Influence of nano particles on the performance parameters of lube oil – a review

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Abstract

This review focuses on the effect of nanoparticles in lubricating oil performance. The impact of chemical composition, particle size, and nanoparticle shape is evaluated on lubricants' lubricating capabilities. The effects of base oils and surfactants, and dispensers are also covered. This review demonstrates a comparative study of nanoparticles based on the maximum reduction in friction and wears values and the obtained minimum coefficient of friction (COF). The above three performance parameters collectively provide a better understanding of the role of nanoparticles in lubricating oil performance.

List of abbreviations

3D Three-Dimensional
AFM Atomic force microscopy
AISI American Iron and Steel Institute
API American Petroleum Institute
COF Coefficient of Friction
DIA Diameter
EDS or EDX or EDAX Energy Dispersive x-Ray Spectroscopy
FE-SEM Field Emission Scanning Electron Microscope
HRSEM High-Resolution Scanning Electron Microscope
HRTEM High-Resolution Transmission Electron Microscopy
LEN Length
LSM Laser Scanning Microscopy
Max. Maximum
Min. Minimum
MWCNTs Multi-Walled Carbon Nanotubes
nm Nano Meter
NPs Nanoparticles
OM Optical Microscope
PAO Polyalphaolefin
PTFE Polytetrafluoroethylene
Ref. Reference
SAE Society of Automotive Engineers
SAXS Small-angle x-ray scattering
1. Introduction

In general terms, efficiency is the ratio of output to input. There are two available methods to improve the efficiency of a mechanical system that come to mind, the first is to reduce input, and the second is to minimize losses. The system’s output also varies in the first case. Still, the system response becomes unaltered or better in the second case. Thus, friction is a significant element on the way to reduce energy loss. In typical applications, friction cannot be eliminated but reduced to some level where energy loss is minimal. So, there is a need for an efficient lubrication system. Nowadays, lubricating oil contains 90% hydrocarbons and the rest of the additives, which play an essential role in its behaviour. Organic phosphorous and sulfide compounds have played positive roles as friction modifiers and wear resisters [1].

Nano lubricant is a homogenous mixture of base oil, nanoparticles, and dispersants or surfactants. In recent years, nanoparticles played an essential role in the field of additives. Generally, the size of the particles is less than 100 nm. Many researchers say that nanoparticles within lubricating oil act as friction modifiers and positively impact thermal requirements [2].

The lubrication mechanism derives from the physical and chemical interactions between molecules of lubricants, material surfaces, and the environment. Based on nanoparticle interaction within the tribological surfaces, four mechanisms are derived [1], [3], [4]. First, nanoparticles of the spherical-shaped act as the tiny balls in between the tribological surfaces, which changes the sliding action into the rolling action results in the reduction of COF [3], [5–7]. Second, sometimes nanoparticles form a protective layer over the mating [8–12]. Third, nanoparticles fill in the asperities, and friction cracks result in a smoother surface, termed the mending effect [13]. Forth, Surface roughness cuts down due to nanoparticles’ abrasive action, termed the polishing effect [14]. Figure 1 shows a pictorial representation of the lubrication mechanism.

Nanoparticles could be used as an add-on in diesel and biodiesel to improve fuel efficiency, engine performance, exhaust emission, combustion [15–18]. They were also effective in the area of heat transfer [19], [20].

After analysing the number of articles in nano lubricants, many questions arise in mind, such as how can the quantity of nanoparticles be optimized to enhance the tribological performance? What are the properties of nanoparticles relevant for lubrication? Can we measure their effects? During the literature review of several
hundreds of publications, it is observed that each study is based on unique conditions, such as base oil, additive concentration, nanomaterials, and their surface functionalities, workpiece material, test parameters, lubrication regime, etc many others. There is no single standard condition that can be used for a fair comparison. The researchers took a nanoparticle, two or more nanoparticles, or nanocomposites for their study. Therefore, the performance parameters were analysed for better comparison. Statistical analysis is based on experimental results collected from about 80 papers on nano lubricant additives listed in various tables. For the analysis, the minimum (Min.) value of COF, the maximum (Max.) % reduction in COF, and the maximum % reduction in wear are taken as the performance parameters of the nanoparticles in the lubricating oil. The study of individual parameters does not clarify the picture regarding the performance of nanoparticles in lubricating oil. Comparison of all three parameters at the same time is required for each nanoparticle. Therefore, this review summarizes the results and shows a new way of selecting nanoparticles according to performance parameters. The effect of chemical composition, particle size, and nanoparticle morphology on lube oil has been analysed. The impact of nanoparticles on lubricating oil with a base oil and the optimum value of nanoparticles with their performance parameters is summarised. The results and shows a new way of selecting nanoparticles according to performance parameters. The comprehensive review provides detailed information about nano lubricants in a precise manner.

2. Impact of nanoparticles chemical composition on the performance of lube oil

Nanoparticles of every composition and section have been well studied. It is separated by metals, metal oxides, sulfides, carbon and its derivatives, two or more nanoparticles, or nanocomposites for their study. Therefore, the performance parameters were analysed for better comparison. Statistical analysis is based on experimental results collected from about 80 papers on nano lubricant additives listed in various tables. For the analysis, the minimum (Min.) value of COF, the maximum (Max.) % reduction in COF, and the maximum % reduction in wear are taken as the performance parameters of the nanoparticles in the lubricating oil. The study of individual parameters does not clarify the picture regarding the performance of nanoparticles in lubricating oil. Comparison of all three parameters at the same time is required for each nanoparticle. Therefore, this review summarizes the results and shows a new way of selecting nanoparticles according to performance parameters. The effect of chemical composition, particle size, and nanoparticle morphology on lube oil has been analysed. The impact of nanoparticles on lubricating oil with a base oil and the optimum value of nanoparticles with their best performance characteristics are also shown in this review. This comprehensive review provides detailed information about nano lubricants in a precise manner.

2.1. Metals

Metallic nanoparticles have unique physical and chemical properties as lubricant additives [21–29]. Nanoparticles like Ag, Bi, Co, Cu, Fe, Ni, Pd (palladium), Sn, etc come under this section. Within the metal segment of nanoparticles, Cu is the most concentrated Nanoparticles (NPs) due to its low melting point, small particle size, and desired ductility [11], [13], [27–36]. Copper nanoparticles show superior antiwear and anti-frictional properties. In Reference [32], Cu nanoparticles with 0.3% by weight give the best results with a mineral base oil and show a good stability period of 8 months. In another case, Cu nanoparticles do not offer any significant improvement in synthet esters. Still, they can improve the antiw ear property of mineral oil by up to 64% with a 0.3% concentration [22].

| Types                  | Nanoparticles                                      |
|------------------------|---------------------------------------------------|
| Metals                 | Ag, Bi, Co, Cu, Fe, Ni, Pd                        |
| Metal oxide            | Al2O3, CuO, Fe3O4, TiO2, ZnO, ZrO2                |
| Carbon and its derivatives | Graphene, Diamond, SWCNT, MWNTs                  |
| Sulfides               | WS2, MoS2, CuS                                    |
| Rare earth compounds   | LaF3, CeO2                                        |
| Nanocomposites         | Al2O3/SiO2, Al2O3/TiO2, Cu/graphene oxide, WS2/MoS2 |
| Others                 | SiO2, PTFE, BN, Serpentine                        |

Figure 2 shows the statistics presenting the distribution of the nanoparticle composition. According to the analysis, the metal oxide nanoparticles cover the maximum. Metal oxides are followed by metals, sulfides, nanocomposites, other carbon and its derivatives, and rare earth compounds.

