle Size | Conc. | Dispersion Method, Duration & Temperature | Tribometer | Test Parameters | Test Results | Optimum Conc. | Ref. |
|--------------|----------|---------------|-------|------------------------------------------|------------|----------------|--------------|---------------|-----|
| Bi           | Light base oil 7–65 nm | 900 mg/L | Magnetic stirrer, 30–40 min, <80 °C | Four ball tester | 392 N | 1200 rpm | 75 °C, 30 min | Wear Reduction: From 535 to 454 µm, Friction Reduction: From 0.091 to 0.052 | - | [42] |
| Cu           | Cu Paraflin Oil 10–60 nm | 0.02 wt% |  | Four ball machine | 380 N | 1450 rpm | 20 °C, 30 min | Wear Reduction: Reduction of 23%, Friction Reduction: Reduction of 26% | 0.02 wt% | [39] |
| Cu           | Chevron Taro 30 DF 80–120 nm | 3 wt% | Pin-on-disk tribometer |  | 0.1–100 mN | 0.02 mm/s | 25 °C | Wear Reduction: From 0.023 to 0.018 mg, Friction Reduction: From 0.15 to 0.11 | 3 wt% | [45] |
| Cu           | SAE grade 15W-40 50 nm | 2.5, 5, 7.5 and 10 wt% | Mechanical agitation & ultrasonic dispersion, 30 min | Ball-on-ring tribometer | 50 N | 10 to 30 Hz | Rt, 30 min | Wear reduced as the concentration increase until 10 wt% wear increase | 7.5 wt% | [46] |
| Fe, Cu, Co   | Chevron Taro 30 DF 10–60 nm | 3 wt% |  | Pin-on-disk tribometer | 50–300 N | 500 rpm | Rt, 1 h | Addition of Al increase load carrying capacity and improve friction and wear | 0.5 wt% | [44] |
| Ni           | Polyalphaolfin (PAO6) 20 nm | 0.5, 1.0, 2.0 wt% | Ultrasonic probe, 30 min | Block on ring, four ball tester | 165 N, | 2 m/s, 1470 rpm | - | Reduction between 7–30% | 0.5 wt% | [43] |
| Ci           | Polyalphaolfin (PAO6) 25 nm | 0.5 and 2 wt% | Ultrasonic probe, 30 min | Block on ring, four ball tester | 165 N, medium load | 1 m/s, 1470 rpm | - | Reduction of 50% wear for 0.5 wt% and reduction of 16% wear for 2 wt% | 0.5 wt% | [48] |
| Sn & Fe      | Macs base oil 30-60 nm & 20-70 nm | 0.1, 0.5, 1.0 wt% | Ultrasonic probe, 5 min | Vacuum four ball tribometer | 300 N | 1450 rpm | 25 °C, 30 min | Sn and Fe exhibited friction and wear reduction, but Sn effective on friction reduction and Fe effective on anti-wear | 1.0 wt% | [52] |
| Pd           | TBA 2 nm | 1–10 wt% | - | Ball-on-disc tribometer | 1–20 N | 10 cm/s | - | Addition of 2 wt% of Pd improve the tribological properties, above 5 wt% wear rate increase | 2.0 wt% | [53] |
4.2. Metal Oxide

Various metal oxides have been used as lubricant additives, including TiO$_2$, CuO, ZnO, Al$_2$O$_3$, Fe$_3$O$_4$, ZnAl$_2$O$_4$. The lubrication mechanism of metal oxide NPs is similar to the metallic NPs, including rolling effect, sintering and repair effect, and tribofilm formation.

Alves et al. [54] studied the tribological behavior of ZnO and CuO in vegetable oil (sunflower and soybean), synthetic oil, and mineral oil. They found that the addition of CuO in synthetic oil improves tribological properties, ZnO mineral-based lubricants exhibit excellent friction and wear reduction, while the addition of NPs in vegetable oil were not beneficial for wear reduction. The addition of TiO$_2$ in water-based lubricant exhibits excellent tribological performance [55,56], while in engine oil SAE 20W 40, wear showed significant reduction and friction reduced by 50% [57]. Luo et al. [58] investigated the tribological properties of Al$_2$O$_3$ in pure lubricating oil with two types of tribometer. They reported that through the four-ball tribometer, the average coefficient of friction (COF) reduction is 17.61% and 41.75% reduction for wear scar diameter (WSD). Friction is reduced by 23.92% by using a thrust-ring tribometer. This is because of the formation of a protective film on the contact surface and rolling effect. One should note, however, that the addition of Al$_2$O$_3$ had a detrimental impact on PAO and SAE75W-85 [59]. Typical studies of metal oxides as lubricant additives are set out in Table 3.
Table 3. Summary of literature for metal oxide nanoparticles as lubricant additives.

| Nanoparticle | Base Oil | Particle Size | Conc. | Dispersion Method, Duration & Temperature | Tribometer | Test Parameters | Test Results | Optimum Conc. | Ref. |
|--------------|----------|---------------|-------|------------------------------------------|------------|----------------|--------------|---------------|------|
| Al₂O₃        | Pure lubricating oil | 78 nm | 0.05, 0.1, 0.5, 1.0 wt% | - | Ultrasonication, 30 min | Four ball tribometer, thrust-ring tribometer | 147 N, 200 N | 1450 rpm, 1200 rpm | 75 °C, 30 min | Average COF reduction are 17.6% (four ball) and 23.92% (thrust-ring), WSD reduction of four ball test is 41.75% | 0.1 wt% | [50] |
| TiO₂         | Mineral oil | 20–25 nm | 0.25, 1.2 wt% | Mechanical stirrer, 15 min | Reciprocating pin-on-disk | 14.715 N | 0.05 m/s | Ambient, 30 min | Reduction of 0.01 COF | 0.25 wt% | [60] |
| CuO          | Multi-grade engine oil SAE 20W-40 | 10–25 nm | 1.5 wt% | Ultrasonic shaker | Pin-on-disc tribometer | 40, 60, 90 N | 0.5, 1.0, 1.5 m/s | ~ 5 min | Wear significant reduce | Reduced by 50% | 1.5 wt% | [57] |
| Paraffin oil | 50 nm | 0.2, 0.25, 2 & 3 wt% | Ultrasonic bath, 1 h | Four-ball tribomachine | 40 kg | 1200 rpm | 60-70 °C, 15 min | The higher the concentration of CuO, the better the tribological properties | - | [61] |
| ZnAl₂O₄ | Pure lubricant oil | 95 nm | 0.05, 0.1, 0.5, 1 wt% | - | Four ball tribometer, thrust-ring tribometer | 147, 200 N | 1450 rpm, 1200 rpm | 348 K, 1800 s | Reduce up to 31.1% | Reduce up to 33.67% | 0.1 wt% | [62] |
| TiO₂         | Trimethylolpropane (TMP) ester | - | 1 wt% | Ultrasonic bath, 8 h | Four ball wear tester | 40–120 kg | 1200 rpm | Rt, 10 min | Decreased by 11% | Decreased by 15% | 1 wt% | [65] |
| Palm oil     | 22.98 nm | 0.05, 0.1, 0.2 wt% | Ultrasonic bath, 30 min | Four ball tribometer | 40 kg | 1200 rpm | 60-70 °C, 15 min | Only addition of 0.1 wt% TiO₂ exhibit reduction of friction and wear | 0.1 wt% | [55] |
| CuO          | Palm kernel oil (PKO) | 40 nm | 0.34 wt% | High-shear homogeniser, 40 min | Pin-on-disc tribometer | 9.81 N | 0.2 m/s | ~ 60 min | Reducing the WSD by 48% | Reducing the COF by 56% | 0.34 wt% | [66] |
| CuO & ZnO    | Mineral oil, synthetic oil (PAO), sunflower oil, soybean oil | 3.35 & 11.71 nm | 0.5 wt% | Ultrasonic probe, 30 min | High frequency reciprocating test rig (HFRR) | 10 N | 20 Hz | 50 °C, 60 min | CuO in synthetic oil improve tribological properties, ZnO in mineral oil exhibit excellent wear and friction reduction | 0.5 wt% | [54] |
| CuO & Al₂O₃ | PAO 8 & SAE 75W-40 | < 50 nm | 0.5, 1.0, 2.0 wt% | Homogenizer, 10 min & water bath, 3 h | Optimel SERV 4 reciprocating friction and wear tester | 200 N | 50 Hz | 50 °C, 2 h | Reduce up to 14% (WSD) and 16% (COF) by addition of CuO in both base oil, while Al₂O₃ had a detrimental effect on both base oil | - | [59] |
| TiO₂         | Water-based lubricant | 20 nm | 0.2–8.0 wt% | Ultrasonication with stirring, 10 min | Ball-on-disk tribometer | 50 N | 20 mm/s | Rt, 10 min | Can be decreased by 97.6% | Can be decreased by 99.5% | 0.8 wt% | [53] |
| Water-based lubricant | 20 nm | 0.4–8.0 wt% | Ultrasonication with stirring, 10 min | Ball-on-disk tribometer | 5 N | 50 mm/s | 25 °C, 30 min | COF of oxidized disk is lower than clean disk, due to Fe element from steel ball oxidized and form a protective film | 4.0 wt% | [55] |
| Oil-in-water | 30 nm | 0.3–2 wt% | Stirring & ultrasonic vibration | Ball-on-disk tribometer | 50 N | 50 mm/s | 80 °C, 30 min | Addition of 1 wt% oil + 2 wt% TiO₂ reduce 17.6% COF, other concentration are higher than base oil | 1 wt% oil + 2 wt% TiO₂ | [67] |
| CuO          | Water based lubricant | 20 nm | 0.1, 0.2, 0.4, 0.6 & 0.8 wt% | Ultrasonic dispersed, 20 min | Four ball tribotester | 147, 196 & 245 N | 1440 rpm | Rt, 10 min | Addition of 0.2 wt% of CuO the friction reduce up to 69.2% and wear reduce up to 55.1% under different load | 0.2, 0.4, 0.6 wt% at certain load | [68] |
4.3. Metal Sulphides

