lubricants

MDPI

Systematic Review

Nanotechnology in Lubricants: A Systematic Review of the Use of Nanoparticles to Reduce the Friction Coefficient

Milton Garcia Tobar *, Rafael Wilmer Contreras Urgiles, Bryan Jimenez Cordero and Julio Guillen Matute

Grupo de Investigación en Ingeniería del Transporte, Universidad Politécnica Salesiana, 010105 Cuenca, Ecuador; rcontreras@ups.edu.ec (R.W.C.U.); bjimenezc1@est.ups.edu.ec (B.J.C.); jguillenm1@est.ups.edu.ec (J.G.M.)

* Correspondence: mgarciat@ups.edu.ec

Abstract: The study of lubricating oil is paramount for the optimal functioning of modern engines, and it has generated intensive research in the automotive industry. The aim is to improve the tribological properties of lubricants by including nanomaterials as additives in base oils. This article presents an exhaustive bibliographic review of the experiments carried out to optimize the tribological properties of nano-lubricants in order to identify the nanoparticles and experimental processes used and analyze the results obtained. The methodology adopted combines inductive and deductive elements. It begins with the formulation of a general theory on the application of nanoparticles in lubricants, followed by the collection of specific data on the conceptualization and preparation of nano-lubricants. A total of 176 articles focused on the application of nanoparticles in lubricants, especially to reduce the coefficient of friction, are reviewed. These works, with impact levels Q1 and Q2, delve into the application and are analyzed to review the obtained results. Most researchers worked with a nanoparticle concentration range of 0% to 1% by volume.

Keywords: nano-lubricants; nanoparticles; laser ablation; submerged arc; vapor deposition; sol–gel; hydrothermal synthesis; ultrasound stirring; magnetic stirring; PH adjustment

check for updates

Citation: Garcia Tobar, M.; Contreras Urgiles, R.W.; Jimenez Cordero, B.; Guillen Matute, J. Nanotechnology in Lubricants: A Systematic Review of the Use of Nanoparticles to Reduce the Friction Coefficient. *Lubricants* **2024**, *12*, 166. https://doi.org/10.3390/lubricants12050166

Received: 4 April 2024
Revised: 3 May 2024
Accepted: 4 May 2024
Published: 9 May 2024

1. Introduction

Lubricating oil is a fundamental component for the correct functioning of vehicle engines today; therefore, it is one of the areas with the greatest research and innovation within the automotive industry [1–4]. This is mainly due to the functions that it performs, among which the following stand out: reduces friction [5], improves sealing [6], protects against wear and reduces corrosion [7], eliminates contaminants [8] and dissipates heat [9]. It is estimated that 80% of mechanical failures are caused by a wear defect due to friction and lubrication [10].

Holmberg et al. in [11] state that 33% of the energy loss in an internal combustion engine is due to friction, attributing 11.5% to the moving parts of the engine, 5% to the transmission gears, 11.5% to rolling resistance and 5% to brake friction. In this way, due to the importance of lubrication, the need arises to improve the tribological properties of lubricants, which leads to a research approach focused on the inclusion of nanomaterials as additives in base oils [12–16].

In this sense, in the last two decades, the tribological behavior of lubricants has been studied with the addition of various nanoparticles, such as Molybdenum Disulfide (MoS_2) [17], Tungsten Sulfide (WS2) [18], Aluminum Oxide (Al_2O_3) [19], Titanium Oxide (TiO_2) [20], Magnesium Stearate [21], Graphite [22], Graphene [23], MWCNT/ZnO Carbon Nanotubes [24], Silicon Oxide SiO_2/MWCNT [25] and Carbon Nanostructures [26].

These studies have obtained favorable results; for example, [27] shows an increase in the thermal conductivity ratio of a lubricant, from 1 to 1.15, using Copper Oxide (CuO) nanoparticles at concentrations of 0% to 4% of the volume with a size of 10 nm at temperatures of 20 to 50 °C. This finding makes nanofluids attractive as coolants for devices with a high energy density.

Zawawi et al. [28] analyzed the behavior of the friction coefficient of nano-lubricants composed of Aluminum Oxide and Silicon Oxide (Al_2O_3-SiO_2), and they concluded that, for a reduction in the friction coefficient of up to 4.78% and an improvement in the wear rate of 12.96%, the optimal volume concentration of nano-lubricants should be 0.02%. It is true that diverse and extensive nanomaterials are used as additives for lubricating oils; however, it is metal nanoparticles or their oxidants and sulfides that have received the most study and research [29,30] because metal nanoparticles enhance the lubricating oil's tribological characteristics through micro-bearing effects and various other mechanisms [31].

Considering the importance of the results presented in the previous paragraphs, this article presents a bibliographic review of the experiments conducted for the improvement of the tribological properties of nano-lubricants in order to identify the nanoparticles used for these experiments, identify the processes of experimentation and, finally, analyze the obtained results.

2. Materials and Methods

This article uses a mixed-approach methodology that combines inductive and deductive elements in the research. Initially, as shown in Figure 1, a general theory of the application of nanoparticles in lubricants is formulated. Subsequently, the data and specific characteristics of researchers' work are collected in the context of the conceptualization and preparation of nano-lubricants. The methods and selection of nanoparticles are mentioned, which, once applied to a lubricant, have an influence on the coefficient of friction. The methodology adopted follows the PRISMA checklist, allowing inductive and deductive research to feed into each other. A flow diagram is included in the Supplementary Materials. The inductive methodology is applied in the observation of specific cases, leading to the formulation of hypotheses on the confirmation of preparation, as well as the methods commonly applied to the production of nanofluids and their influence on the reduction in the friction coefficient.

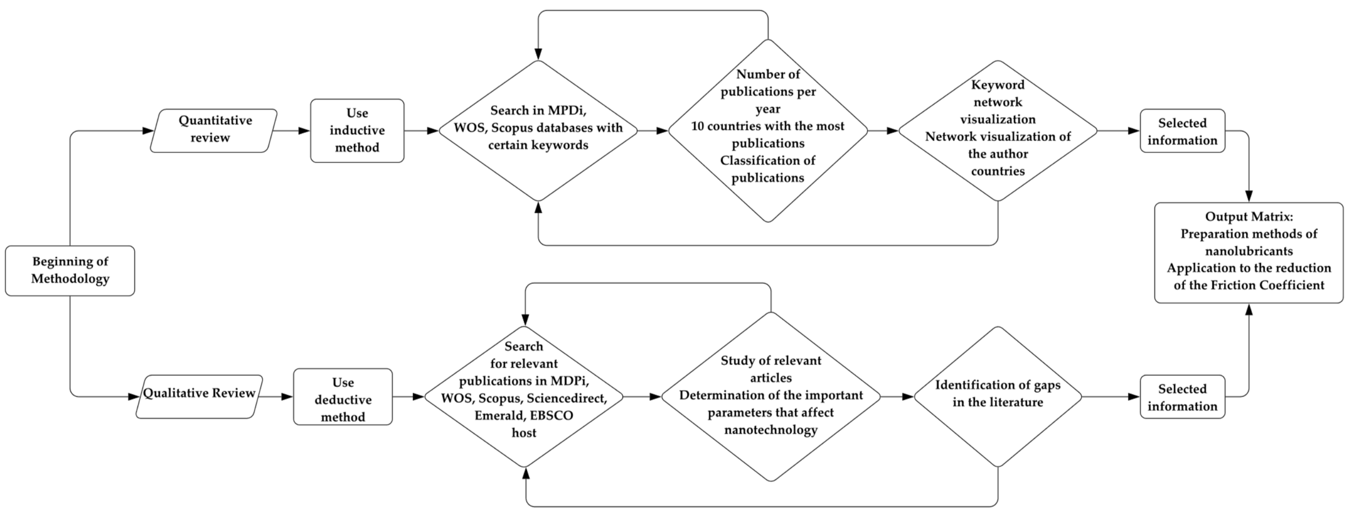

Figure 1. Flowchart diagram of the methodology for the bibliographic review.