Figure 3 shows the effect of different chemical compositions on the performance parameters. According to the analysis, when the lowest value of COF is the point of concentration in the performance parameters. Metallic nanoparticles showed the best performance, followed by sulfides, carbon and its derivatives, nanocomposites, others section, rare earth compounds, and metal oxides. Sulfides perform best when it comes to the maximum reduction in COF as a matter of concentration. And carbon and its derivatives, others section, metals, metal oxide nanocomposites, and rare earth compounds are in order. For the maximum reduction in wear, the compositions are sulfides, other segments, metals, metal oxides, carbon, and its derivatives, nanocomposites, and rare earth compounds. The sulfide segment performs exceptionally well in all three performance parameters.
Nanoparticles such as Ag have been shown to getter friction reducers due to their ductile nature [37], [38]. There is an improvement noted on lubricant characteristics of mineral oil by adding Bi particles [39]. The suspension of Ni particles shows a decrease in the average COF and wear for Polyalphaolefin (PAO) 6 [40], [41]. Metallic nanoparticles are not only known as friction modifiers but also to improve load-bearing capabilities. The load-bearing capabilities of base oil are enhanced by adding Pd [42], [43]. At the comparison node between Fe, Cu, Co, the COF and wear values show a reduction of up to 53% and 50%, respectively, for Fe + Cu [21]. Both Fe and Sn NPs show a reduction in friction, wear, and frictional heat compared to MACs oil [44].

Table 2 shows details about metallic additives for nano lubricants. The name of the NPs and the particle size and morphological characteristics are mentioned within this table. This accurate aggregated description also gives information about base oils and also about surfactants or dispersants. The table also lists the technique used to characterize nanoparticles, nano lubricants, and worm surfaces. The importance of any nanoparticle is

![Figure 2. Statistics showing the chemical composition distribution of nanoparticles.](image1)

![Figure 3. Effect of chemical composition on performance parameters.](image2)
| S. no. | Nanoparticle | Nano particles size | Nano particles shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological test methods | Material of tribo surfaces | Stability | Min. value of COF | Max. % reduction in COF | Max. % reduction in wear | References |
|--------|--------------|-------------------|---------------------|----------|--------------------------|---------------------------|--------------------------|--------------------------|----------|-------------------|-------------------------|--------------------------|-----------|
| 1      | Ag           | 6–7 nm            | Spherical           | Multialkylated cyclopentanes (MACs) lubricant | —         | Scanning Electron Microscope (SEM), Energy Dispersive x-Ray Spectroscopy (EDS), X-ray Photoelectron Spectroscopy (XPS), Transmission Electron Microscopy (TEM) | Optimal SRV Oscillating Friction and Wear Tester | Society of Automotive Engineers (SAE) 52100 Steel | —         | 0.1               | 2%                      | 9.09                    | 16.67     | [37]      |
| 2      | Bismuth (Bi) | 7–65 nm           | Spherical           | BS900 (heavy base oil) and BS6500 (light base oil) | —         | TEM, Small-angle x-ray scattering (SAXS) | Four-Ball Tester | American Iron and Steel Institute (AISI) 52100 Steel Balls Disks: Gray Cast Iron (GG 25, Lamellar Graphite) Pins: Chromium-Plated Steel 100Cr6 | —         | 0.0475            | 300 mg l⁻¹                  | 34.48                   | 14.62     | [45]      |
| 3      | Cu           | Diameter (DIA): 5 nm | —                   | Lubricant Chevron Taro 30 DP 40 and Teboil Ward Chevron | Oleic acid | Atomic force microscopy (AFM), XPS | Pin on Disc | Chromium-Plated Steel 100Cr6 Disks: 20CrMnTi Steel Pins: H62 Bronze 1045 steel More stability quoted as compared to not modified surface | —         | 0.1075            | 0.3%                    | 49.41                   | 22.22     | [46]      |
|        |              | 20–130 nm         | Spherical           | 508SN | Polysobutylenebutadimide | SEM, Scanning Tunneling Microscopy (STM), TEM, x-ray powder diffraction (XRD) | Pin on Disc | — | 0.033 | 0.1% | 25 | — | [13] |
|        |              | 20 nm              | Globular            | Mineral oil SN 650 | — | SEM, EDS, XPS | Disc on Disc (Test Rig) | — | 0.059 | 0.6% | 26.9 | 57.2 | [31] |
|        |              |                    | Spherical           | CAL-1 (5W-40), CAL-2 (5W-40), and CAL-3 (5W-20) and Avocado oil | — | TEM, Three-Dimensional (3D) Optical Profiler | Four Ball Tester | GCr15 Steel Balls | — | 0.049 | 1.6% in CAL-3 | 38.8 | 24 | [47] |
|        |              | 25 nm              | Spherical           | Avocado oil | — | 3D Profilometer, SEM, EDS | Pin on Disc | Pin: Aluminum Alloy 6061 Disc: EN 31 Steel Ball and Disk: AISI 52100 Pin: AISI 1020 10 days stability reported | — | 0.04 | 1% | 50 | 75 | [48] |
|        |              | 10–30 nm           | Oblong              | Paraffinic mineral and Synthetic ester | — | SEM | Pin On Disc And Four-Ball Tester | 8 months stability reported | — | 0.01 | 0.3% with mineral oil | 60 | 20 | [22] |
| S. no. | Nanoparticle   | Nanoparticles size | Nanoparticles shape | Base oil   | Surfactants or dispersants | Characterization equipment | Tribological test methods | Material of tribo surfaces | Stability | Min. value of COF | The optimum value of NPs | Max. % reduction in COF | Max. % reduction in wear | References |
|--------|----------------|--------------------|---------------------|------------|-----------------------------|----------------------------|--------------------------|---------------------------|-----------|------------------|-----------------------------|--------------------------|--------------------------|-----------|
| 4      | Ni             | 20 nm              | Spherical           | PAO6       | —                           | SEM, EDS                  | Block on Ring Configuration and Four-Ball Tester | Rings: AISI D3 Steel Blocks: AISI 1045 Steel Ball: AISI 52100 Steel | —         | 0.015            | 0.5%                        | 30                        | 45                       | [40]      |
| 5      | Pd (palladium NPs) | 7.5–28.5 nm       | Spherical           | PAO6       | Oleylamine and oleic acid   | TEM, XRD, SEM, XPS         | Four-Ball Tester          | GCr15 Steel Balls AISI 52100 Steel | —         | 0.0675           | 0.05%                      | −18.52                   | 18.64                    | [41]      |
| 6      | Fe, Cu, and Co | 50–80 nm           | Spherical           | SAE 10     | Converse emulsions of water in lubricant solution (CEWLS) | SEM, Energy Dispersive X-Ray Spectroscopy (EDX) | Four-Ball Tribotester     | 100 Cr6 Bearing Steel             | Not Required | 0.05             | 1%                         | 9.09                     | 94                       | [42]      |
| 7      | Sn and Fe      | Sn: 30–60 nm       | Spherical           | Multialkylated cyclopentanes (MACs) | SEM                  | Four-Ball Tester          | AISI 52100                | —                         | 0.0625      | 1% FeSn          | 37.5                        | 38.75                    | 30                       | [49]      |

References:
- [40]
- [41]
- [42]
- [49]
checked only by tribological testing methods. And as friction and wear are superficial phenomena. Therefore,
information about the surface material of the tribological member and the tribological test is an essential
component. So, this table lists the information about the tribological test methods and the surface material of the
test components. The stability of nanoparticles is also mentioned in nano lubricants. Finally, the minimum
value of COF obtained in the tribological test is also mentioned. The optimum quantity of nanoparticles is
mentioned at which nano lubricants show their highest efficiency. This optimum value is displayed as % of
nanoparticle/unit volume. The maximum reduction in COF and wear value is also listed. The particular case is
laid on the table. The average value of COF and wear is taken for this analysis. A negative value of COF and a
decrease in wear indicate an increase in COF and wear values.