Metal sulphides have been widely used for decades, as solid or liquid lubricant additives, including MoS\textsubscript{2}, WS\textsubscript{2}, FeS, CuS. It has been confirmed that nanoMoS\textsubscript{2} in liquid lubricants is better than microMoS\textsubscript{2} due to the smaller particles size for friction reduction [69]. MoS\textsubscript{2} as a lubricant additive in dioctyl sebacate results in more friction and wear reduction than microMoS\textsubscript{2} because of the extra formation of a solid and complex absorption film on the contact surface [70]. Fullerene-like NPs (IF) are the layered compounds with a hollow polyhedral structure. The addition of IF-MoS\textsubscript{2} and IF-WS\textsubscript{2} in PAO could significantly improve tribological properties [71]. Gulzar et al. [72] studied the tribological properties of chemical modified palm oil with the addition of MoS\textsubscript{2} and CuO, wherein nanoMoS\textsubscript{2} showed better tribological properties than nanoCuO. An interesting study discussed the anti-friction ability of nanoFeS with 20–200nm particle size as engine oil lubricant additive [73]. COF significantly decreases with the addition of nanoFeS and shows persistent anti-friction behavior under dry sliding. Figure 6 shows the formation of the sulfur diffusing area by the diffusion of S atom on the friction surface leading to friction reduction. The summary of metal sulphides as lubricant additives is shown in Table 4.

Figure 6. Diffusion of S-atom from FeS nanoparticles into the material surface [73].
### Table 4. Summary of metal sulphides nanoparticles as lubricant additives.

| Details of Nanolubricant | Dispersion Method, Duration & Temperature | Tribometer | Test Parameters | Wear Reduction | Friction Reduction | Optimum Conc. | Ref. |
|--------------------------|------------------------------------------|------------|----------------|----------------|-------------------|--------------|------|
| **Nanoparticle** | **Base Oil** | **Particle Size** | **Conc.** | **Tribometer** | **Load** | **Speed** | **Temp. & Duration** | **Test Results** | **Ref.** |
| **FeS** | API SL/CF 10W-40 engine oil | 20–200 nm | 0–2% | Mechanical stirring and ultrasonic dispersion | Pin-on-disc system | 50 or 150 N | 150 rpm | > 20 min | Wear surface are more smoother and flatter | Decrease from 0.08 to 0.13 to 0.024 at different load | 2 wt% | [73] |
| **MoS₂** | SE15W40 | ~50 nm | 0, 0.5, 1.0, 2.0 & 5.0 wt% | High shear homogenizer, 30 min | Disc-on-disc frictional testing machine | 1500 N | 500 rpm | Ambient temperature, 180 s | Enhance significantly the tribological performance of base oil | - | [74] |
| **WS₂** nanorod | Mineral oil | 10–15 nm | 2 wt% | High speed dispersion machine, 20 min & ultrasonic bath, 30 min | Four ball tribotester | 170, 245 & 320 N | 1200 rpm | > 30 min | Addition of WS₂ nanorod in oil show better tribological properties than base oil and 2H-WS₂ | 2 wt% | [75] |
| **MoS₂** | Coconut oil & paraffin oil | 90 nm | 0.25, 0.5, 0.75, 1% | Ultrasonic shaker, 1 h, 50 °C | Pin-on-disc tribometer, four ball tester | 2 to 4 MPA, 392 N | 0.47 to 1.414 m/s, 600 rpm | > 0.2 °C, 60 min | Friction and wear reduce with the increase of concentration until reach optimum concentration | 0.53% for coconut oil and 0.58% for paraffin oil | [76] |
| **IF-MoS₂** Blend of PAO 4 & PAO 40 | 150 and 350 nm | 1 wt% | Magnetic agitator | High frequency reciprocating rig (HFRR) | 10 N | - | 80 °C | All IF-MoS₂ were effective in friction and wear reduction, maximum friction reduced from 0.2 to 0.06 | 1 wt% | [69] |
| **IF-MoS₂**, **IF-WS₂**, **2H-MoS₂** PAO 6, PAO 40 | 50–80 nm | 1 wt% | Ultrasonic bath | Ball-on-flat device, Pin-on-flat device | 17.9 N, 2, 5 & 10 N | 20 mm/s, 2.5 mm/s | 25 °C | IF-MoS₂ exhibited the smallest wear rate and COF as low as 0.03 | 1 wt% | [71] |
| **Multi-wall nanotubes MoS₂** PAO | 100–500 nm | 5 wt% | Ultra-sound, 1 h | Ball-on-disc tester | 10 N | 0.005 m/s | RT | Reduced between 5–9 times | Reduced by more than 2 times | 5 wt% | [77] |
| **IF-MoS₂**, **IF-WS₂** PAO-6 | 100 nm | 120 nm | - | Mechanical stirrer IKA T25 Ultra-Turrax disperser, 30 min | Retractable disc Tribometer | 30, 60 & 90 N | 2.1 m/s | 25, 50 & 80 °C, 30 min | IF nanoparticles exhibited enhanced tribological performance as compare to 2H-MoS₂, and reduction of 40% COF | - | [78] |
| **Re-IF-MoS₂**, **2H-MoS₂** | - | 2 µm | - | Mechanical stirrer IKA T25 Ultra-Turrax disperser, 30 min | Retractable disc Tribometer | 30, 60 & 90 N | 2.1 m/s | 25, 50 & 80 °C, 30 min | IF nanoparticles exhibited enhanced tribological performance as compare to 2H-MoS₂, and reduction of 40% COF | - | [79] |
| **MoS₂** Dioctyl sebacate | 50–100 nm | 0.25, 0.5, 1.0, 1.5, 2.0 wt% | Ultrasonic oscillation, 30 min | High frequency reciprocating ball-on-disc tribometer | 7.84 N | 0.1 m/s | 60 °C, 75 min | Reduced by ~35% | Reduced by ~37% | - | [70] |
4.4. Carbon-Based Nanoparticles