The researchers collected data on the one-step and two-step methods used to achieve lubricant stability and durability. These data were then focused on individual cases, thus deriving general principles applicable to the production of finished lubricants. However, the deductive methodology was used to develop generalizations where theoretical principles were analyzed to understand and explain specific phenomena of importance in the preparation of nanofluids. Once the methodology was defined, bibliographic materials were then applied, both academic articles and books intended for scientific dissemination. Information relevant to the characteristics of nano-lubricants was extracted from these materials.

3. Preparation of Nano-Lubricants

The base fluid to which nanoparticles are added in a stable suspension state is known as a nano-lubricant. Dispersion stability is an important challenge in the use of nanoparticles in lubricants, and this is because nanoparticles agglomerate easily due to their high surface tension, leading to the formation of non-dispersible aggregates [32].

To achieve a better dispersion of nanoparticles, methods are used to reduce their high surface energy, such as surface functionalization. This approach offers a solution to these challenges by altering the chemical composition of the nanoparticles to enhance their dispersibility and maintain their stability, using a variety of techniques, ranging from physical to chemical methods [33].

The physical method mainly focuses on the adsorption of surfactants on the surface of nanoparticles to modify their surface characteristics. Regarding chemical methods, a series of compounds have been created to functionalize the surface of nanoparticles of metals and metal oxides, giving them specific properties such as hydrophobicity, hydrophilicity and charge, which contribute to improving both their dispersion and their stability [34–36].

To understand the stability of the dispersion of nano-lubricants, colloidal theories can be used, which attribute the stability of the suspension to the interaction between the nanoparticles and the thermal agitation energy received by the base fluid [37].

3.1. Methods for the Preparation of Nano-Lubricants

In experimentation, the preparation of nano-lubricants is an important step to achieve stability and durability in mixtures; therefore, to produce nanofluids, two methods have been used, known as the one-step method and the two-step method [38–40].

3.1.1. One-Step Method

In the one-step method, nanoparticles are simultaneously and directly produced and dispersed in a base fluid [41–46].

Several techniques are used for this process. The first, the laser ablation technique, is schematized in Figure 2 in [47]. It consists of focusing on the surface of a material (gas or liquid) using a laser beam, which causes its vaporization at the irradiated point. The impact between the evaporated part and the surrounding molecules results in the formation of a laser-induced plasma plume, which is subsequently confined in a specific region to disperse the nanoparticles so that the coagulation phenomenon is correctly controlled in the final stages of the process [48–50].

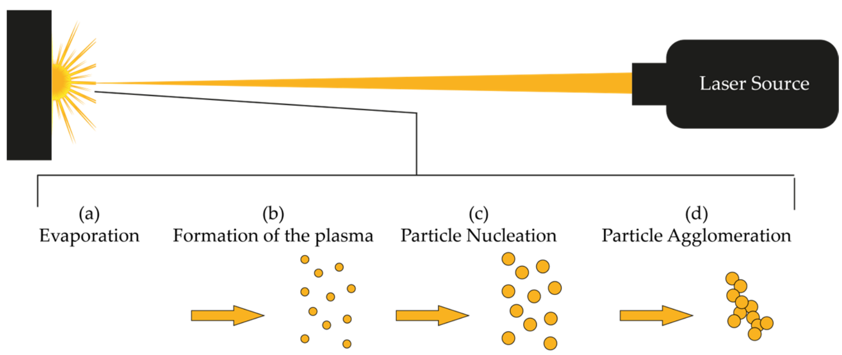

Figure 2. Generation of particles with the laser ablation process.

The second technique is the submerged arc, used in [51–53]. Its principle is based on submerging a pure copper rod in a dielectric liquid located in a vacuum chamber. At this point, the temperature increases to a range between approximately 6000 and 12,000 °C, producing an arc in the rod, which subsequently melts and vaporizes together with the dielectric liquid [54], as detailed in Figure 3.

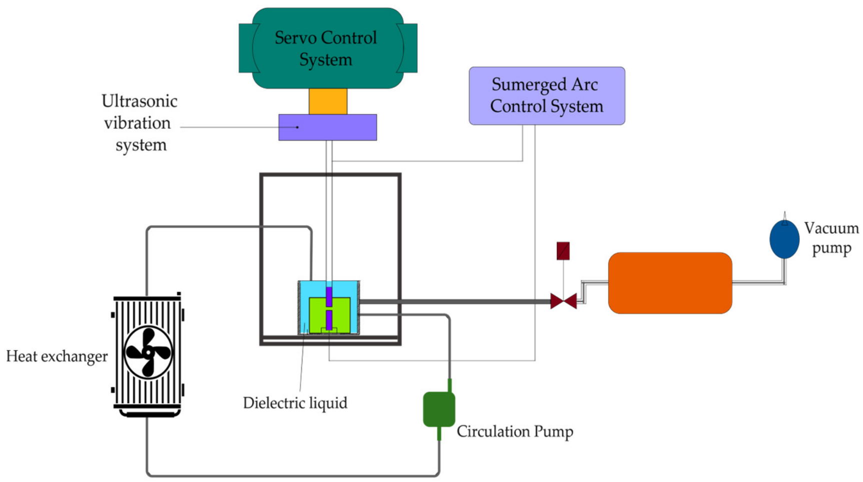

Figure 3. Schematic diagram of a submerged arc nanoparticle synthesis system.

High-pressure steam removes vaporized metal, and, when applied in a vacuum chamber, the metal undergoes a condensation process, nucleation and growth, thus transforming into nanoparticles.

Finally, the vapor deposition technique, used in [55,56], is characterized by forming a thin layer of base fluid on the wall of a container under the action of the centrifugal force produced by a rotating disk (Figure 4). Subsequently, in a tank filled with inert gas at low pressure, the material is heated and evaporated. After this process, the nanofluid is ready when the vapors of the raw material condense due to the interaction with a thin film of swirling water and settle in the base fluid [57].

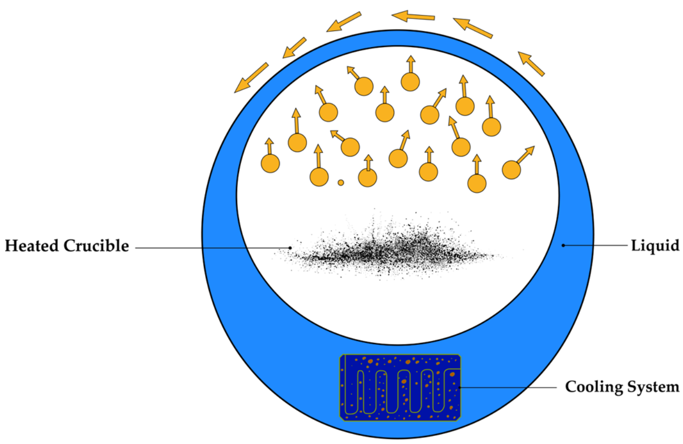

Figure 4. Schematic diagram of vapor deposition method.

3.1.2. Two-Step Method

The two-step method consists of first preparing nanoparticles as dry powders through chemical or physical processes and then, through intense agitation, dispersing them in a base fluid. This method is the most used due to its low cost and ability to produce nanofluids on a large scale [58–60].

In the two-step method, the preparation of nanoparticles is carried out prior to mixing with the base fluid using the following techniques:

The sol–gel technique is applied in [61–63] and specifically explained by Behnajady et al. [64] in the following steps: First, using the ultrasonic bath technique, a mixture of titanium and a solvent is sonicated. Deionized water is then added drop by drop to the mixture using magnetic agitation to carry out the hydrolysis process. In the end, the product from the previous steps is dried and calcined, producing a crystalline powder (see Figure 5).