2.2. Metal oxide
Lubrication mechanisms of Oxides are analogous to those of metallic NPs, including the formation adsorption
film, rolling effect, and sintering. Some common metal oxides are Al2O3, ZnO, Fe3O4, ZrO2, Co3O4, etc, which
positively affect oil performance [50–52].

Al2O3 are hard particles but positively respond to the lube oil’s frictional and wear characteristics [52–55].
There are studies available on the anti-frictional and antiwear behaviour of [56–58]. CuO NPs at 0.1% exhibit
better antiwear performance compared with other concentrations [59]. The effect of CuO particles with TiO2,
ZnO, Al2O3, and nano diamond has been investigated [60]. Some oxides like magnetic Fe3O4 can reduce
COF by forming a protective film between the tribo [63], [64].

Several studies reported on the performance of [65–71]. When TiO2 nanoparticles were added to engine oil,
the co-efficient of friction was reduced by 86% with 0.3% concentration by weight of the oil compared to the oil
without TiO2 nanoparticles for load 4 kg [70]. Almost identical performance has been reported in [65], a 0.3%
(TiO2) concentration in engine oil with a similar reduction in COF of 86%. The optimum concentration of
ZrO2 is 0.5% for the reduction in friction coefficient up to 27.34% under the thrust-ring test [72].

The essential information about the metal oxides nanoparticles as lubricant additives is mentioned in table 3.

2.3. Sulfides
Sulfides are an essential and long-used nano additive. Lube oil with sulfides nanoparticles shows more
antifriction and antiwear properties. Some common examples of sulfides nanoparticles are MoS2, WS2,
and CuS.

MoS2 and WS2 are widely accepted for their chemical stability and fullerene-like structure. Hollow
polyhedral structures called fullerene-like NPs (IF-NPs) provide stability to the oil particles [74]. The 0.25%
MoS2 microlubricant results in an almost 40% reduction in friction and a 6% reduction in wear compared with the
base oil in fully flooded EHL contacts [75]. In another example, MoS2 can reduce COF by up to 70% and show
superior antiwearing properties with a concentration of 1% [76].

Table 4 presents examples of sulfides used as nano additives along with a description of nano lubricants.

2.4. Nanocomposites
Nanocomposites are the field of taking advantage of two or more nanoparticles at the same time. In
nanocomposites, two or more nanoparticles are combined into a base oil. Sometimes researchers also synthesize
nanocomposites. The nanocomposite is an area where two dislike nanomaterials and can increase lube oil
quality like Cu/SiO2 Nanocomposite. Many researchers say that some nanocomposite shows better
performance than the performance of individual nanoparticles in lube [86], [87]. The trends also suggest that
research on nanocomposites has increased over the years. Many nanocomposites are evaluated for their
performance in lubricating oils, which are Al2O3/SiO2, Al2O3/TiO2, Cu/Graphene oxide, WS2/MoS2, etc.

The lubricating oil with Al2O3/TiO2 nanoparticle of 75 nm average diameter and KH-560 shows good
dispersion stability. It can reduce friction and wear with an optimum concentration of 0.1% [87], [88]. The
performance of lubricating oil using Al2O3/SiO2 nanoparticles as additives was improved compared to pure
Al2O3 or SiO2 particles [89], [90]. A solid/liquid dual lubrication system was seen by mixing WS2–MoS2 films
with two specific oils, including MAC and CPSO. The tribological performance of the WS2–MoS2/MACS
system was much better than that of WS2–MoS2/CPSO [86]. Nano-Cu/graphene oxide exhibits better
performance than single GO nanoparticles [91]. Cu/SiO2 nanocomposite as a lubricant additive can effectively
improve the friction-reducing and anti-wear ability load-carrying capacity of distilled water [91]. ZnAl2O4 NPs
as a lubricant additive can significantly improve antifriction and antiwearing characteristics of lube oil, with the
optimum concentration of 0.1 wt% [92].

Table 5 shows examples of Nanocomposites used as nano additives along with a description of nano
lubricants.
2.5. Others
Nanoparticles such as SiO₂, PTFE (polytetrafluoroethylene), BN, Serpentine, etc., fall under this other section. More than half of the research under this section focuses on SiO₂ nanoparticles. SiO₂ shows some significant improvements in friction and wear capabilities of lubricating oil. SiO₂ can improve anti-frictional and antiwear properties by 77.7 and 74.1% in sunflower oil with 1.25% of SiO₂ [98].

The nano-BN oils significantly improve the performance of the base oil [99], [100]. The concentration of 0.1% BN particles shows better performance as compared to SE 15W-40 [101]. PTFE NPs show excellent potential to improve the EP performance of lube oil [102], [103]. 1.5 wt% of serpentine into oil is the most efficient in reducing friction and wear [104].

Many studies have focused on SiO₂ NPs because of their friction and wear-reducing ability in lubricating oil [98], [105–111]. It is observed that small nano-SiO₂ nanoparticles exhibited optimal friction-reduction performance under low frequency. In contrast, for large nano-SiO₂, it occurred under high frequency [108]. SiO₂ with surface modifier KH-550 has the potential to improve the performance of lubricating oil [105]. In [110], a significant decrease in COF upon the increase of SiO₂ nanoparticles (0 to 0.6 wt%) has been reported. In another case, when comparing the performance between SiO₂, graphite, Cu, CuO, and WS₂, SiO₂ in 15W40 lubricating oil showed the highest reduction in COF and wear by 25.55% (at 588 N load) and 59.91% (at 588 N load) [111].

Table 6 shows nanoparticles from other sections used as nano additives along with a description of nano lubricants.

2.6. Carbon and its derivatives
Carbon shows a variety of properties from soft to hard when comparing graphite to diamond. Carbon and its derivatives are studied as nano additives for their different sizes and shapes. Graphene, Diamond, SWCNT (Single Wall Carbon Nano Tube), MWNTs (Multi-Wall Carbon Nano Tube) are important carbon derivatives. The tube form of nanoparticles is mainly studied for carbon. According to this analysis, graphene, diamond, carbon nanotubes are uniformly covered and improve oil capacities. Nano diamond in ethylene glycol exhibits anti-frictional properties. It has a more negligible wear effect in stainless Steel - stainless steel aboriginal contact [112]. The COF of graphite mixed with oil decreased by 28%, and the antiviral properties of the mixture improved by 32% compared to pure 10W40 oil [113].