From here use of carbon-based NPs as lubricant additives is still an innovation. These include diamond, graphene, and graphite. Peng et al. reported that diamond NPs in paraffin oil exhibit excellent tribological properties due to the formation of a protective film, which separates the friction surface [79]. It should be noted that changes of adhesion to abrasion wear mechanism improve the tribological behavior of PAO with an optimum concentration of 0.2 wt% diamond NPs [80].

The lubrication mechanism of graphite NPs can be the mending effect, the formation of tribofilm, and rolling effect. Gupta et al. [81] reported the highest tribological performance of improvement up to 80% by graphite with dispersant. The enhancement of AW properties is related to the combination of formation of tribofilm and mending effect, and the tribofilm formation mechanism contributes to EP enhancement. Sivakumar et al. [82] reported graphite oxide as the lubricant additives which are synthesized by the waste carbon sources, that reduce friction wear and surface roughness by up to 21.1%, 18.5%, and 42.3%, respectively.

Graphene is highlighted out of all the NPs due to its unique properties, including excellent mechanical, physical, and electrical properties. Further, graphene has been used in various applications, and is frequently named a “supermaterial” or “all-in-one material” in the world of material science [83]. The improvement of friction and wear is up to 80% and 33% with the addition of graphene in engine oil and the enhancement is related to the ball-bearing effect and ultimate strength properties of graphene [84]. A comparative study between modified natural flake graphite and modified graphene platelets in SN350 base oil has been conducted by Lin et al. The results showed that modified graphene platelets have better tribological properties [85]. Graphene by exfoliation should also be mentioned [86,87]. The ocradecylamine reduced graphene oxide nanolubricants in boundary regime and hydrodynamics regime has been evaluated by Vats et al. The results showed that the COF reduced by 61.8% and 75% in those regimes and WSD significantly decreased by 92.5% in the boundary regime [88]. Besides, the viscosity of these nanolubricants improved by 60% through flow analysis. The summary of carbon-based NPs as lubricant additives is shown in Table 5.
Table 5. Summary of carbon-based nanoparticles as lubricant additives.

| Nanoparticle | Base Oil | Particle Size | Conc. | Dispersion Method, Duration & Temperature | Tribometer | Load | Speed | Temp. & Duration | Wear Reduction | Friction Reduction | Optimum Conc. | Ref. |
|--------------|---------|---------------|-------|-------------------------------------------|------------|------|-------|-----------------|----------------|-----------------|---------------|-----|
| **Category: Mineral oil** |
| Diamond | Paraffin oil | 110 nm | 0.025–5 wt% | Ultrasound, 30 min | Ball-on-ring tester | 50–300 N | 500 rpm | RT, 60 min | Maximum reduction of wear up to ~23.73% | Maximum reduction of COF up to ~14.77% | 0.2 wt% | [79] |
| | CPC 868 commercial oil | 4.37 ± 0.45 mm | 1, 2, 3 vol% | Stirring, 1 h, 60 °C & supersonic redispersed | Blocks-on-ring configuration | | - | 4.87, 6.084, 7.30 m/s | - | Nano-diamond improve anti-scuffing performance and addition of 2.5 vol% result large friction reduction | - | [80] |
| Graphite | APT Group III 150 N base oil | 55 nm | 1–4 wt% | Ultrasonic probe, 35 min | Four ball tester | 392, 500 & 794 N | 1200 rpm | 75 °C, 1 h | Highest performance improvement up to 80% by graphite with dispersant | 3 wt% | [81] |
| Graphene | Engine oil | - | 0.0125–0.08 mg/mL | Probe sonicator, 60 min | Four ball tester | 392 N | 650 rpm | 75 °C, 60 min | Improve up to ~33% | Improve up to 80% | 0.025 mg/mL | [82] |
| Modified natural flake graphite (MNFG) & modified graphene platelets (MGP) | SNS30 base oil | 25 µm | 0.01–0.1 atm wr% | Magnetic stirrer, 1 h, 80 °C | Four ball machine | 147 N | 1200 rpm | 75 ± 2 °C, 60 min | COF of MGP-based oil was lower than base oil and MNFG-based oil, overall lubricious properties of lubricating oil had improved with the addition of MGP | 0.075 wt% | [83] |
| Graphite (liquid phase exfoliation) | SAE10W-30 | 3–5 µm | 0.025, 0.05, 0.075 & 0.1 wt% | Stirring, 120 min | Pin-on-disk tribometer | 125.66 N | 191 rpm | 25 ± 1 °C, 7200 s | Addition of graphite in SAE 10W-30 decrease wear rate and reduces COF | 0.05 wt% | [84] |
| Octadecylamine reduced graphene oxide (ODA-rGO) | Liquid paraffin oil | 500 nm | 0.2 wt% | Ultrasonic bath, 120 min | Four ball tester (boundary lubrication regime), ball-on-disc tribometer (EHL regime) | 392, 20 N | 1200 rpm, 1–2000 mm/s | 60 min, - | Significantly reduced by 92.5% | Reduce by 61.8% in boundary regime and 75% in EHL | 0.2 wt% | [85] |

| **Category: Synthetic oil** |
| Diamond | PAO | 60–90 nm | 0.1, 0.2, 0.4, 0.6 & 0.8 wt% | Ultrasonic probe, 30 min | Ball-on-disc | 100 N | 0.58 m/s | - | Concentration increase, result in more wear and friction | 0.2 wt% | [86] |
| Graphite | PAO 4 | 10–50 nm | 0.01 wt% | Stirring, 10 min & ultrasonic vibration, 15 min | Ball-plate contact wear testing machine | 10 N | 5 mm/s | 25 ± 2 °C, 100 °C & 175 °C, 6000 s | Wear rate reduce at least 90% with addition of graphite at 175 °C | From 0.2 decrease to 0.12 at RT & from 0.55 decrease to ~0.16 at 100 °C | 0.01 wt% | [87] |
| Graphene—different degree exfoliation | PAO 6 | 1–2 µm | 0.1, 0.1, 1.0, 2.0 wt% | Magnetic stirrer, 3h & ultrasonication, 0.5 h | Reciprocating-sliding tester | 2 N | - | - | Few layer graphene (FLG) with larger interlayer spacing exhibit lower friction | 0.5 wt% for FLG-Ms based oil | [88] |
| Graphene | PAO 9 | - | 0.01–0.5 wt% | Ultrasonicator, 15 min | Four ball tribometer | 400 N | 1450 rpm | RT | Reduced by 14% | Reduced by 15% | 0.02–0.08 wt% | [89] |