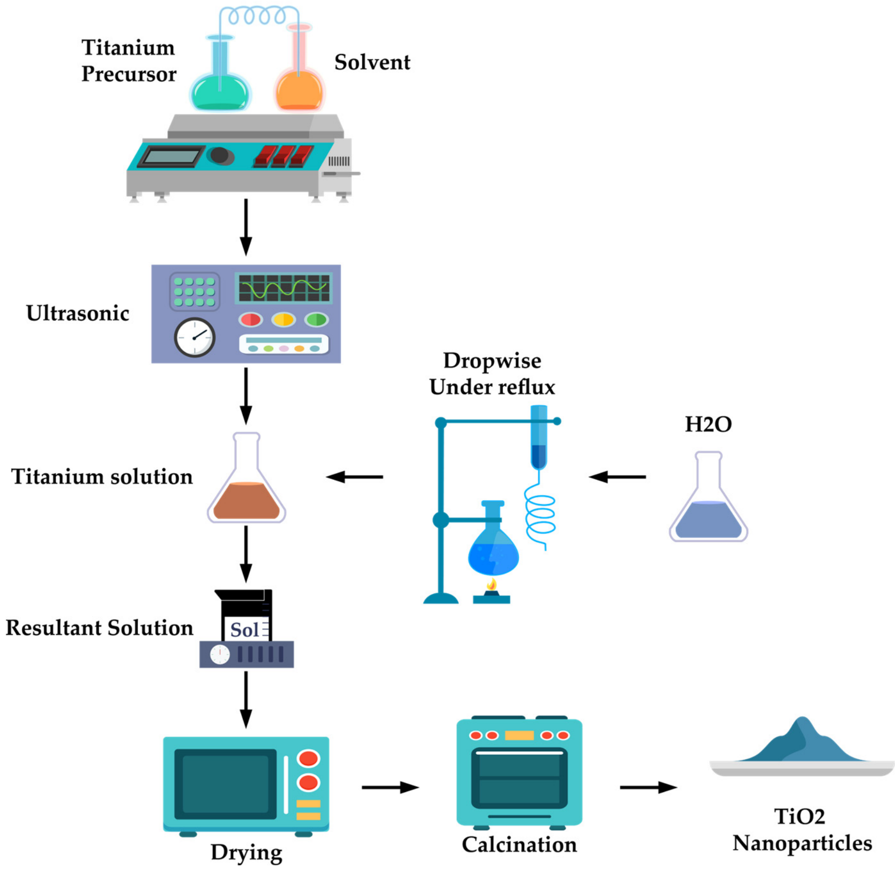

Figure 5. Scheme of the preparation of TiO_2 nanoparticles via sol–gel.

Another technique is Hydrothermal synthesis [65–67], which is applied in a high temperature range. In addition, low- or high-pressure conditions are established depending on the main composition of the reaction in order to control the morphology of the materials. The main advantage of hydrothermal synthesis is a negligible loss of materials [68].

Once the nanoparticles are obtained by the two-step method, a nanofluid is prepared, which involves the suspension and dispersion of the nanoparticles using the techniques described below.

Ultrasound technique: This technique consists of stirring the nanoparticles in a base fluid (Figure 6) with ultrasonic sound waves with a frequency greater than 20 kHz. In this way, the formation of nanometer-sized agglomerates is reduced by breaking intermolecular interactions. The agglomeration of the dispersed nanoparticles will lead to declined thermal performance, thermal conductivity and viscosity [57,69–74].

Magnetic stirring technique [75–78]: This technique consists of the action of a rotating magnetic field created by stationary electromagnets or a set of rotating electromagnets that operate with stirring mechanisms.

PH adjustment: A different consideration establishes PH adjustment as a supplement to the previous techniques. The pH of the base fluid is adjusted to improve the suspension and dispersion of the nanoparticles. This technique raises the value of the zeta potential, which can be related to the stability of colloidal dispersions. The zeta potential decreases as the Ph value increases [79–82].

Wei et al. [83] and Shao et al. [84] apply a technique in which they combine all the processes described above in the preparation of a nanofluid to achieve better efficiency and stability.

Finally, Figure 6 summarizes the methods and techniques used for preparing nano-lubricants through a diagram.

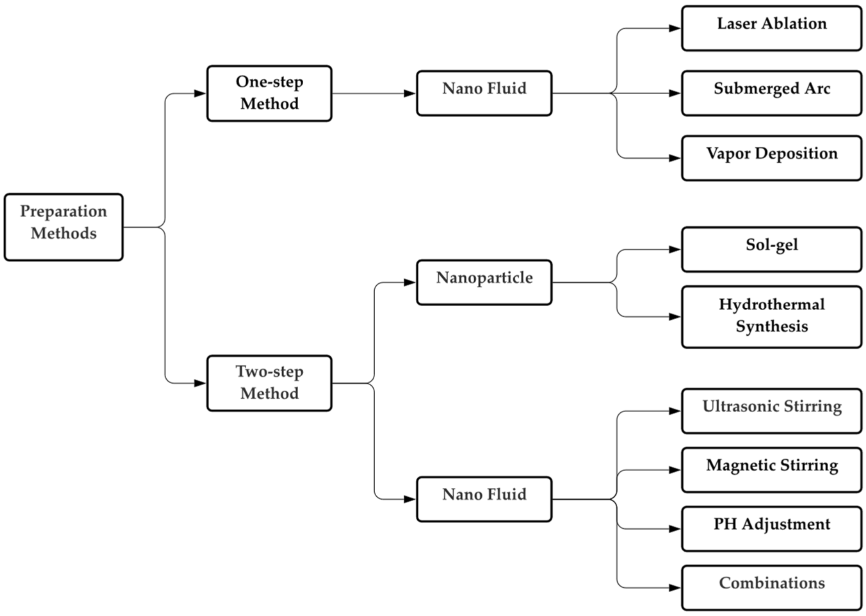

Figure 6. Summary of the preparation methods of a nano-lubricant.

3.2. Nanofluid Stability

After preparing a nanofluid, it is necessary to verify its stability as a prior step to experimentation. The first technique is the UV–Vis spectrophotometer technique, which is applicable for all base fluids [85] and has achieved excellent results in several studies [86–88]. This technique bases its operation on the action of taking advantage of the change in the intensity of light when it passes through a fluid. Using a wavelength of 200 to 900 nm, the instrument analyzes fluid dispersions and measures absorption by liquid [89]. Jiang et al., in [90], apply the method as follows: First, by scanning, the aim is to find the maximum absorbance of the nanoparticles in order to prepare a standard that fits a linear relationship using at least three diluted concentrations (0.01–0.03%). Finally, the relative stability is measured, and the treated nanofluid is allowed to rest for a few days.

Another way to measure nanofluid stability is the zeta potential test, which uses the study of electrophoretic behavior to check the stability of nanofluids [91]. In an experiment conducted by Wang [92], a 0.05% weight fraction of nanosuspension was needed to calculate the particle magnitude and zeta potential. The zeta potential and the stability of the suspension had particles with a similar charge; therefore, there was mutual repulsion causing these particles to not agglomerate. In [93], Lee et al. mention that a suspension with a zeta potential greater than 30 mV in R absolute value has correct stability.

The photo capture technique is the most important to observe the sedimentation of nanofluids. Photos are captured after preparation with the reservation of suspension quantities. When viewing the photos, sedimentation will be evident, as seen in [94–96].

Likewise, the Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) tools are very useful to distinguish the shape, size and distribution of nanoparticles. However, with these tools, the real situation of nanoparticles in a base fluid cannot be visualized. These tools are only used on dry samples [92,94,97,98].

The light scattering method is also used to visualize the structure of colloidal particles in a suspension. The intensity of light scattered in a particle is related to its volume. Since the interaction of electromagnetic radiation with a small particle is weak, the scattering of light is mostly transmitted, and only a small amount is scattered [99,100].

Another method used to estimate the stability of nanoparticles is sedimentation balance, which consists of submerging the tray of a sedimentation balance in a fresh nanofluid. The weight of the sedimentation or its volume indicates the stability of the nanofluid. In general, nanofluids are considered stable if the concentration of the supernatant particles remains constant over time [101–103].

Finally, the colloidal stability of a nanofluid can also be determined by the three-omega method. It can be evaluated by detecting the increase in thermal conductivity caused by the sedimentation of nanoparticles in a wide range of volume fractions [104,105].

4. Influence of Nanoparticles on Lubricants

Nanoparticles play a vital role in friction zones, specifically in the limit lubrication regime, where the wear and friction margins reach their maximum value [106].

Typically, the lubrication mechanism of nano-additives can be described to have four main effects: micro-bearing, protective film, polishing and repair effects [107–111]. The main mechanism of nano-additive lubrication highlighted in the reviewed studies is the micro-bearing effect.