It is of interest to study the tribological properties of graphene in recent years [114–116]. Graphene additives can reduce COF up to 78% with 0.5 wt%. In the same case, the scar diameter was significantly reduced compared to pure PAO2 lubricants under a load of 120 N and a rotation speed of 250 rpm [114]. The addition of Gr resulted in a significant reduction in friction and wear values compared to the reference oil (5W-30) [115]. Diamond is another derivative of carbon that is intensively used as a friction modifier [112], [117–119]. Nano-diamond ethylene glycol dispersions exhibit friction and wear lowering effects in stainless Steel–stainless steel tribological contact [112].

Table 7 presents examples of Carbon and its derivatives used as nano additives along with a description of nano lubricants.

2.7. Rare earth compounds
LaF₃, CeO₂, and CeBO₃ are some common examples of rare earth compounds. LaF₃ nanoparticles as a lubricant additive can effectively reduce friction, improve antiwear capacity, and increase the load-carrying capacity of fluoro silicone oil under optimal concentrations of 0.08 wt% [122].

The stearic acid-modified cerium borate nanoparticles exhibited a spherical morphology with an average of 8 nm and were dispersively stable in rapeseed oil. Moreover, SA/CeBO₃ nanospheres markedly enhanced tribological performances of rapeseed oil [123]. When lubricated by ZrO₂ additive oil, the Ta-Si/steel contact COF becomes the lowest [124].

Table 8 shows examples of rare earth compounds used as nano additives along with a description of nano lubricants.

3. Impact of particle size
The diameters in spherical and tubular shapes, the thicknesses in the sheets are characteristic dimensions. Typically, the size of nanoparticles is less than 100 nm. Due to the small size of nanoparticles can enter in between the contact of tribological members. The high surface-to-volume ratio also enables NPs to react with the surroundings. Hence this section elaborates the effect of nanoparticle size on the performance of lube oil.

Since the size of the particles governs the mechanical and physical properties of the nanoparticles, it is essential to use nanoparticles of optimum size. In [126], CaCO₃ nanoparticles show better performance at
| S. No. | Nanoparticle | Nano Particle Size | Nano Particle Shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribo Surfaces | Stability | Min. value of COF | The optimum value of NPs | Max. % reduction in COF | Max. % reduction in wear | Reference |
|-------|--------------|--------------------|---------------------|---------|---------------------------|---------------------------|-----------------------------|--------------------------|-----------|----------------|---------------------------|-----------------|--------------------------|-----------|
| 1     | Al₂O₃        | 78 nm              | Spherical           | Lube Oil with VI95 | KH-560 | SEM, EDS                  | Four-Ball Tester and Thrust Ring Friction Tester | GC215 Steel Balls | Chemically modified nano composite shows good dispersion stability | 0.055 | 0.1% | 19.12 | 41.75 | [53] |
| 2     | CuO          | 50 nm              | Spherical           | Castor Oil (CO) Paraffin oil (PO) | Sodium dodecyl sulfate (SDS) | Sodium dodecyl sulfate (SDS) | SEM, AFM | Four Ball Tester | AISI 52100 Steel | Visual inspection, upto 72 h | 0.05 | 0.1% | 34.6 | 28.3 | [58] |
| 3     | Fe₂O₃        | 10 nm              | Spherical           | Liquid paraffin | Oleic acid | TEM, XRD | HFRR Tribometer | Ball on Flat Contact Tester | Stability reported up to 30 days | — | 0.1% | 16.13 | 21.82 | [59] |
| 4     | Magnesium borate | 10 nm              | Amorphous           | 500-SN base oil | Sorbitol monostearate - 1% | SEM, XPS, TEM, XRD | Four-Ball Tester and Block on Ring Tribometer | AISI 52100 steel | Stability reported up to 30 days | — | 0.035 | 25 | 64.7 | [63] |
| 5     | TiO₂         | 10–25 nm           | Spherical           | Engine oil 4T Synth 10W-30 | — | Ultraviolet (UV) spectrometer | Pin: Aluminium alloy (LM 25) (Al-Si7Mg) | — | Dispersion analysis using UV spectrometer Improves after surface modification | 0.015 | 0.3% | 86.49 | 92 | [70] |
| 6     | ZnO          | 20 nm              | Spherical           | Polyalphaolefin (PAO6) | Octacare (OL100 and OL300) base oil | TEM, IR, Polarized Microscopy (PM), XPS | Four-Ball Tribometer and Ball-on-Disk Tribometer | AISI K 19,195 Steel | — | 0.5% | 26.32 | 28.69565 | [65] |
| 7     | ZrO₂         | <50 nm             | Amorphous           | 20# machine oil | — | TEM, EDS, XRD | Four-Ball Tester and A Thrust-Ring Tester | Balls: AISI-52100 Ring Specimen: 45 Steel | — | 0.01661 | 0.5% | 27.34 | — | [72] |
| 8     | Al₂O₃ and TiO₂ | Al₂O₃: 8–12 nm TiO₂: 10 nm | Spherical           | Engine oil (5W-30) | Oleic acid | Field Emission Scanning Electron Microscope (FE-SEM), EDS, XPS, XRD, 3D Surface Profile | Test Rig | Piston ring/cylinder liner interface in an engine according to ASTM G181 | DLS method, stability period mentioned is 14 days | 0.038 | 0.25% Al₂O₃ | 35 | 21 | [54] |
| S. No. | Nanoparticle | Nano Particles Size | Nano Particles Shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribo Surfaces | Stability | Min. value of COF | The optimum value of NPs | Max. % reduction in COF | Max. % reduction in wear | Reference |
|--------|--------------|---------------------|----------------------|----------|---------------------------|----------------------------|-----------------------------|-----------------------------|-----------|----------------|-----------------------------|--------------------------|---------------------------|-----------|
| 9      | CuO and Al₂O₃ | <50 nm              | CuO: Spherical, Al₂O₃: Tubular | GL-4 (SAE75W-85) and Poly-alpha olefin 8 (PAO8) | — | SEM, Energy Dispersive X-Ray Spectroscopy (EDAX) | Optical SRV 4 Tester and Four-Ball Tribotester | AISI 52100 Steel | — | 0.37 | 0.25% TiO₂ | 46 | 29 | [60] |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.13 | 2% Al₂O₃ + PAO8 | 16.13 | −25 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.115 | 2% CuO + PAO8 | 25.81 | 11.76 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.13 | 0.5% Al₂O₃ + GL4 | 0 | 0.735 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.125 | 0.5% CuO + GL4 | 3.85 | 13.24 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.085 | 0.1% CuO + API-SF | 18.4 | 16.67 |           |
| 10     | CuO, TiO₂, Nano-Diamond | CuO: 5nm TiO₂: 80 nm Nano-Diamond: 10nm | Spherical | API-SF (V1100) engine oil and a Base oil (V1107) | Glycol | TEM, Optical Microscope (OM), SEM, and EDX | Reciprocating Sliding Tribotester | Chromium-Coated Steel Ball and Plate | — | 0.095 | 0.1% CuO + PAO8 | 5.8 | 78.79 | [6] |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.095 | 0.1% CuO + PAO8 | 5.8 | 78.79 |           |
| 11     | CuO and ZnO with 0.5% | ZnO: 11.71 nm CuO: 4.35nm | ZnO: Hexagonal CuO: Monoclinic | Soybean oil Sunflower oil Mineral oil Synthetic oil (polyalphaolefin) | — | SEM, XRD, EDS | High-Frequency Reciprocating Test Rig (HFRR) | A rigid steel ball (570–750 HV) | — | 0.113 | Mineral + CuO | −8.65 | −2.597 | [62] |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.099 | Mineral + ZnO | 4.81 | 5.009 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.084 | PAO + CuO | 22.22 | 7.677 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.086 | PAO + ZnO | 11.11 | 3.459 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.061 | Sunflower + CuO | −19.61 | −5.867 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.06 | Sunflower + ZnO | −17.65 | −7.733 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.057 | Soybean + CuO | −7.55 | −13.12 |           |
|        |              |                     |                      |          |                           |                            |                             |                             |           | 0.062 | Soybean + ZnO | −16.98 | −18.18 |           |
higher frequencies with larger and lower frequencies with smaller dimensions. In another case, the IF-MoS₂ [76] nanoparticle also exhibits similar properties. It refers to the ability of the particle to enter the point of contact. The probability of NPs entering the contact area increases with the decrease in the size of the particles [127].