| **Category: Biolubricants** |
| Graphite | LBD200 vegetable based oil | 35&80 nm | 0.05–0.25 vol% | Ultrasonic cleaner, 1–1.5 h, 25 °C | Pin-on-disc friction and wear tester | 2, 10 N | 100 rpm | 24 °C | The increase the volume fraction of nano-graphite, the lesser the COF and wear | 0.25 vol% | [90] |
| Graphene | Palm oil based vegetable oil | - | 25, 50, 100 ppm | Ultrasonicator, 1 h | Four ball tribotester | 392 N | 1200 rpm | 75 °C, 1 h | Wear and friction decrease with the addition of 25 & 50 ppm graphene | 50 ppm | [91] |

| **Category: Others/Mixed test oil** |
| Graphene | SAE20W40 + Modified jojoba oil | - | 0.05, 0.075, 0.1 wt% | Magnetic stirrer, 120 min | Pin-on-disc setup | 50, 100, 150 N | 1–5 m/s | - | JIS 20.00 vol% of SAE20W40 + 20 vol% of modified jojoba oil with the addition of 0.075 wt% result in the lowest wear and friction | 0.075 wt% | [92] |
| Hydraulic oil | - | 2 µm | 1 wt% | Magnetic stirrer, 30 min & Ultrasonic mixing, 1 h, 30 °C | Ball-on disk | 3 N | 1.2–3.84 mm/s | 25–125 °C | Multilayer graphene as additive results relatively high and unstable tribological properties | 1 wt% | [93] |
4.5. Nanocomposites

These are multicomponent materials, including WC-Al$_2$O$_3$/graphene platelets, Cu/graphene oxide, TiO$_2$/SiO$_2$, Ag/graphene, graphite oxide/Cu, and Al$_2$O$_3$/TiO$_2$, etc. Due to the synergistic effect of the combination of NPs, nanocomposites usually provide better performance than single NPs. One should note that the nanocomposites which include graphene exhibit excellent tribological performance [14,96–98]. The tribological properties of WC-Al$_2$O$_3$/graphene platelets has been investigated. The test under 40 and 60N load show that the COF incorporated with graphene is 40.4% and 33.3% lower than test carried out without graphene. Further, the addition of graphene changes from significant abrasive wear to minor abrasive wear [99].

It is of interest to study tribological properties of TiO$_2$/SiO$_2$ NPs in palm TMP ester, even without the use of surfactant, because the dispersion stability is stable and also effective in friction and wear reduction. At the same time, the surface is enhanced by the mending and polishing effect [100].

Composites of Cu-MoS$_2$ and Ag-MoS$_2$ reduce the COF and essentially improve wear resistance [101]. Copper/carbon nanotube nanocomposite results in a reduction of friction and wears by up to 23.7% and 33.5%, respectively [102]. Both studies report that the improvement of lubrication is related to the synergistic effect of nanocomposites. Various studies of nanocomposites as lubricant additives are shown in Table 6.
| Nanoparticle | Base Oil | Particle Size | Conc. | Dispersion Method, Duration & Temperature | Tribometer | Test Parameters | Test Results | Optimum Conc. | Ref. |
|--------------|----------|---------------|-------|------------------------------------------|------------|----------------|-------------|---------------|-----|
| Ag/graphene (with laser irradiation) nanocomposite | Paraffin oil | 56 nm | 0.05, 0.1, 0.15 & 0.2 wt% | Ultrasonication, 30 min | Four ball tribometer | 392 N | 1200 rpm | Rt, 30 min | Reduction up to 36.4% | Reduction up to 40% | 0.1 wt% | [97] |
| Nano-Cu/graphene oxide composite | Paraffin oil | 5–10 nm | 0.05 wt% | Ultrasonication, 30 min | Four ball tribometer | 200 N | 1200 rpm | Rt | Reduced by 52.7% | Reduced by 27% | 0.05 wt% | [14] |
| Ag-Pd/graphene composite | 10w40 engine oil | 3–9 nm | 0.6–0.1 wt% | Ultrasonication, 30 min | Four ball machine | 343 N | 1200 rpm | 75 ± 1 °C, 1 h | Reduced up to 27.4% | Reduced up to 30.4% | - | [108] |
| Al2O3/TiO2 | 5w-30 engine oil | 8–12 nm | 0.05, 0.1, 0.25 & 0.5 wt% | Magnetic stirrer, 4 h | Piston ring/cylinder liner tribotester | 40–230 N | 0.5–1.45 m/s | 100 ± 30 rpm, 500 rpm | Reduce as much as 10.4% | Reduce as much as ~16.12% | 0.75 wt% | [100] |
| Copper/carbon nanotube nanocomposite | Rapeseed oil | 4–7 nm | 0.05, 0.1, 0.2, 0.3 & 0.5 wt% | Ultrasonication, 30 min | Ball-on-disk apparatus | 1–12 N | 100–500 rpm | 30 min | Reduction up to 23.7% | Reduction up to 35.5% | 0.2 wt% | [102] |
| Graphene oxide/copper nanocomposite | polyethylene glycol (PEG 200) | 15–20 nm | 0.02, 0.04, 0.06, 0.08 & 0.1 wt% | Ultrasonication, 60 min | Multifunction sliding friction tester & four ball friction device | 1–8 N & 392 N | 3 Hz & 1200 rpm | 60 min | Improve wear resistance up 47% | Improve friction resistance up 40% | 0.08 wt% | [98] |
| WC-Al2O3 with graphene platelets (GPLs) | - | <2 µm | 0.3 wt% | GPLs | - | Reciprocating tribometer | 40 & 60 N | 350 rpm | 25 °C, 150 min | The specific wear rate are one order of magnitude lower than without addition of GPLs, the CDF reduce up to 40.4% | 0.3 wt% | [99] |
| Cu-MOFs & Ag-MOFs | Litol and VNIINP greases | - | 2–50 wt% | Ultrasonication | Ball-on-disc tribometer | 5 N | 5 cm/s | 30 min | Cu-MOFs and Ag-MOFs reduced the COF and essentially improve wear resistance | - | [104] |
| (Zn-Ni)Al2O3 | - | 30 nm | - | Ultrasonication with magnetic stirrer, 120 min, 30 °C | Pin-on-disc method | 10 N | 10 mm/s | Rt | Weight loss from 4.4 mg to 3 mg | From 0.578 to 0.392 | - | [107] |
| Hybrid | Cu-Al2O3/graphene platelets | - | <100 nm | 0.3, 0.6, 0.9, 1.2 wt% | Planetary ball mill, 2 h | Pin-on-disc tribometer | 5, 10, 15 & 20 N | 0.4, 0.7, 1 m/s | - | The wear resistance increase and COF is decrease by increasing the concentration of graphene platelets | 1.2 wt% | [108] |

**Table 6. Summary of nanocomposites as lubricant additives.**
4.6. Rare Earth Compounds

Rare earth compounds can be used as lubricating additives or doped to other NPs. Typically, the lubrication mechanism of rare earth compounds is the formation of a tribofilm or absorption film. La-doped Mg/Al layered double hydroxide NPs modified by sodium dodecyl sulfate show better friction properties than those without modification in diesel engine oil CD 15W–40. The lubrication mechanism has been concluded as the formation of tribofilm on the friction surface leading to friction reduction [108]. Cerium oxide provides excellent tribological properties even in titanium complex grease or lithium grease [109,110]. Furthermore, the tribological properties of rare earth compounds such as LaF$_3$ and CeVO$_4$ have also been investigated [111,112]. Few examples of rare earth compounds as lubricant additives are shown in Table 7.
Table 7. Summary of rare earth compounds as lubricant additives.