The diminutive size of nanoparticles allows them to penetrate the surface asperities in the contact zone [112], as shown in Figure 7. Also, when added to a fluid, their size is small enough to remain dispersed by Brownian motion. However, suspended particles can adhere to each other and form agglomerates, resulting in a loss of wear protection and friction reduction ability, hence the importance of the correct preparation of the nano-lubricant [89].

Rebaso et al. [113] concluded that friction significantly reduced as the stirring time increased in the preparation of their oil enriched with MoS_2. Therefore, the stirring time in the preparation of a nano-lubricant plays an important role in the stability of the dispersion and consequently affects lubrication performance [114–118].

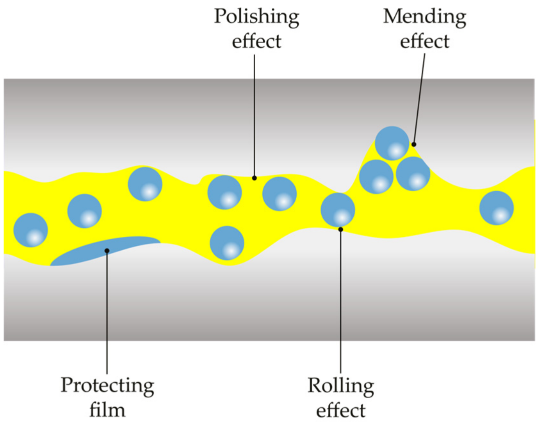

Figure 7. Nanoparticle lubrication mechanisms [119].

The proper concentration is another important factor affecting the lubrication characteristics of nano-lubricants [119–122]. The addition of nanoparticles in an inadequate concentration, whether in excess or shortage, can cause negative effects in some cases, due to either increased friction or wear [123].

The intrinsic mechanical property of nanoparticles, such as hardness, is determined by their size, which, in turn, affects their tribological behavior. For materials in the size range of 100 nm or larger, hardness increases with particle size concentration [124]. If the hardness of the nanoparticles is greater than that of the surface material, the result is notching and scratching, as indicated by Peña et al. [125] in their study. The high hardness (8–9 Mohs) of nano-Al_2O_3 resulted in abrasive wear and the agglomeration of nanoparticles.

The shape of nanoparticles also plays an important role in this regard because the behavior of a nano-lubricant depends on the space between the nanoparticle and the lubricated surface at the time of loading [121].

Spherical shaped nanoparticles show a high loading capacity due to their ball-bearing effect. Figure 8 shows the linear contact that is associated with nanosheets and the planar contact that is associated with nanoplatelets. In most studies related to nano-lubricants, spherical nanoparticles have been used [18,22,126–130].

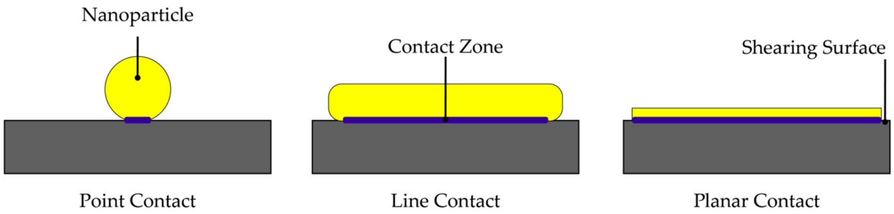

Figure 8. Effect of nanoparticle shape on the contact pressures experienced upon loading.

Investigations of the tribological performance of nanoparticles as additives in lubricating oils are carried out with experiments using different tools such as four-ball tribometer, piston ring, ball-on-disc and pin-on-disc tools, using normal conditions of the ASTM, DIN and AISI standards [130–132].

5. Result Analysis

5.1. Preparation Methods

In the previous sections, the importance of preparing a nano-lubricant is defined, whereby, under this concept, the methods with the greatest application in the articles investigated are presented. A group of 39 works is considered for the analysis of the preparation methods used, considering that the publication date of these investigative works is greater than 2010 and with a significant impact (Q1 and Q2).

Of the analysis group, 23.07% used the one-step preparation method and 76.92% used the two-step method, as shown in Figure 9 and described in Table 1, which also details the type of dispersion used by the authors and its duration. La et al. [133] applied 12 h of ultrasonic stirring to their nano-lubricant, with this being the longest stirring time applied compared to the rest of the studies.

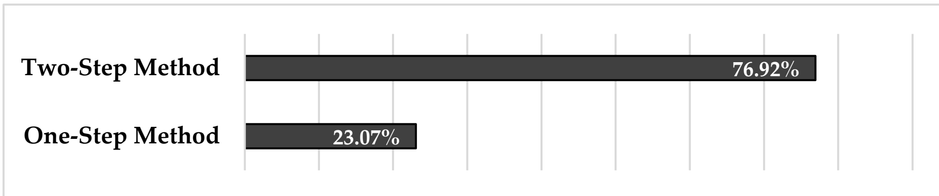

Figure 9. Distribution of used methods.

Table 1. Methods, stirring process and stirring time applied in previous research.

Author	Method Used		Stirring Process	Stirring Time
	Two Steps	One Step		
Ali et al. [134]	*		Ultrasound/Magnetic Stirring	6 h
Liu et al. [135]	*		Ultrasound	3 h
Singh et al. [136]	*		Ultrasound	1.5 h
Guo et al. [137]		*	Ultrasound	30 min
La et al. [133]	*		Magnetic Stirring/Ultrasound	3 h/12 h
Chouchan et al. [138]		*	Magnetic Stirring	8 h
Vardhaman et al. [139]	*		Ultrasound	2 h
Mousavi et al. [140]	*		Ultrasound	45 min
Kałuzny et al. [141]	*		Ultrasound	1 h
Mello et al. [32]		*	Magnetic Stirring	7 h
Wu et al. [142]		*	Ultrasound	1 h
Ali et al. [143]	*		Magnetic Stirring	4 h
Wang et al. [144]	*		Ultrasound	1 h

Table 1. *Cont.*

Author	Method Used		Stirring Process	Stirring Time
	Two Steps	One Step		
Paul et al. [145]	*		Ultrasound	6 h
Ghasemi et al. [146]	*		Magnetic Stirring/Ultrasound	15 min/20 min
Ali et al. [147]	*		Magnetic Stirring	4 h
Ali et al. [148]	*		Magnetic Stirring	4 h
Hemmat et al. [149]	*		Ultrasound	3 h
Sgroi et al. [17]	*		Ultrasound	5 h
Sepyani et al. [150]	*		Ultrasound	5 h
Ran et al. [151]	*		Magnetic Stirring/Ultrasound	20 min/30 min
Moghaddam et al. [152]	*		Ultrasound	1 h
Wu et al. [153]	*		Ultrasound	40 min
Hemmat et al. [154]	*		Magnetic Stirring	2 h
Ali et al. [155]	*		Magnetic Stirring	4 h
Asadi et al. [156]	*		Magnetic Stirring/ Ultrasound	2 h/1 h
Wu et al. [157]		*	Magnetic Stirring	1 h
Zheng et al. [158]	*		Magnetic Stirring/ Ultrasound	10 min/ 15 min
Meng et al. [159]	*		Ultrasound	5 h
Mungse et al. [160]		*	Ultrasound	4 h
Koshy et al. [120]		*	Ultrasound	1 h
Jia et al. [161]		*	Ultrasound	2 h
Zin et al. [162]	*		Ultrasound	1 h
Arumugam et al. [163]	*		Ultrasound	2 h
Wan et al. [164]	*		Magnetic Stirring	30 min
Ettefaghi et al. [165]		*	Ultrasound	1 h
Ettefaghi et al. [166]	*		Magnetic Stirring	3 h
Demas et al. [167]	*		Ultrasound	2 h
Eswaraiah et al. [168]	*		Ultrasound	1 h

Conversely, Zheng et al. [158] applied 10 min of magnetic stirring and 15 min of ultrasonic stirring to their mixture; these are the values of the shortest stirring times. Thus, these two authors represent the extremes of agitation application time in nanofluids. In total, 56.41% of the experiments used the ultrasound dispersion method, 28.20% used magnetic stirring, and the remaining 15.38% mixed both methods (Figure 10a).