The performance of SiO₂ nanoparticles was evaluated for various sizes ranges from 58 to 684 nm and finally quoted that 58 nm size nanoparticles show better tribological properties. On the other hand, CuO nanoparticles are also examined for 2.5, 4.4, and 8.7 nm and found better results on 2.5 nm.

The performance of SiO₂ nanoparticles was evaluated for different sizes from 58 to 684 nm and finally quoted that 58 nm size nanoparticles showed better tribological properties [106]. Similarly, CuO nanoparticles were also examined for 2.5, 4.4, and 8.7 nm sizes, and better results were found at 2.5 nm [128].

The nanoparticle size has been divided into four sections for better understanding. They are <30 nm, 31–60 nm, 61–100 nm, and >100 nm. Figure 4 shows the statistics for the size distribution of nanoparticles. The analysis indicates that the dominant concentration of researchers in the past has been under the size of <30 nm.

Medium-sized segments (30–60 nm) of nanoparticles may be part of future studies in nano lubrication due to the potential of NPs in this field is high enough studies reported in this section.

Figure 5 shows the effect of nanoparticle size on lubricating oil performance. The analysis shows that the size segment <30 nm shows the best results. When the minimum value of COF is the point of concentration in the performance parameter followed by 61–100 nm, 31–60 nm, and >100 nm size segments. Again, the size segment <30 nm shows the best results for the maximum reduction concentration in COF followed by >100 nm, 61–100 nm, and 31–60 nm. The order of size segments is 61–100 nm, <30 nm, >100 nm, and 31–60 nm when maximum reduction in wear is the point of concentration. The nanoparticles with less than 60 nm particle size show equilibrium type reduction in COF and wear. This means that the reduction in COF and wear is almost equal. But the difference between COF and wear reduction seems to widen with increasing size.

4. Impact of the morphology of nanoparticles

The shape of nanoparticles is again an important feature that affects the performance of lubricating oil [129]. The lubrication mechanism explains the importance of particle shape in nano lubrication. It talks about the pressure-carrying capacity of the nanoparticles. Generally, the shapes of nanoparticles are classified into five sections: spherical, granular, nanosheet, nanotube, and onion.

The spherical shape shows their importance because of the low surface energy. The onion-shaped nanoparticle has spherical shapes with a laminar structure inside. Suppose the shape of the onion is stable. In that case, it behaves like a spherical otherwise, it acts as a sheet form of nanoparticles. The most significant advantage of the onion shape is that it has tangled bonds and a spherical shape.

The superior tribological properties are exhibited by the onion, leaf, and spherical particles. The spherical-shaped particles show high load-bearing capacity as well as EP properties due to ball-bearing effects. In spherical particles, the sliding motion turns into rolling motion which eventually reduces the friction [88], [130]. The spherical-shaped NPs also reduce the contact area with a point contact. A line and area contacts are found on nanotubes and nanoplates, respectively.

In [131], There is evidence where MnO₂ nanoparticles improve oil performance by first rolling action and then converted into a protective film on the surface. On the other example, the layered structure of MnO₂ nanoparticles can reduce the value of the friction coefficient by forming a tribo film on the surface [132], [133]. The 2D structure of MnO₂ is a potential nanoparticle as a friction modifier [134], [135].

Figure 6 shows the statics of the nanoparticle’s morphology. Since spherical particles can reduce the value of friction and wear. Therefore, the concentration of analysis is more focused on spherical-shaped nanoparticles. Next to a spherical shape, granular, nanosheet, nanotube, and onion-shaped particles are arranged in the order of evaluation.

Figure 7 shows the effect of nanoparticle shape on the performance parameters. Onion-sized particles perform best when the minimum value of COF is the focal point of the performance parameters. And other particles come in the form of nanosheets, nanotubes, spherical and granular in order. Nanosheets perform best when the maximum percentage reduction in COF is a matter of concentration. Then come onions, nanotubes, spherical and granular, respectively. Onion performs best when it comes to maximum percent wear reduction followed by nanotube, granular, nanosheet, and spherical ordering.

The cumulative study of performance parameters for a broad section, such as chemical characterization of the shape of nanoparticles, does not provide factual information about individual nanoparticles. Any application may require more details on the nanoparticle. Single performance parameter explains less about nanoparticles. So, three performance parameters for different nanoparticles were considered in this review, which provides a clear picture of the performance of nanoparticles in lubricating oil. Here author represents a
Table 4. Sulfides nanoparticles as lubricant additives.