| Nanoparticle | Details of Nanolubricant | Dispersion Method, Duration & Temperature | Tribometer | Test Parameters | Test Results | Optimum Conc. | Ref. |
|--------------|--------------------------|------------------------------------------|------------|----------------|--------------|---------------|-----|
| Layered double hydroxide (LDH)-La-doped Mg/Al | Diesel engine oil (CD 15W-40) 185.96 nm 0.5 g LDH per 100 mL oil Ultrasonic bath, 80 °C | Four ball tester | Load 392 N | Speed 1200 rpm | Temp. & Duration Rt, 60 min | Wear Reduction Reduced by 12.9% | Friction Reduction Reduce from 0.111 to 0.080 | - [103] |
| CeVO₄ (Cerium orthovanadate) | Liquid paraffin oil 30–50 nm 0.2, 0.4, 0.6 & 0.8 wt% | Seta shell four ball machine | Load 300 N | Speed 1459 rpm | Temp. & Duration 30 min | Result show addition of CeVO₄ exhibited good anti-wear | 0.6 wt% [107] |
| Category: Mineral oil |
| Category: Others |
| CeO₂ | Titanium complex grease <10 nm 2 wt% | - | Four ball machine | Load 392 N | Speed 1450 rpm | Temp. & Duration 25 °C, 10 s; 75 °C, 60 min | Tribological properties were significantly improved | 2 wt% [108] |
| Lithium grease <500 nm 0.2, 0.4, 0.6 & 0.8 wt% Ultrasonic dispersion instrument, 20 min | Four ball friction and wear testing machine | Load 392 N | Speed 1200 rpm | Temp. & Duration 75 °C, 60 min | Wear Reduction Decrease up to 13% | Friction Reduction Decrease up to 28% | 0.6 wt% [104] |
| LaF₃ | Fluoro silicone oil 10–30 nm 0.02, 0.04, 0.06, 0.08 & 1.0 wt% | - | Four ball friction and wear tester | Load 300 N | Speed 1450 rpm | Temp. & Duration 25 °C, 30 min | The friction and wear decrease, until the concentration reach 1.0 wt% | 0.08 wt% [108] |
5. Lubrication Mechanism of Nanoparticles

From here nanoparticles as the lubricating additives in lubricants are applicable to reduce the friction and wear and increase the load capacity of mechanical parts. Studies of lubrication mechanisms will serve as a decisive parameter to understand the tribological properties of nanolubricants. The lubrication mechanism of nanoparticles already purposed includes the ball bearing effect, protective film formation, mending effect, and polishing effect. These mechanisms are mainly classified into two groups. The first group is the direct action of NPs in lubrication enhancement (ball bearing effect/protective film formation) and the second group is surface enhancement (polishing/mending) [113].

5.1. Rolling Effect

Additionally known as the ball-bearing effect, normally the spherical or quasi-spherical nanoparticles act as ball bearings that roll between the contact surface and convert sliding friction to the combination of sliding and rolling friction [79], as shown in Figure 7. Various studies examining the ball-bearing mechanism have been carried out. Viesca et al. [48] evaluated carbon-coated copper nanoparticles and stated that tribological improvement is related to the ball-bearing mechanism. Wu et al. [55] investigated the tribology properties of TiO₂ nanolubricants by ball-on-disk tribometer. They reported this type of nanolubricants evidenced the ball-bearing effect between ball and disk with a demonstration from SEM micrograph as shown in Figure 11a. Raina and Anand [80] demonstrated the nearly spherical shapes of diamond nanoparticles ability to reduce the sliding contact surface, and this is associated with the ball bearing mechanism.

![Figure 7. Rolling mechanism by NPs-based lubricant [22].](image)

5.2. Protective Film Formation

Nanoparticles are more likely to form an amorphous layer (protective film) on the friction surfaces in this mechanism [79], as shown in Figure 8. Tribo-film is the protective film on material surfaces. Tribo-film and near-surface materials decide the tribological behavior of the contacting surface. The reaction between substrate and nanoparticles form the film under the environment condition or tribo-sintering [114]. Several experimental studies have reported the mechanism of tribo-film formation to provide excellent lubrication. Meng et al. [108] reported that silver decorated graphene nanocomposite forms a protective film that smoothenes and reduces the surface roughness of the contact area. Protective film formation has an energetic effect on the life of friction parts reported by Wang et al. [115]. Zhao et al. [86] demonstrated that the protective tribofilm formed by graphene indeed attains slippage between friction surfaces, therefore leading to better lubrication, as shown by the SEM and HRTEM micrograph of protective film formation in Figure 9. Some studies reported wear reduction [64,116], wear and friction reduction [112] via the protective film formation mechanism. Liu et al. [117] determined the strength and ductility of the protective film. They report that strength is necessary under low frequency while ductility important under high frequency. The formation of a protective film can be demonstrated using analysis techniques such as scanning electron
microscopy/energy dispersive X-ray spectroscopy (SEM/EDS), X-ray photoelectron spectroscopy (XPS), and Raman spectroscopy.

![Diagram of Protective Film Formation Mechanism](image_url)

**Figure 8.** Protective film formation mechanism by NPs-based lubricant [22].

![SEM Micrograph of Tribofilm Formation](image_url)

**Figure 9.** (a) SEM micrograph of tribofilm formation on steel substrate; (b) HRTEM micrograph of tribofilm formation beside the friction interface [86].

### 5.3. Mending Effect

The mending or self-repairing effect characterized by nanoparticles deposition on the rubbing surfaces compensates mass losses [79], as shown in Figure 10. In addition, nanoparticles are also deposited on the wear surface and fill the grooves during this mechanism. Yadgarov et al. [78] report that low friction and wear scar is because of the mending effect, and IF-nanoparticles also contribute to this. The self-repair effect has been reported by using graphene/Ag nanocomposite [97]. SEM/EDS analysis can be used to verify the mending effect on the rubbing surface. Figure 11b shows the direct evidence to support this lubrication mechanism on the rubbing surface.

![Diagram of Mending Effect Mechanism](image_url)

**Figure 10.** Mending effect mechanism by NPs-based lubricant [22].
5.4. Polishing Effect

The polishing effect also called the smoothing effect, reduces the lubricating surface roughness by nanoparticle assisted abrasion [113], as shown in Figure 12. Ignole et al. [60] reported that TiO$_2$ nanoparticles consisting of anatase and rutile phase had a more polishing effect on the surface. Wu et al. [56] also reported that TiO$_2$ nanoparticles filled the defects found on the friction surfaces. One of the mechanisms mentioned by Koshy et al. for the surface roughness reduction is that the nanoparticle fills the asperities [76]. They measured the surface roughness of the friction surface by atomic force microscopy (AFM) and the AFM images (before and after sliding) show the reduction of surface roughness, as shown in Figure 13. In addition, the SEM micrograph provides evidence of the polishing effect with the presence of Al$_2$O$_3$/TiO$_2$ nanocomposites, as shown in Figure 14.

Figure 11. (a) The demonstration from the SEM micrograph for rolling effect; (b) the mending effect on the rubbing surface analyzed through the SEM/EDS analysis [56].