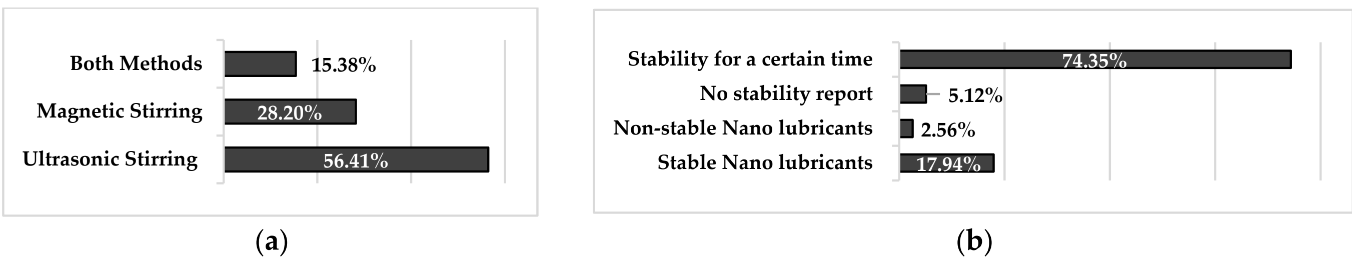

Figure 10. (**a**) Distribution of dispersion techniques used; (**b**) stability of nano-lubricants.

Figure 10b shows the authors who achieved stable nano-lubricants (17.94%) and non-stable nano-lubricants (2.56%), as well as the authors who did not report stability (5.12%) and the authors who achieved stability for a certain time (74.35%). Figure 11 details the stability times achieved by 74.35% of the studies examined in this analysis.

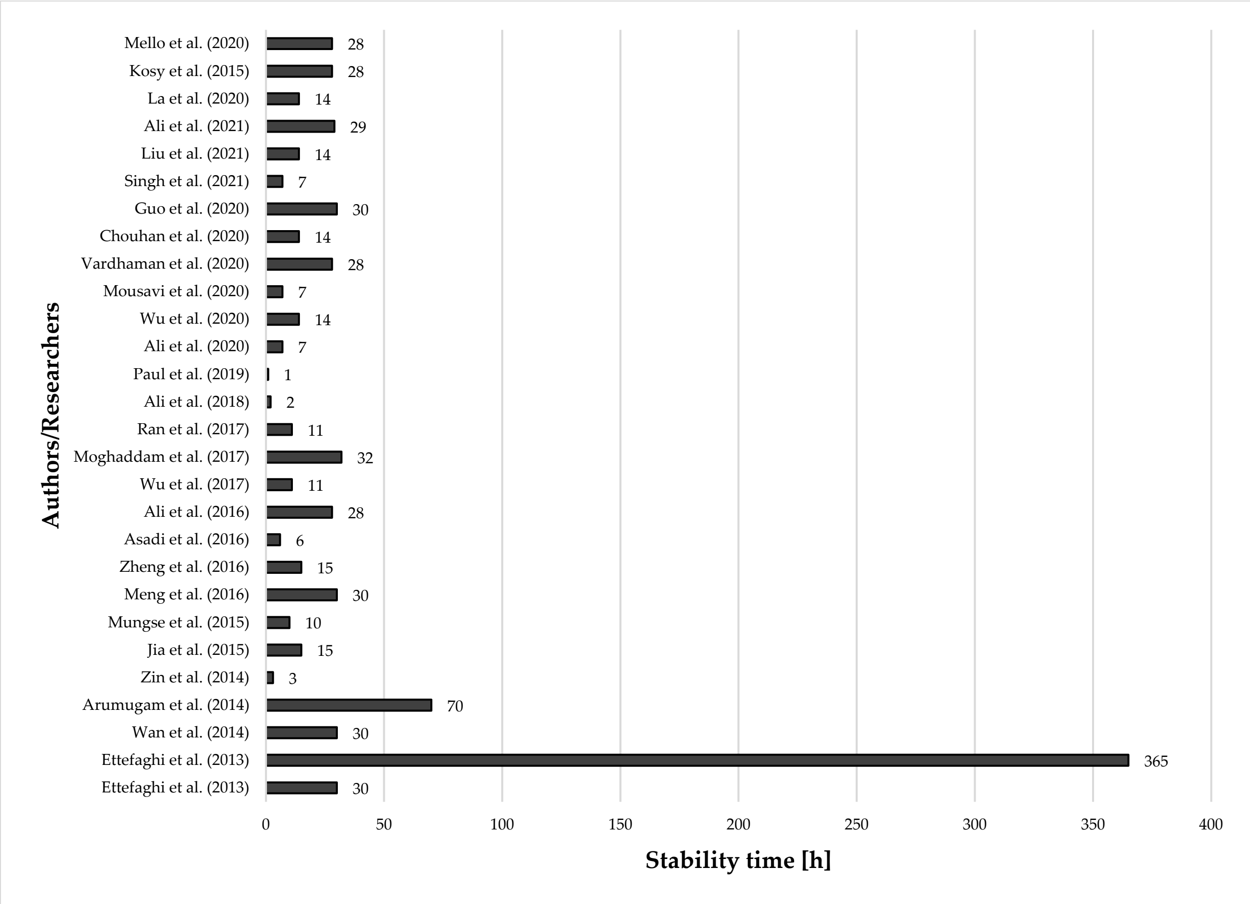

Figure 11. Stability times achieved by 74.35% of the authors [32,120,133–140,142,143,145,148,151–153,155,156,158–166].

5.2. Reduction in the Coefficient of Friction

To analyze the results of the reduction in the friction coefficient, 39 articles are considered. These are analyzed under the criteria of the maximum percentage reduction in the friction coefficient achieved, the concentrations of nanoparticles applied, the concentrations that produced the best results and the temperatures at which the experiments were carried out.

Figure 12 details the results obtained by the researchers in terms of reducing the friction coefficient. Singh et al. [136] achieved the highest percentage reduction in the friction coefficient, with a 91.6% reduction in the friction coefficient in their experiment.

This author experimented with graphite nanoparticles at room temperature, using an SAE-30 base oil and the pin-on-disc tool, with the application of variable forces between 20 and 50 N at 300 rpm. To understand Figure 12, it should be considered that some authors experimented with more than one type of nanoparticle.

Likewise, after the literature review, it was found that 64.10% used a concentration range in their experiments, with the remaining 35.89% only using a concentration value, as detailed in Table 2.