| S. No. | Nanoparticle | Nano Particles Size | Nano Particles Shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribosurfaces | Stability | Min. value of COF | The optimum value of NPs | Max. % reduction in COF | Max. % reduction in wear | Reference |
|--------|--------------|---------------------|----------------------|----------|---------------------------|-----------------------------|---------------------------|---------------------------|----------|-----------------|-----------------------------|--------------------------|--------------------------|-----------|
| 1      | CuS          | 20 nm               | Spherical            | Liquid Paraffin | Oleic acid | SEM, TEM                   | Four ball tester           | ASI 52100 Steel          | —                      | 0.0652 0.5% | —               | —                          | —                        | —                       | [77]      |
| 2      | IF-MoS₂      | Crystalline: 80 nm  | Spherical            | Polyalphaolefin (PAO6) | — | High-Resolution Transmission Electron Microscopy (HRTEM), SEM, XPS | Pin On Flat Tribometer | — | 0.025 with 1% of poorly crystalline | 85.71 58.33 | — | — | — | [78] |
| 3      | MoS₂         | 0.5–2 μm            | Spherical            | 500 SN base oil | — | TEM, SEM, HRTEM | Oscillating Friction and Wear Tester | AISI 52100 (100Cr6) Steel | — | 0.085 0.1% | 29.17 62.07 | — | — | [8] |
| 4      | MoS₂         | 150 and 350 nm      | Spherical            | Blend of PAO 4 and PAO 40 | — | HRTEM, EDX, XPS | — | AISI 52100 (100Cr6) Steel | — | 0.06 1% | 70 91.11 | — | — | [76] |
| 5      | MoS₂         | 250 nm              | Flower-like          | Polyolester and naphthenic oil | No dispersant | XRD, FTIR, TEM | Pin on Disc | Pin: AISI-52100 Steel Disk: Grey Cast Iron | Visibly stable for approximately four days for the polyolester oil and over eight days for the naphthenic oil | 0.03 1% with naphthenic oil | 86.36 | — | — | [79] |
| 6      | MoS₂         | 50–100 nm           | Spherical            | Dioctyl sebacate (DOS) | — | XRD, SEM, EDS, TEM, Laser Scanning Microscopy (LSM), XPS | Ball on Disc Tribometer | GCr15 Steel Ball | — | 0.06 0.5% | 45.45 40 | — | — | [80] |
| 7      | MoS₂         | DIA: 100 nm Length (LEN): 20μm | Nanotubes | Polyalphaolephin (PAO) oil | — | SEM, HRTEM, EDS, Ex-situ optical micrographs | Ball on Disc Tribometer | Ball and Disc: AISI 52100/ DIN 100Cr6 Steel | — | 0.0495 2% | 28.78 | — | — | [81] |
| 8      | MoS₂         | DIA: 100–500 nm     | Multi-Wall Nanotubes (MWNTs) | Polyalphaolephin (PAO) oil | — | TEM, Optical micrographs, SEM | Ball on Disc Tribometer | Ball and Disc: AISI 52100/ DIN 100Cr6 Steel | — | 0.07 5% | 56.25 88.89 | — | — | [82] |
| 9      | MoS₂         | <2 μm               | Spherical            | Trichlorooctadecylsilane | XRD, SEM, EDX | — | — | — | 0.0226 0.25% | 37.95 10.07 | — | — | [75] |
| S. No. | Nanoparticle | Nano Particles Size | Nano Particles Shape | Base Oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribo Surfaces | Stability | Min. value of COF | Max. % reduction in COF | Max. % reduction in wear | Reference |
|--------|--------------|---------------------|----------------------|----------|---------------------------|--------------------------|--------------------------|--------------------------|----------|-----------------|------------------------|--------------------------|-----------|
| 4      | WS₂          | 50 to 350 nm        | Fullerene Like       | SN 90, SN 150, bright stock | —          | XPS                      | Test rig                 | AISI 2510, Brass, Bearing Steel Plate | —         | 0.03            | 5%                     | 48.28                    | 22        | [84]      |
|        |              | Tubes and Spherical form with coatings | Polyalphaolefin-4 (PAO-4) | —       | TEM, Optical Microscope, High-Resolution Scanning Electron Microscope (HRSEM), EDS | Ball on Flat Test Rig | —                        | AISI 316, AISI 50100 | —         | 0.075          | 1%                     | 55.88                    | 70.21     | [85]      |
Table 5 Composite nanoparticles as lubricant additives.

| S. No. | Nanoparticle | Nano Particles Size | Nano Particles Shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribo Surfaces Stability | Min. value of COF | The optimum value of NPs | Max. % reduction in COF | Max. % reduction in wear | Reference |
|--------|--------------|---------------------|----------------------|----------|---------------------------|---------------------------|--------------------------|-------------------------------------|----------------|--------------------------|-----------------|--------------------------|-----------|
| 1      | Al₂O₃/TiO₂   | Al₂O₃:8–12 nm TiO₂: 10 nm | Spherical | Synthetic oil (5W 30) | Oleic acid | FE-SEM, EDS, and 3D Surface Profiler | Test rig | Piston Ring: 320 VH Cylinder Liner: 413 VH Steel Ball GC215 | Chemically modified nano composite shows good dispersion stability | 0.038 | 0.1% (0.05% + 0.05%) | 47.61 | 17 | [87] |
|        |              | 75 nm Spherical     | Lube Oil (VI 95)  | KH-560 (3-glycidoxypropylmethoxysilane) | SEM, EDS | Four-Ball Tester and Thrust Ring Friction Tester |          | Steel Ball GC215 | | 0.052 | 0.1% (Four ball tester) | 20.51 | 44 | [88] |
| 2      | Al₂O₃/SiO₂   | Al₂O₃:13 nm SiO₂: 30 nm | — | Polyalkylene Glycol (PAG 46) | — | FE-SEM | Tribology Test Rig | Aluminium AI 2024 | Visually sedimentation observed after 14 days | | | 0.06525 | 0.06% | 4.78 | 12.96 | [90] |
|        |              | 70 nm Elliptical shaped | lubricant oil | KH 560 | TEM, SEM, EDS | Four-Ball and Thrust Ring Tester |          | — | Checked for 3 months | 0.028 | 0.5% (Four ball tester) | 20 | 22.16 | [89] |
| 3      | WS₂/MoS₂    | Thickness THK: 100 nm | Feather-Like Morphology | MACs (multi-alkylated cyclo-pentanes) and CPSO (chlorinated-phenyl with methyl-terminated silicone oil) | — | SEM, TEM, EDS | Ball-on-Disk | AISI 440C Steel Ball | | | 0.06 | MACs-WS₂/MoS₂ | 45.45 | 57.02 | [86] |
| 4      | BN/calcium borate | BN: 100–200 nm Coating THK: 12 nm | Spherical BN NPs coated with calcium borate | Mineral-base oil (saturated cyclo-paraffin and paraffin hydrocarbon) | No surfactant | TEM, XRD, XPS | Four-Ball Tester | Steel Balls GC215 | | | 0.08 | FCPSO-WS₂/MoS₂ | 42.86 | −1982.46 | [93] |
| 5      | Copper nanoparticle/Gra- | Nano sphere and Nano sheets | Spherical Liquid paraffin oil | Stearic acid | XRD, TEM, SEM | Four Ball Tester | Steel Balls GC215 | | | 0.065 | 0.05% | 27 | 52.7 | [94] |
| S. No. | Nanoparticle | Nano Particles Size | Nano Particles Shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribo Surfaces | Stability | Min. value of COF | The optimum value of NPs | Max. % reduction in COF | Max. % reduction in wear | Reference |
|--------|--------------|---------------------|----------------------|---------|-----------------------------|-----------------------------|--------------------------|------------------------|----------|-----------------|--------------------------|--------------------------|---------------------------|-----------|
| 6      | Cu/ SiO₂     | Cu: 20 nm, SiO₂: 2 nm | Spherical            | Distilled water     | 3-mercaptopropyl-trimethoxysilane (MPTS) | XRD, TEM, SEM, EDS         | Four-Ball Tester        | GCr15 Bearing Steel | —        | 0.14            | 2%                        | 51.72                    | 38.46                     | [91]      |
| 7      | Mg/Al/Ce ternary layered double hydroxides (LDHs) | 190.1 nm, Hexagonal layered structure | Diesel engine oil (CD 15W-40) | Succinic acid and lauric acid | XRD, SEM, FT-IR Spectroscopy, EDS | Four-Ball Tester and Air Compressor Test | GCr15 Steel (SAE-52100) | —        | 0.063           | 0.5g/100 ml              | 44.74                    | 30.2                      | [95]      |
| 8      | La-doped Mg/Al layered double hydroxide (LDH) | 185.6 nm, Hexagonal Laminate Structure | Diesel engine oil (CD 15W-40) | Sodium dodecyl sulfate (SDS) | XRD, SEM, FT-IR Spectroscopy, EDS | Four-Ball Tester and Air Compressor Test | GCr15 Steel (SAE-52100) | —        | 0.082           | 0.5g/100 ml              | 26.13                    | 16.5                      | [96]      |
| 9      | Lanthanum-doped TiO₂ | 20 nm, Spherical | Rapeseed oil | Oleic acid | XRD, SEM and FTIR Spectroscopy, XPS | Four-Ball Tester | GCr15 Steel | —        | 0.051           | 0.25 %                   | 5.56                     | 7.27                      | [97]      |
| 10     | Zinc alumininate (ZnAl₂O₄) | 95 nm, Spherical | Lubricant oil | Oleic acid | XRD, SEM, IR Spectrum, EDS | Four-Ball Tester and Thrust Ring Tester | — | —        | 0.0643 | 0.1% | 33.37 | 31.15 | [92] |
Table 6. Others section of nanoparticles as lubricant additives.