Figure 12. Polishing effect mechanism by NPs-based lubricant [22].
There is no ideal concentration, even with the addition of below 1 wt% concentration NPs [94] or above 2 wt% concentration NPs [55], but adding more NPs in the lubricant does not mean any concomitant increased reduction in friction and wear. Still, there is an optimum concentration for maximum reduction of friction and wear. Rajubhai et al. [49] investigated tribological characteristics of copper NPs in Pongamia oil with different concentrations of 0.025, 0.05, 0.075, and 0.1 wt% with the results revealing that 0.075 wt.% is the optimum concentration with minimum evidence of friction and wear. Shaari et al. [65] reported that an addition of 0.1 wt.% TiO$_2$ in palm oil exhibits the lowest friction and wear. Stephen et al. [93] investigated the tribological effect of graphene in palm oil with the addition of 25, 50, and 100 ppm and reported that 50 ppm is the optimum concentration. Zhang et al. [52] added Sn and Fe in macs base oil with concentrations of 0.1, 0.5, and 1.0 wt%, with the results showing that optimum concentration of both nanoparticles is 1.0 wt%, although Sn was more effective in friction reduction and Fe more effective in wear reduction. The addition of MoS$_2$ in palm oil with concentrations of 0.1, 0.05, 0.075, and 0.1 wt% with the results revealing that 0.075 wt.% is the optimum concentration with minimum evidence of friction and wear. Shaari et al. [65] reported that an addition of 0.1 wt.% TiO$_2$ in palm oil exhibits the lowest friction and wear.

6. Parameters of Nanoparticle Affect the Tribological Properties

6.1. Concentration of Nanoparticles

Concentration is one of the most critical factors that affect the tribology characteristics of nanolubricants. In most cases, the addition of NPs in the lubricant is useful in reducing friction and wear. There is also no ideal concentration, even with the addition of below 1 wt% concentration NPs [94] or above 2 wt% concentration NPs [55], but adding more NPs in the lubricant does not mean any concomitant increased reduction in friction and wear. Still, there is an optimum concentration for maximum reduction of friction and wear. Rajubhai et al. [49] investigated tribological characteristics of copper NPs in Pongamia oil with different concentrations of 0.025, 0.05, 0.075, and 0.1 wt% with the results revealing that 0.075 wt.% is the optimum concentration with minimum evidence of friction and wear. Shaari et al. [65] reported that an addition of 0.1 wt.% TiO$_2$ in palm oil exhibits the lowest friction and wear. Stephen et al. [93] investigated the tribological effect of graphene in palm oil with the addition of 25, 50, and 100 ppm and reported that 50 ppm is the optimum concentration. Zhang et al. [52] added Sn and Fe in macs base oil with concentrations of 0.1, 0.5, and 1.0 wt%, with the results showing that optimum concentration of both nanoparticles is 1.0 wt%, although Sn was more effective in friction reduction and Fe more effective in wear reduction. The addition of MoS$_2$ in palm oil with concentrations of 0.1, 0.05, 0.075, and 0.1 wt% with the results revealing that 0.075 wt.% is the optimum concentration with minimum evidence of friction and wear. Shaari et al. [65] reported that an addition of 0.1 wt.% TiO$_2$ in palm oil exhibits the lowest friction and wear.
reduction and Fe more effective in wear reduction. The addition of MoS$_2$ in coconut oil and paraffin oil was investigated by Koshy et al. [76]. The optimum concentration of MoS$_2$ obtained from these base oils is slightly different. The optimum concentration of coconut oil is 0.53 wt%. In comparison, paraffin oil is 0.58 wt%. This investigation can show that the optimum concentration of nanoparticle is related to the base oil too. Furthermore, Alves et al. [54] added an optimum concentration of 0.5 wt% nanoCuO and nanoZnO to investigate tribological properties in mineral oil, PAO, sunflower oil, and soybean oil, but this research contains a contradiction on their experiment results. Azman et al. [66] added an optimum concentration of 0.34 wt% nanoCuO in palm kernel oil. The results show that friction and wear is reduced by 56% and 48%, respectively.

6.2. Size of Nanoparticles

NP size is an important parameter that directly affects the tribological performance of nanolubricants. The smaller the particle size, the easier it is to penetrate the rubbing surface. The reaction is dependent on the surface-to-volume ratio and the particle size determines the hardness of NPs, which conversely affects the tribological properties [114]. For nanomaterials with a size range of 100 nm or higher, a decrease in particle size corresponds with an increase in the hardness. This is due to the Hall–Petch regime. In contrast, for particle sizes usually below 10nm, a decrease in particle size corresponds with the softer nanomaterials. This explanation is called the inverse Hall–Petch regime.

If the hardness of NPs is higher than the hardness of tribo-pair materials, this will result in indentation and scratches [6]. Peña-Parás et al. [59] reported that 8-9 Mohs hardness of nanoAl$_2$O$_3$ higher than the metal substrate causes the NPs in base oil re-agglomeration and abrasion. Thus, the size and hardness of NPs should be considered in the preparation of nanolubricants.

Furthermore, the ratio of root mean square (RMS) roughness of the lubricated material surface to the NPs radius is essential in selecting suitable NPs size. Nanolubricants must keep providing the lubrication on the contact zone during operation to protect the material surface. For this reason, if the NP size is larger than the gap between asperities, the NPs could not fill in the contact zone, potentially leading to inadequate lubrication.

To obtain stable nanolubricants, the NPs must homogeneously disperse in the base oil. Therefore, the dispersion stability can be determined by the sedimentation rate and calculated by using Stokes’ law:

$$V_z = \frac{2(\rho_{NP} - \rho_F)gr^2}{9\mu}$$

where, $V_z$ is settling velocity, $\rho_{NP}$ is the mass density of NPs, $\rho_F$ the is mass density of fluid, $g$ is gravity, $r$ is the radius of NPs, and $\mu$ is dynamic viscosity.

Based on the Stokes’ law, smaller particle size indicates better dispersion stability and results in achieving stable nanolubricants. Chen et al. [47] evaluated the tribological properties of Ni-based nanolubricants with 7.5, 13.5, and 27.5 nm of diameter. They reported that Ni-based nanolubricants with 7.5 nm diameter exhibited effective anti-wear ability compared to another two. The investigation by Su et al. [92] demonstrated that graphite-based nanolubricants with smaller particle sizes are more effective in improving tribological performance at the same volume fraction.

6.3. Morphology of Nanoparticles

The shape of NPs is vital in the preparation of nanolubricants, because it is relevant to the pressure experienced by NPs through loading. NPs have five types of form: spherical, granular, onion, sheet, and tube. Most NPs are in the spherical shape, followed by granular, sheet, onion, and tube. After nucleation, to achieve equilibrium, the particle crystalline structures tend to change, and the surface energy will be minimized. NPs form in spherical shape if there is isotropic surface energy [38]. Normally, spherical shape NPs favor the rolling mechanism, it will act as ball-bearing roll between the friction surfaces. Mostly spherical shaped nanoAl$_2$O$_3$ act as ball bearing and lead to improving load
capacity, friction, and wear reduction [58] and nearly spherical shaped nanoCu show improvement in tribological properties from SEM and EDS analysis [48]. In addition, the relationship between the shape of NPs contact to the lubricated surface are important too. Spherical shaped NPs result in point contact with surface(s) through loading. The line contact is related to nanosheets, yet nanoplatelets are planar contact [114]. The schematic diagram demonstrating the effect of nanoparticle shape upon loading is shown in Figure 15.

Figure 15. Schematic diagram of the effect of nanoparticle shape upon loading: (a) point contact, (b) line contact, (c) planar contact [118].