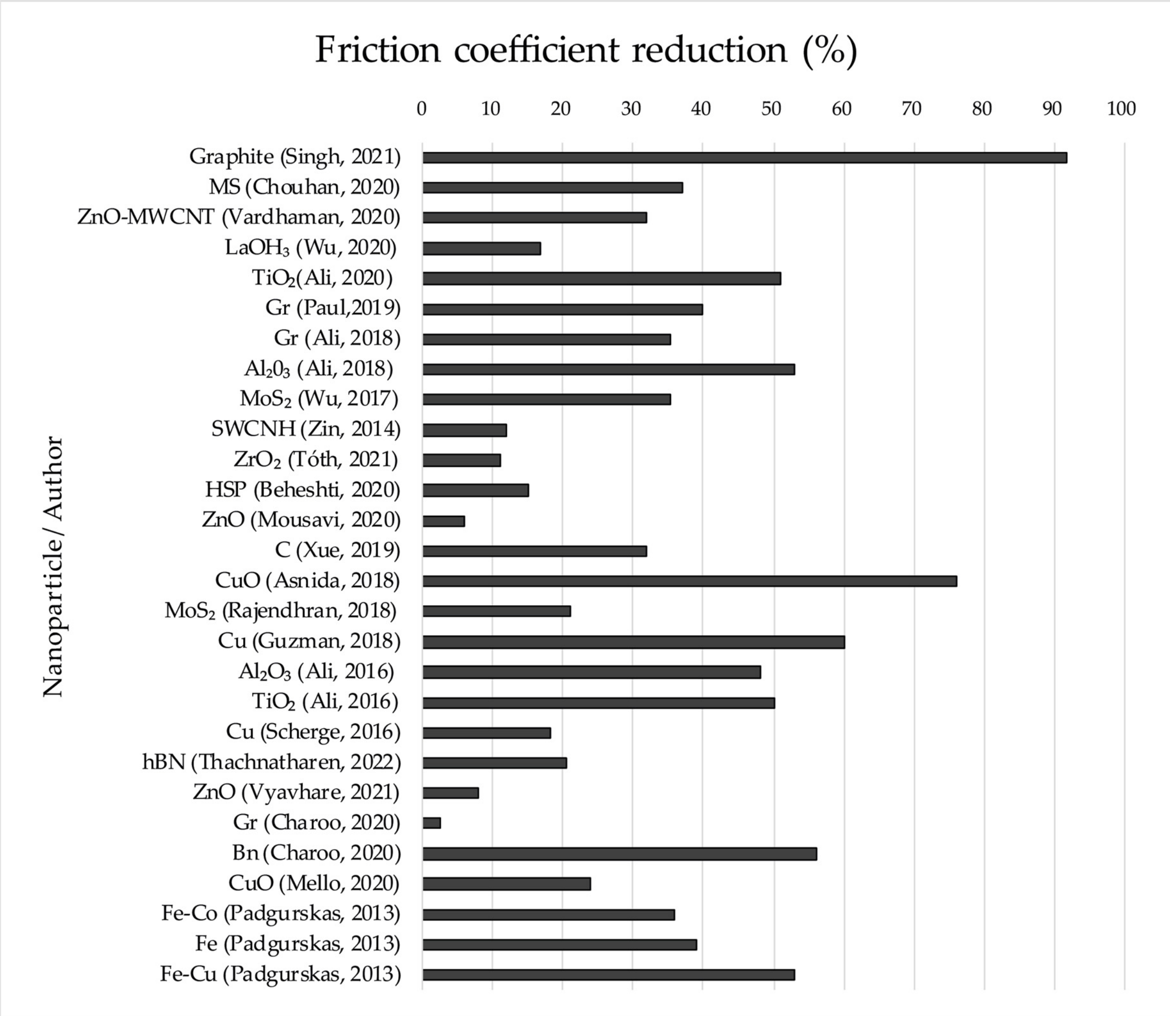

Figure 12. Research results [121,125,126,129,130,132,134,135,140,148,156–162,164,167–171].

Table 2. Single concentration used by some authors.

Author	Concentration [%]
Singh et al. [136]	0.3
Thachnatharen et al. [169]	0.025
Vyavhare et al. [172]	0.33
Charoo et al. [170]	0.5
Avilés et al. [173]	0.5
Mello et al. [174]	0.5
Kamal et al. [5]	0.1
Cheng et al. [175]	0.04
Wu et al. [153]	1
Ivanov et al. [176]	0.016
Rasheed et al. [171]	0.01
Ali et al. [177]	0.25
Padgurskas et al. [178]	0.5
Demas et al. [167]	3

Figure 13 shows the ranges of the concentration values applied, of which most of the authors [137–140,142,143,145,147,179–183] considered a concentration value of less than 1%, with four tests carried out.

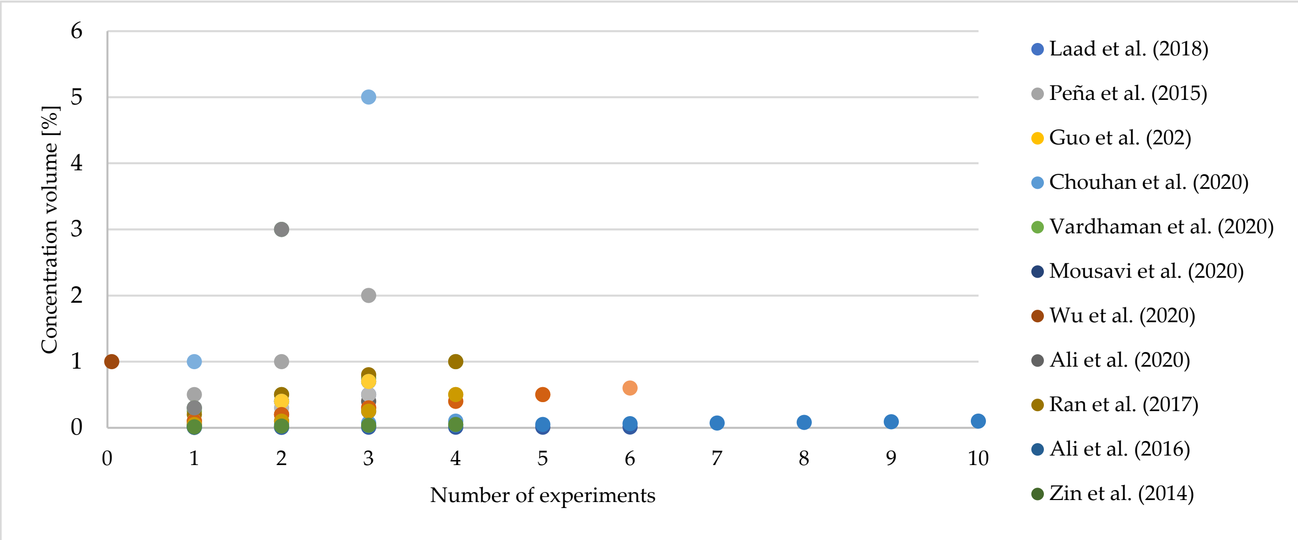

Figure 13. Concentration ranges applied in research [15,125,137–140,142,143,145,147,151,155,162,179–190].

Table 3 details the concentrations that were efficient for these researchers. The most efficient concentration values were less than 1; however, two authors [125,184] found the efficient concentration to be 2% and 3%.

Table 3. Effective concentration used by the authors who used a concentration percentage.

Author	Effective Concentration [%]
Mousavi et al. [179]	0.7
Tóth et al. [180]	0.4
Chouhan et al. [138]	0.05
Wu et al. [142]	0.1
Beheshti et al. [181]	0.3
Vardhaman et al. [139]	0.25
Mousavi et al. [140]	0.4
Guo et al. [137]	0.3
Mousavi et al. [182]	0.4
Paul et al. [145]	0.1
Ali et al. [143]	0.4
Xue et al. [183]	3
Ali et al. [143]	0.4
Asnida et al. [185]	0.008
Laad et al. [15]	0.5
Rajendhran et al. [186]	0.5
Borda et al. [187]	0.3
Ran et al. [151]	0.5
Ali et al. [188]	0.25
Ali et al. [155]	0.1
Scherge et al. [184]	3
Jeng et al. [189]	0.07
Peña et al. [125]	2
Zin et al. [162]	0.01
Zhang et al. [190]	0.0375

Finally, of all the studies reviewed, 51.28% carried out their experiments at room temperature, while the remaining 48.71% carried out tests at temperatures within the range of 20 °C to 100 °C.

5.3. Base Lubricants

This study collected the results of 67 high-impact articles, in which the base lubricants most used for testing were as follows: SAE 5W-30 with 10 investigations, representing 16% of the total articles; SAE 10W-40 with 7 investigations, representing 11% of the total articles, and SAE 20W-50 with 6 investigations, representing 10% of the total articles.

The frequency with which these lubricants were used reflects the criteria of how affordable they are in the local market, as well as their ease of marketing.

Furthermore, their standard properties facilitate mixing with the nanoparticle for the subsequent study of this property. Table 4 shows the type of base oil, as well as how many and which authors use said oil, while Figure 14 graphically outlines this information.

Table 4. Base lubricants used in investigations.

Base Lubricant	#Articles/Citations
Lubricant/PAO6	[134]
SAE 20W-40	[135]
SAE 30	[136]
Paroline Lubricant/Oil	[137]
Lubricant/HD 50	[133]
SAE 10W-40	[138,139,146,149,156,159,160]
SAE 40	[140,152,162,179]
SAE 5W-30	[17,141,143,145,147,148,155,176,177,188]
Lubricant/PAO	[32,157,158,161,166]
SAE 20W-50	[142,165,166,169–171]
Lubricant/Hexadecane	[144]
SAE 50	[150,154]
Lubricant/60SN	[151]
Lubricant/Paraffin	[153]
Lubricant/500 N	[120]
Rapeseed Oil/SAE 20 W-40	[163]
SAE 15W-40	[164,190]
500W	[168]
Lubricant/Group III	[172,180]
SAE 10W-30	[15,181,185]
Lubricant/Ionic Liquid	[173]
Diesel Oil	[182]
Lubricant/PAO40	[174]
SN/GF-5 Lubricant	[183]
Lubricant/SN 500	[175,186]
Lubricant/Mineral	[187,189]
Chevron Taro 30 DP 40	[184]
SAE 75 W-85	[125]
SAE 10	[178]

It is important to consider sustainability in the nano-lubrication process. In this sense, a large number of nanoparticles are environmentally friendly, since they minimize the use of hazardous materials and additives, which is useful for environmental and economic sustainability. Nanoparticles can also facilitate a reduction in energy consumption during their production, reducing the carbon footprint, meeting the requirements of green tribology [36].