| S. No. | Nanoparticle | Nano Particles Size | Nano Particles Shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribo Surfaces | Stability | Min. value of COF | Max. % reduction in COF | Max. % reduction in wear | Reference |
|--------|--------------|---------------------|----------------------|----------|-----------------------------|----------------------------|----------------------------|---------------------------|-----------|-----------------|------------------------|--------------------------|-----------|
| 1      | BN           | DIA: 120 nm, THK: 30 nm | Disk Shape          | SE 15W-40 | Oleic acid                  | XRD, TEM, AFM, SEM          | Friction Tester            | No. 45 stainless steel | —         | 0.015          | 0.1%                   | 76.92                    | [101]     |
| 2      | Hexagonal boron nitride (hBN) | 70 nm, 0.5 μm, 1.5 μm, and 5.0 μm | Hexagonal          | Avocado oil | —                           | SEM                        | Pin on Disc                | Pin: Oxygen-Free Electronic Copper (C101) Disk: 2024 Aluminium | —         | 0.0144        | 5%                     | 64                      | 72        | [99]     |
| 3      | Polytetrafluoroethylene (PTFE) | 90–100 nm | Spherical | API Group III 150N | Oleic acid, PIBS, Lubritrol 6412TM and Oloa 11000 | SEM, EDAX, and Raman Spectroscopy | Four-Ball Tester | AISI E 52100 | Stability Checked up to 3 weeks | 0.1        | with 5% of Oloa 11000 and No Nano Particle | 37.5 | 10.54 | [100] |
| 4      | Serpentine ultrafine powders | 0.1–5 μm | Irregular | Diesel engine oil (grade: 50 CC) | Boric acid ester and Span 60 | SEM, XRD, EDS | Sliding Friction Tribotester Test Rig | 1045 Steel Contact | —         | 0.04          | 1.5%                   | 58.1                    | 89        | [104] |
| 5      | SiO₂         | 15–20 nm | —        | ST3W/30 gas mobile oil (GMO) | TEM, IR, XPS, TG, EDS, FTIR | RFT-III Reciprocating Tribotester and Four-Ball Tester | Reciprocating Column: 45# Steel Balls: GCr15 Steel | Stable after 5 months | —         | 0.026         | 0.3%                    | 42.86                   | 28.86     | [105] |
| S. No. | Nanoparticle | Nano Particles Size | Nano Particles Shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribo Surfaces | Stability | Min. value of COF | Max. % reduction in COF | Max. % reduction in wear | Reference |
|-------|--------------|---------------------|---------------------|----------|----------------------------|---------------------------|---------------------------|---------------------------|-----------|-----------------|-----------------------------|----------------------------|-----------|
| 5     | MoS₂ and SiO₂ | 58 to 684 nm        | Spherical           | Liquid paraffin | Oleic acid                 | SEM, EDS, AFM             | Ball on Ring              | Ball: Bearing Steel GCr15 Ring: AISI 52100 Steel | Visual Check 30 days     | 0.065 | 0.2%           | 25.71                       | 30.77                       | [106]     |
|       |              | 102 ± 33 nm         | Spherical           | Rust and oxidation lubricant (ISO 32 and 68) | Silane coupling agents, APTEOS and TMSDETA | SEM, EDS, Static Multiple Light Scattering (MLS) | Four ball Tester         | AISI 52100 Steel | Agglomeration starts within 8 days | 0.06 | 0.5%          | 42.86                       | −13.64                      | [107]     |
| 40 and 90 nm | Spherical | PAG (Polyalkylene Glycol) | — | — | SEM, EDS, Optical Interferometer, Rheometer | — | — | — | 0.1125 | 0.2% | 4.26 | 37.5 | [108] |
| 6     | MoS₂ and SiO₂ | 90 nm MoS₂; 30 nm SiO₂ | Spherical – Engine oil | No dispersant | FE-SEM | Ball on Flat Tribometer | Magnesium Alloy/Steel Contacts | — | 0.045 | 0.7% SiO₂ | 43.75 | 7.5 | [109] |
| 7     | SiO₂ and TiO₂ | 20–30 nm SiO₂; 25–35 nm TiO₂ | Spherical | Sunflower Oil | — | FE-SEM – SEM | Block on Ring Sliding Tester | Blocks: AISI 304 Steel Rings: AISI 52100 Steel | — | 0.0144 | 1.25% SiO₂ | 77.7 | 74.1 | [98] |
|       |              | 0.055 | 0.7% MoS₂ | 31.25 | 20 | 0.0032 | 0.79% TiO₂ | 93.7 | 70.1 | [98] |
| S. No. | Nanoparticle                      | Nano Particles Shape | Base oil         | Surfactants or dispersants | Characterization equipment | Tribological Test Methods       | Material of Tribosurfaces | Stability  | Min. value of COF | Max. % reduction in COF | Max. % reduction in wear | Reference |
|-------|-----------------------------------|----------------------|------------------|-----------------------------|-----------------------------|-------------------------------|-------------------------------|-------------|-------------------|---------------------------|---------------------------|-----------|
| 1     | Carbon nanotubes                  | DIA: 10–20 nm        | Castor oil       | Oleic acid                  | SEM                         | Four-Ball Tester              | —                           | —           | 0.035            | 0.02 %                   | 24                       | 6.6       | [120]     |
| 2     | Diamond                           | 15 nm                | Ethylene glycol   | —                           | SEM, EDS, Optical Profilometer | Pin-on-Disk Tribometer       | Disk: Stainless Steel (AISI440B) Ball: Stainless Steel (AISI420) | —           | 0.11             | 1.1 %                   | 31.25                     | 62.96     | [112]     |
|       |                                   | <30 nm               | Mineral oil and PAO oil | —                           | Trubology Test Rig and Four-Ball Tester | —                           | GC15 Steel and Conveyor Belt | —           | 0.08             | 0.031 % with Mineral Oil | 63                       | 52        | [119]     |
| 3     | Fullerene NPs                     | 10 nm                | Fullerene Shaped | Mineral oil                  | SEM, AFM                    | Disc on Disc                 | Grey Cast Iron (GC200)       | —           | 0.006            | 0.1 %                   | 76                       | —         | [1]       |
| 4     | Graphene                          | 10 μm                | Sheets           | Polyalphaolefin-2 (PAO2) oil | SEM, EDS, 3D Optical Micrograph | Four Ball Tester             | AISI-52100 Steel            | Sedimentation starts within two weeks | 0.025       | 0.05%           | 78                       | 14.47                    | [114]     |
|       |                                   | DIA: 5–10 μm         | Nano-Sheets      | Control EDGE professional A5 (SW-30) | SEM, TEM, XRD | Bench of Ring/Liner Assembly | Paton Ring/Liner Reciprocating | 11 days    | 0.035            | 0.4 wt%                  | 29–35                     | 22–29     | [115]     |
| 5     | Oxidized graphite flakes          | —                    | Flakes           | 10W40 oil                    | XPS, Raman Spectroscopy Optical micrographs | Ball on Disk Tribometer     | Balle: 100Cr6 Steel Disc: 316 LN Steel Black: SAE 01 tool Steel Ring Stainless Steel | —           | 0.118            | 0.05%                    | 28                       | 32         | [113]     |
| 6     | Onion-like carbon (OLCs), single/multi-wall carbon nanotubes (SWNT/MWNT), or nano graphene platelets (NGPs) | DND: 4–5 μm          | Onion-Like Carbon, Multi-Walled Carbon Nanotubes (MWNT), SWCNT, Platelets | Polyalphaolefin (PAO6) | Molybdenum dudic(dithiophosphate)(MoDDP) | Block on Ring                 | —                           | —           | 0.002            | 0.015% ND                | 69.17                     | 66.86     | [118]     |
| 7     | Nanodiamond and SiO₂              | Nanodiamond: 110 nm SiO₂ | Spherical        | Liquid paraffin              | SEM, IB, EDS, wear tester   | Ball on Ring                  | Bearing Steel GCr15          | —           | 0.07             | 0.2% ND                  | 34.88                     | 36.81     | [121]     |