Onion morphology has an external spherical shape and internal lamellar structure. Stability of the onion morphology corresponds to the tribological performance. If it is stable, it will be similar to the spherical morphology, or else it becomes sheet morphology by exfoliating. The advantage of onion-shaped NPs is a lack of dangling bonds [38]. The presence of dangling bonds generates high local energy, which could affect some physical properties of NPs. Therefore the reaction of NPs with the environment is easier or reduces the energy by agglomeration [119]. Since dangling bonds are absent in onion morphology, the reaction between particles and environment will be weakened, which results in less particles attaching to the substrate. The sheet-like NPs consist of graphene, ZrP, hBN, and transition metal dichalcogenides. Lubrication in this case is about the exfoliation between adjacent layers by sliding and leading to friction reduction.

Furthermore, in addition to NP morphology affecting tribological properties, the internal nanostructure is also a factor. The tribological properties of WS2 nanorod as nanoadditives in mineral oil has been investigated [75]. They also compared the tribological properties of WS2 nanorod with 2H-WS2 (mix layer). WS2 nanorod lubricant shows better tribological properties with the formation of a thin tribofilm on the substrate, followed by 2H-WS2 and base oil. Tribological performances had been improved by liquid-phase exfoliation graphene as an additive in SAE 10W-30 oil. Another study explained the layered structure of transition metal dichalcogenides in friction reduction with the formation of tribofilm [120]. Compared to the typical transition metal dichalcogenides, IF-NPs consist of layered compounds with a hollow polyhedral structure. Hence, this results in excellent lubrication with three lubrication mechanisms: rolling, sliding, and exfoliation [121]. The significant improvement of tribological performance of the metallic substrates is with the addition of IF-MoS2 [71]. Rabaso et al. [69] reported the benefits of using IF-MoS2 including size and morphology, which does not affect the tribological performance, and is more effective than bulk h-MoS2. In investigating how to obtain further improvement in the tribological performance of IF-NPs, Yadgarov et al. [78] doped the IF-MoS2 with rhenium and reported that it obtained a better result than IF-MoS2.

6.4. Dispersion Stability of Nanoparticles

The high surface area to volume ratio in NPs leads to high surface energy. High surface area means the molecular attraction is strong and causes the particles to agglomerate. The aggregation of NPs results in sedimentation and also a loss of tribological improvement ability. Thus, the dispersion stability of NPs is strongly desirable for reliable lubrication performance. Stability is defined as the NPs not agglomerating at a significant rate. Several methods can enhance dispersion stability. The currently proposed methods are ultrasonic agitation, high-shear mixing, homogenizing, ball milling,
and magnetic force agitation [122]. Various studies have mentioned the method that they used for dispersion including magnetic stirrer [42,60], ultrasonic probe agitation [84], homogenization by triple-roller mill [51] and planetary ball mill [112], ultrasonic bath agitation [65], ultrasonic shaker agitation [57,61], high shear homogenizer [74], and mix method [46,73,86]. According to the literature, the majority of researchers use ultrasonic agitation for NPs dispersion, even though some of them just mentioned ultrasonication for dispersion or failed to mention any method at all. Zhao et al. [86] reported that graphene disperses in base oil with similar dispersion stability leading to eliminating the factor that affects lubrication properties. Furthermore, dispersion duration is also an important parameter to reduce or control agglomerations. It has been concluded that with the increase of mixing time, the size of NPs aggregates decreases by using magnetic force agitation [123]. The dispersion duration was carried out by the researchers as short as 5 min [52], and as long as 8 h [64], while the majority dispersion duration is 30 min or 1 h.

In addition, it is not only the dispersion methods that can reduce the agglomeration of NPs. The surface functionalization has developed to enhance dispersion stability. These include electrostatic stabilization and steric stabilization. Electrostatic stabilization is when the ionic surfactants have been absorbed on the NPs surface, while steric stabilization is achieved by applying a polymer or surfactant coat on the NPs surface. The surface-functionalized NPs should have better lubrication compared to bare NPs. The former prevents material transfer that leads to avoiding direct contact and cold-welding between shearing surfaces. Additionally, a rigid internal core and soft external shell in the hybrid structure of functionalized NPs allows for high load carrying capacity and does not reduce the lubrication [6]. Hence, surface-functionalized NPs provide more benefit compared to bare NPs.

The surface functionalization technique and related studies will be discussed. Surface modification is one of the methods to enhance dispersion stability. The common modification agent such as oleic acid is widely used in various studies to enhance dispersion stability [44,63,85]. In addition, other modification agents have been studied. NanoCu has been surface modified using a mixture of resin, methylbenzene, and amine compound, and the prevention of agglomeration and good oil-dispersion ability has been confirmed [8]. NanoCu surface modification by methyl-methyl acrylate provides a benefit in reducing friction and wear [50]. The surface-modified nanoPd by tetrabutylammonium chains results in the extension of loading parts life and electrical conduction [53,124]. One should note that dual modified CuO by sodium oleate (SOA) and alkylphenol polyoxyethylene ether disperse in water, resulting in excellent dispersion stability and improvement in lubricity [68]. Another noted study showed that the surface-capped triangle Cu nanoplates prepared by cetytrimethylammonium bromide (CTAB) were effective in wear loss reduction (82%) and friction reduction (12%) by the formation of tribofilm at the interface of the parts [51].

Furthermore, the second method is to use a surfactant to enhance dispersion stability. Surfactants can also be considered as a dispersant, and using this method is easier and more economical than the surface modification method because the surfactant can be directly added in nanolubricants. Still, the cons of using surfactants have a limitation on thermal conductivity enhancement. Used surfactants include oleic acid [46,62,72,91], sodium-dodecyl [103], sorbitol monooleate (SPAN 80) [74,75,90], and polyisobutylene succinimide (PIBSI) [81]. Demas et al. [125] studied the dispersion stability of nanoBN and nanoMoS$_2$ by using five types of surfactant. They proved that using a surfactant not only benefits in suspending the NPs, but also decreases friction and wear by itself. Four types of dispersant have been selected to explore the dispersion stability and influence of EP properties in API Group III 150N base oil with or without hBN particles [126]. All dispersants impart their dispersion stability and influenced tribological properties of oil. One should note that 1% dispersant did not influence EP properties of oil, and 5% dispersant shows more improvement of dispersion stability along with a 10% EP performance increase. The EP performance increased by up to 30% by adding the hBN particle.
Methods to Analyze Dispersion Stability of Nanolubricants

There are a number of ways to evaluate the dispersion stability of nanolubricants. These include the sedimentation method, zeta potential analysis, spectral absorbency analysis, and metallographic micrograph stability test [114]. In addition, the centrifugal method has also been mentioned [68]. Table 8 provides a summary of the evaluation of dispersion stability of nanolubricants.