However, sustainability applies not only to nanoparticles but also to the base oil for comprehensive nano-lubricant production. Biomaterials based on vegetable oils offer a sustainable, biodegradable and low-cost alternative for various applications in engineering and biomedicine [191]. Taha-Tijerina et al. found that halloysite nanotubular structures (HNSs) reinforcing natural ester lubricants significantly reduce the friction coefficient and wear scar diameter, offering environmentally friendly alternatives to mineral fluids for industrial applications [192]. Gupta et al. focused their research on the development of ecological nano-lubricants, using mahua and linseed oils with h-BN nanoparticles as additives.

The addition of h-BN nanoparticles improved the rheological and tribological properties of the oils, making them more effective as lubricants. The study highlighted the potential of using these bio-based lubricants with nanoparticles for sustainable development and as a sustainable alternative to mineral oil [193]. Finally, Hameed et al. stated that a mixture of 20% mahua biofuel with Al_2O_3 and CeO_2 nanoparticles at 100 parts per million each resulted in a reduction in brake-specific fuel consumption (BSFC) of 3.25%; an increase in thermal efficiency brake performance (BTE) of 1.39%; and a reduction in hydrocarbon (HC) emissions, nitrogen oxides (NOX) and carbon monoxide (CO) of 30.73%, 1.27% and 44.13%, respectively [194].

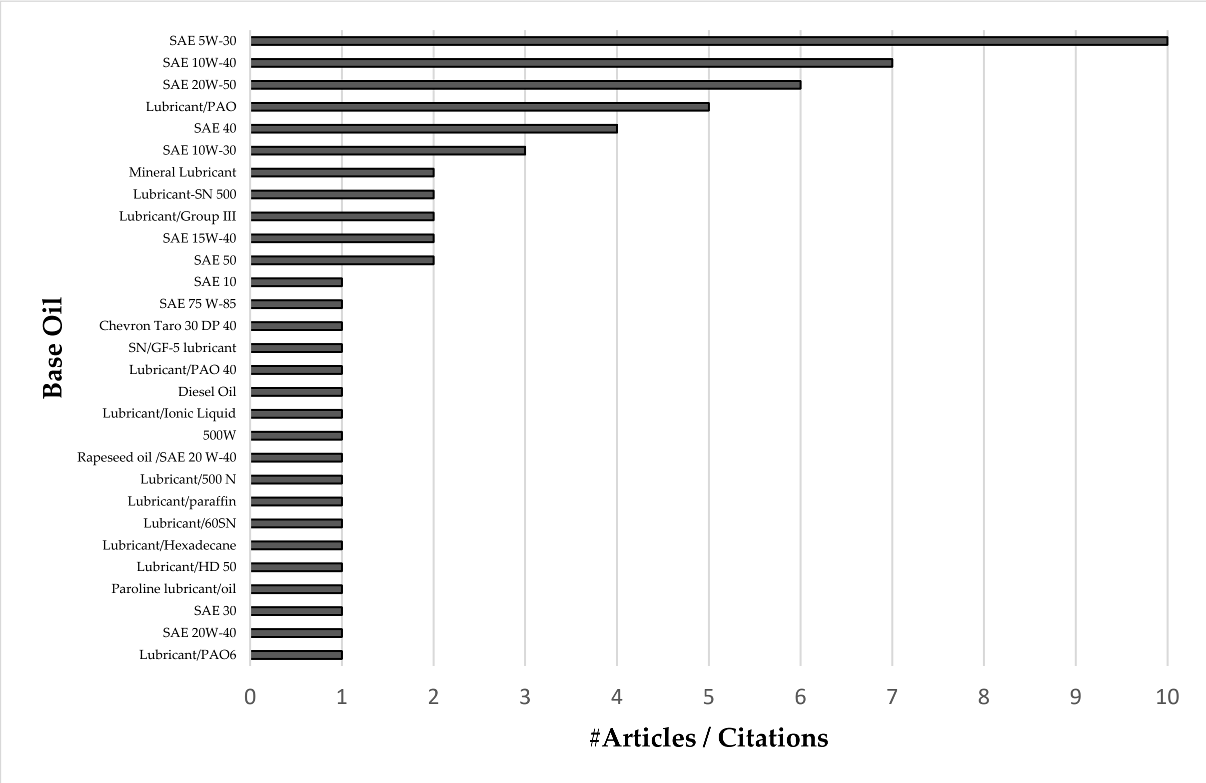

Figure 14. Statistics of base lubricants used.

5.4. Nano-Additives

For an analysis regarding nano-additives, a total of 63 impactful articles were taken into account. The most used nano-additives were as follows: MoS_2 (Molybdenum Disulfide) and ZnO (Zinc Oxide) with six investigations each, representing 10% of the total articles, and Gr (Graphene) and Al_2O_3/TiO_2 (Aluminum Oxide and Oxide of Titanium) with five investigations each, representing 8% of the total articles; this information is collected in Table 5 and schematized in Figure 15.

Table 5. Nano-additives used in research.

Nano-Additive	#Articles/Citations
Al_2O_3/TiO_2	[134,148,155,177,188]
MWCNT/TiO_2	[135]
Graphite	[136]
MoS_2	[17,120,137,153,164,167]
Gr	[133,147,158,171,173]
Gr-MS-Zn	[138]
ZnO/MWCNT	[139]
ZnO/MoS_2	[140]

Table 5. *Cont.*

Nano-Additive	#Articles/Citations
MWCNT	[141,165,166]
CuO	[32,163,174,185]
La(OH)3/rGO	[142]
Cu/Gr	[143]
GO	[144,145,160,168]
TiO_2	[15,146]
ZnO	[149–151,157,172,182]
MWCNT/CuO	[152]
MWCNT/SiO_2	[153]
MWCNT/ZnO	[156]
GO/Ag/GNP	[159]
Cu/rGO	[161]
C	[162,183]
ZnO/MoS_2	[179]
ZrO_2	[180]
hBN	[169]
(BN), (WS2), (Gr)	[170]
Hairy Silica Particles (HSPs)	[181]
Ni- MoS_2	[186]
Cu	[184,187,190]
GrO	[175]
ND	[176]
Fe (Carbon Capsules)	[189]
CuO/Al_2O_3	[125]
CuO, Cu, Fe, Co, Fe/Cu, Fe/Co, Co/Cu	[178]