Note: Table 7: Carbon and its derivatives nanoparticles as lubricant additives.
| S. No. | Nanoparticle     | Nano Particles Size | Shape | Base oil  | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Tribosurfaces | Stability | Min. value of COF | Max. % reduction in COF | Max. % reduction in wear | Reference |
|--------|------------------|---------------------|-------|-----------|-----------------------------|-----------------------------|---------------------------|--------------------------|-----------|-------------------|--------------------------|---------------------------|-----------|
| 8      | Graphene and MoS₂ | 2 nm                | Nanosheets | Hydraulic oil | –                           | SEM, AFM, Micrographs       | Ball on Disk              | Bearing Steel and Brass  | —         | 0.18              | 28                       | 28.67                     | [116]     |
|        |                  |                     |       |           |                             |                             |                           |                          |           | 0.05              | 1% MoS₂                  | 80                        | 86.67     |

Table 7. (Continued.)
| S. No. | Nanoparticle | Nano Particles Size | Nano Particles Shape | Base oil | Surfactants or dispersants | Characterization equipment | Tribological Test Methods | Material of Trib Surfaces | Stability | Min. value of COF | Max. % reduction in COF | Max. % reduction in wear | Reference |
|-------|--------------|---------------------|---------------------|----------|---------------------------|---------------------------|--------------------------|--------------------------|----------|-------------------|--------------------------|--------------------------|----------|
| 1     | LaF₃         | 10–30 nm            | Hexagonal           | Fluoro-silicone oil | 3-(heptadfluoroisopropyl) propyltriethoxysilane | TEM, XRD, FT-IR, TGA, SEM, XPS, FTIR | Four-Ball Tester          | GCr15 Bearing Steel (SAE-52100) | —        | 0.055             | 0.08 %                   | 31.25                                 | 42       | [122]               |
|       |              | 10–30 nm            | Hexagonal           | Liquid paraffin    | Tributyl phosphate        |                           | Four-Ball Tester          | GCr15 Bearing Steel (SAE-52100) | —        | 0.0975            | 0.4%                     | 13.33                                 | 14.52    | [125]               |
| 2     | SA/CeBO₃    | Dia: 8 nm           | Spherical           | Rapeseed oil       | Stearic acid              | SEM, EDS, XRD, XPS, EDS, FTIR | Four-Ball Tester          | Steel Balls GCr15          | —        | 0.055             | 1.5%                     | 25.42                                 | 7.143    | [123]               |
| 3     | Cerium oxide (CeO₂) and zirconium dioxide (ZrO₂) | CeO₂: 500 nm, ZrO₂: 300 nm | Spherical           | Polyalphaolefin (PAO4) |                           | SEM, EDS                  | Cylinder-on-Disk Tribotester | Roller: Carbon Chrome Steel (SU2) with Tetraedral Amorphous Carbon (ta-G) Coating Disk | 0.05     | 0.2% ZrO₂         | 40                      | −43.17                                | [124]    |                     |

0.088  0.2%  CrO₂  −10  77.05
Figure 4. Statistics showing the size distribution of nanoparticles.

Figure 5. Effect of nanoparticle size on performance parameters.

Figure 6. Statistics showing the shape distribution of nanoparticles.
new way of showing the performance comparison of nanoparticles. Single paper results have been taken to compare the performance of nanoparticles in the case of more than one paper on the same nanoparticles.

Figure 8 shows the performance parameters compared to the various nanoparticles listed above. Some nanoparticles do not have red or green streaks, which means that the author does not include this part in his study.

This analysis reveals that fullerene nanoparticles achieved a minimum value of coefficient 0.006 with a reduction in COF of 76% [3]. The minimum value of COF in Cu is 0.01, and the maximum reduction in COF and wear is 60% and 20%, respectively [22]. In hBN, the minimum COF achieved is 0.0144, with the maximum reduction in COF being 64% and wear reduction being 72% [99]. TiO₂ can achieve a minimum value of 0.015 (COF), reducing COF and wear to 86.49% and 92.4%, respectively [70]. Fullerene, Cu, BN, and TiO₂ perform very well compared to other nanoparticles. In these nanoparticles, the value of COF is desirably low, and the decrease in COF and wear is high, which is a favorable condition for any nanoparticles.

5. Future scope

At the time of analysis, it is observed that the performance parameters change by 10%–15% upon small (in mg) changes of the nanoparticles. The performance of the lube oil in two consecutive additions of nanoparticles is
unknown. Therefore, there is a need to develop a method to characterize the performance parameter of nano lubricants between two successive additions.

Various researchers have well covered the composition of nanoparticles. It has shown their performance well under multiple conditions and materials. The compatibility of nanoparticles with surface material remains untouched so far. This is a critical research gap for future research in the field of nano lubrication.

Medium-sized segments (31–60 nm) of nanoparticles may be part of future studies because this section can improve the characteristics of the oil. The authors use a fixed number to represent the size, which means all the nanoparticles’ dimensions. Researchers can also focus on the size range. As is known, small-sized nanoparticles can efficiently provide rectification effects, and large-sized nanoparticles can easily show rolling effects. So, the combination of both can improve the quality of nano lubricants, which will be the subject of future studies.

Studies about multiple-shaped comparisons are lagging. It may perform unfavorably, but its analysis should be needed in the future. Take an example of a nanotube and a spherical-shaped particle. Spherical shapes of nanoparticles can help reduce COF and improve nanotube wear.

6. Conclusions

The analysis shows that the literature concerning the potential of nanoparticles to improve lubrication performance is still active. Evidence is available where the nanoparticles’ chemical composition, size, and shape are essential in lubricating oil performance. Nanoparticles having multiple chemical compositions, sizes and shapes have been evaluated under different environmental conditions with various base oils. And there is no doubt that nanoparticles have led to extraordinary improvements in the efficiency of lubricants. It can be said with confidence that many nanoparticles have also been evaluated for their effectiveness. Still, now a significant concentration is on environmentally friendly lubricants. Also, the areas mentioned in the future scope are subjects of attention.

Some more conclusions from this review of the literature are listed here.

- The performance of sulfide nanoparticles is awe-inspiring in terms of performance characteristics.
- Basic information about nanoparticle size, shape, base oil, and surfactant or dispenser provides a clear picture of nano lubricants.
- Performance of Size $< 30$ nm The performance of nanoparticles is astonishing.
- Nanoparticles such as spherical and globular play exceptionally well in lubricating oil performance.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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