Table 8. Summary of evaluation on dispersion stability.

| Nanoparticle | Lubricant | Method | Surface Modified/Dispersant | Result | Ref |
|--------------|-----------|--------|-----------------------------|--------|-----|
| Graphite     | API Group III 150 N base oil | Sedimentation | 1 wt% Polyisobutylene succinimide (PIBSI) | Without dispersant sediment after 6 days, while with dispersant the stability up to 50 days | [81] |
| Graphite     | PAO 4     | Sedimentation | 1 wt% Sorbitan monoolate (span 80) | The precipitation occurs after 72 h which including dispersant | [90] |
| CuO          | Palm kernel oil (PKO) Water based lubricant | Sedimentation | Coated by sodium oleate (SOA) and alkylphosphoric polyoxyethylene ether | Fully precipitated after 72 h | [66] |
| CuO & MoS₂   | Chemical modified palm oil | Spectral absorbency | Oleic acid | Dispersion stability of MoS₂ > CuO in 72 h | [72] |
| Graphene oxide (GO) | Paraffin oil | Sedimentation | Octadevylamine | Reduced GO precipitated after 10 days, octadevylamine reduced GO is stable even after 15 days | [88] |
| Graphene     | 350 SN base oil | Spectral absorbency | Steric and oleic acids | Evaluated by UV-vis spectrophotometer | [85] |
| Al₂O₃        | Pure lubricating oil | Zeta potential analysis, spectral absorbency | KH-560 can hydrolyze | Without modified withstand for 20 days, while modified withstand for 50 days | [58] |
| ZnAl₂O₄      | Pure lubricant oil | Spectral absorbency | Oleic acid | ZnAl₂O₄ modified at 70 °C had the best stability | [63] |
| MoS₂         | Coconut oil & paraffin oil | Spectral absorbency | Sodium dodecyl sulfate mixed with heptane solution | Surface modified > unmodified | [76] |
| La(OH)₃/RGO  | CF-4 20W-50 diesel engine oil | Sedimentation | - | Minimum precipitation occurs after 28 days | [96] |
| Al₂O₃/TiO₂   | 5W-30 engine oil | Spectral absorbency | Oleic acid | The dispersion stability decrease clearly after 1000 h | [100] |
| Cu/CNTs      | Raposed oil | Sedimentation | Spontaneous polydopamine (PDA) | Stability of unmodified NP decrease after 12 h, modified maintain for 10 days | [100] |
| Ag/graphene  | Paraffin oil | Spectral absorbency, sedimentation | Laser irradiation | With Laser irradiation, stability stable even after 60 days | [97] |
| TiO₂/SiO₂    | Palm oil | Sedimentation, spectral absorbency | - | High rate sedimentation after 3 days | [100] |
| TiO₂         | Water-based lubricant Oil in water | Spectral absorbency | Polyethyleneimine (PEI) | After 120 h, the dispersion is stable | [56] |

The sedimentation method is the easiest method to determine the stability of nanolubricants because only the observation of the nanolubricants is involved, and it is usually conducted after nanoparticles disperse in the lubricant. During the stability analysis, a photograph of the test nanolubricants should be taken. However, the drawback of this method is the long duration required. Furthermore, the environmental conditions and volume should be fixed for all test samples to obtain precision results, and any relocation or disturbance has to be avoided during this analysis. The duration of this analysis is usually in the range of days to months. The dispersion stability of CuO in palm kernel oil has been researched, revealing that it fully sediments at day 16 [66]. Wu et al. reported significantly less precipitated La(OH)₃/RGO in diesel engine oil after 28 days [96]. A comparative study of graphite with or without dispersant in API Group III 150N base oil should be mentioned, with 1 wt% PIBISI the stability of nanolubricant remained stable for up to 50 days. In comparison, without dispersant, stability only lasts 6–7 days [81]. In contrast, including 1 wt% sorbitan monooelate as a dispersant in graphite-PAO4 lubricant, graphite fully sediments after 3 days [90]. Hence, the duration of this stability analysis is due to the different combination of lubricants and NPs, and the analysis is considered complete when the NPs fully sediment or the dispersion stability lasted for a long time.

Spectral absorbency analysis is the most efficient method to evaluate the dispersion stability of nanolubricants. Ultraviolet-visible (UV-vis) absorption spectroscopy measurements are used in this method to characterize the stability of a variety of materials in lubricants quantitatively. This measurement is a reliable method to evaluate the dispersion stability of nanolubricants. It has
the characteristic absorption bands in the wavelength range of 190–1100 nm [122]. Xia et al. [67] reported the wavelength of absorbance of TiO$_2$ nanolubricant in the range of 250-500nm and maximum absorbance at 378nm. In addition, the quantitative concentration of nanofluids will be provided through this measurement, due to the linear relation of supernatant nanoparticles concentration to the absorbency [122]. Thus, this is an advantage of using this method. Furthermore, for this analysis, different test durations have been reported by researchers. Xia et al. [67] carried out the spectral absorbency analysis over 72 h for oil in water enriched with TiO$_2$, showing that stability is over 80%. Similarly, Gulzar et al. [72] conducted this analysis over 72 h for nanoCuO and nanoMoS$_2$ lubricant. Song et al. [63] showed the absorbance spectrum of three different temperature modified nanoZnAl$_2$O$_4$ lubricants over 140 h. A comparative study revealed the optical absorbance spectral behavior of engine oil enriched with nanocomposite Al$_2$O$_3$/TiO$_2$ in four different durations: 48, 168, 336, and 1000 h [110].

The zeta potential measurement also known as the surface charge analysis, is a technique used to determine the colloidal stability of nanoparticles. This method shows the zeta potential difference between the dispersion medium and the stern layer of fluid attached to the dispersed nanoparticle [122]. Typically, the range of zeta potential is from +100 to −100 mV, and it is related to the colloidal stability of nanolubricants. Thus, high zeta potential means electrically stabilized, while low zeta potential means dispersion instability due to the absence of a force to prevent the agglomeration of particles. In addition, if the zeta potential value is in the range of 0 to ±5mV, the particle tends to flocculation or coagulation, and ±10 to ±30mV is considered as incipient instability. However, ±25 mV is the arbitrary value that decides the dispersion stability, in the range of ±40 to ±60 mV results in good stability, and greater than ±60 mV is excellent stability [127]. Luo et al. [58] reported that the modified Al$_2$O$_3$ nanolubricant has the average zeta potential value of 25.1 mV. The modified nanoCuO has a higher dispersion stability six times that of the unmodified nanoCuO in water [68].

7. Conclusions

Tribology is a science that has a close relationship with the development of physics. This field is already involved in the microscale and nanoscale, both of which influence lubrication, friction, wear, and sliding mechanisms. The tribological characteristics and lubrication mechanism of various types of nanoparticles as lubricant additives were reviewed here. The present review also covered the parameters of nanoparticles that affect the tribological properties, the dispersion method, techniques on enhancing dispersion stability, and nanolubricants characterization. Even though a lot of research studies have been done, the most crucial challenge is to prepare and maintain homogenous and good stability nanolubricants for a long duration. Thus, the stabilization of nanoparticles in various base oils must be investigated using multiple modification techniques.

The size, concentration, and morphology of nanoparticles are relevant to the improvement of tribological characteristics. However, the methods to determine the correlation between these factors are still lacking, but it is still promising. Besides, it is essential to discover the optimum concentration of nanoparticles in base oils. This would not only exhibit the maximum improvement but also save in terms of the cost of production. Thus, the authors recommend here the use of simulation software to optimize the concentration of nanoparticles in base oils which exhibit excellent tribological properties.

Based on the literature, there are two techniques for enhancing the dispersion stability of nanolubricants. Surface modification seems to provide more effective stabilization of nanolubricants, and it does not significantly affect the fuel properties of nanolubricants. In addition, ultrasonication is an auxiliary method in the previously mentioned techniques.

Overall, a majority of extant studies reported that nanoparticles enriched with lubricating oils improved tribological performance. The lubrication mechanism of nanoparticles cannot be fully yet understood since the mechanism is complex, and it contains various types of nanoparticles. However, for environmental protection purposes, the formulation of environmentally friendly nanolubricants is essential, which does not contain sulfur or phosphorus and will not affect the improvement of tribological properties.
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