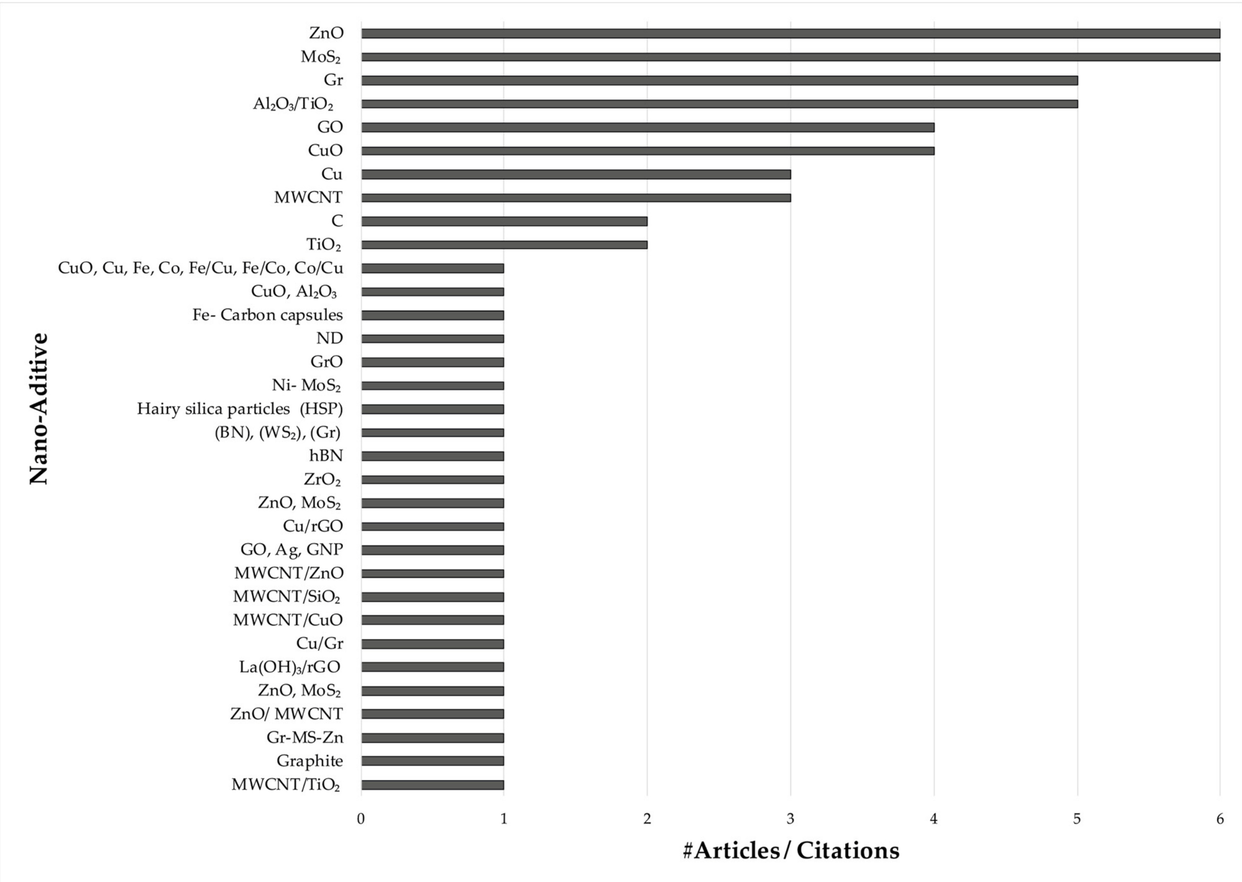

Figure 15. Statistics of nano-additives used.

The properties of nanoparticles are critically dependent on their dimensions, shape and morphological structure, which are characterized using different imaging methods: Field-Emission Scanning Electron Microscopy (FESEM), Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) [40]. Most of the studies presented characterized nanoparticles using FESEM. The nanostructure of Al_2O_3 and TiO_2 nanoparticles is fairly spherical, which provides a very good rolling medium within engine oil [155,177,188]. The characterization of MoS_2 nanoparticles clearly indicated its layered lamellar structure [120]. In addition, ZnO NWs are vertically aligned, with a hexagonal shape and a relatively smooth surface [55]. The characterization of SiO_2 nanoparticles indicated the uniform distribution of their sizes and their spherical shape [128]. ZnO nanoparticles possess a polygonal shape with a wide range of sizes and an elongated morphology [139].

Other authors employed TEM to observe the morphology and particle size of TiO_2 [51,53].

Finally, MWCNT nanoparticles are characterized using SEM and TEM. The tubular and filamentous morphology of nanotubes are shown to be very good when observed using these microscopes. Nanotubes, which are made, have an average diameter of about 10–20 nm and an average length of 10 µm [165,166].

6. Discussion

The application of nanoparticles in lubricants to reduce the friction coefficient has been the subject of numerous investigations, as demonstrated by this review of 194 articles, mainly with Q1 and Q2 impact levels. The examination of these studies reveals that the two-step method is the most common method for the formation of nano-lubricants since it is more economical than the one-step method. The dispersion of nanoparticles in a base fluid is mostly achieved by ultrasonic agitation, suggesting its effectiveness and wide application in the scientific community.

Crucially, although nanoparticles can reduce the coefficient of friction by penetrating the asperities of contact surfaces in boundary lubrication zones, their ability to increase wear by agglomerating is a major challenge. Controlling the stability of nano-lubricants is therefore essential to maximize their benefits.

Despite the efforts made, only a small percentage of researchers have managed to develop long-term stable nano-lubricants. A notable example is the work of Koshy et al., who managed to stabilize their MoS2-based nano-lubricant for 365 days. This highlights the need to continue researching and improving nano-lubricant stabilization techniques for practical application.

Regarding the concentration of nanoparticles, most researchers focused on a volume concentration range of 0% to 1%. This suggests that higher concentrations may not be necessary or may even be counterproductive in terms of lubricant stability and effectiveness.

Conversely, the use of advanced characterization techniques, such as spectrophotometry, the Z potential, SEM/TEM and light scattering, is crucial to understand the dispersion of nanoparticles in a base fluid and evaluate the stability of nano-lubricants. These tools allow researchers to visualize the distribution and agglomeration of nanoparticles, which is essential for optimizing the tribological properties of lubricants.

Additionally, it is important to consider the environmental impact of nano-lubricants and their production. Studies are needed to evaluate their biodegradability and possible harmful effects on the environment.

The potential benefits of using non-edible vegetable oils for bio-lubricant production include sustainability by utilizing crops grown on wasteland; avoiding interference with growing food on limited agricultural land; controlling soil erosion, land degradation and deforestation; and promoting a closed-loop life cycle with balanced carbon emissions. Furthermore, non-edible vegetable oils offer a high viscosity index, a high flash point, excellent lubricity and superior biodegradability, making them a suitable alternative raw material to mineral oil and capable of reducing environmental effects.

The addition of Al_2O_3 and CeO_2 nanoparticles in biodiesel blends, specifically with mahua biofuel, has shown promising results in improving combustion efficiency; reducing the emissions of pollutants such as CO, HC, NOx and smoke; and improving overall engine performance. Studies emphasize the potential of nano-additives in biodiesel blends to achieve cleaner combustion and higher efficiency in diesel engines.

7. Conclusions

In conclusion, the application of nanoparticles in lubricants offers great potential to reduce the friction coefficient in boundary lubrication zones. However, more effort is required to develop long-term stable nano-lubricants and improve the understanding of their behavior under different operating conditions.

The two-step method and ultrasonic stirring are the most widely used for the preparation and dispersion of nanoparticles, respectively. These methods, along with the control of nanoparticle concentration, are key to maximizing the tribological benefits of nanostructured lubricants.

Further research is needed to optimize the tribological properties of commonly used base lubricants, such as SAE 5W-30, SAE 10W-40 and SAE 20W-50, to ensure optimal lubrication in automotive applications.

The most widely used nano-additives, such as ZnO, MoS_2, Gr and Al_2O_3/TiO_2, offer promising opportunities to improve the tribological properties of lubricants. However, a greater understanding of their long-term effects and those under different operating conditions is required for their practical implementation.

8. Future Perspectives

To advance in this field, it is necessary to explore new nanoparticles and preparation methods that can improve the stability and effectiveness of nano-lubricants. Furthermore, more studies should be conducted on the tribological behavior of nano-lubricants under real operating conditions, especially in automotive applications.

Optimizing the tribological properties of the most used base lubricants is also essential. Research must be conducted to find the right balance between nanoparticle concentration and lubricant stability, as well as to evaluate its long-term performance.

Additionally, it is important to consider the environmental impact of nano-lubricants and their production. Studies are needed to evaluate their biodegradability and possible harmful effects on the environment.

In summary, the use of nanoparticles in lubricants represents a promising area of research that has the potential to significantly improve the efficiency and durability of lubrication systems. However, more research and development are needed to bring these laboratory advances to practical and commercial applications.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/lubricants12050166/s1.

Author Contributions: Conceptualization, M.G.T., B.J.C. and J.G.M.; methodology, M.G.T. and R.W.C.U.; investigation, B.J.C. and J.G.M.; writing—original draft preparation, M.G.T., B.J.C. and J.G.M.; writing—review and editing, R.W.C.U.; supervision, M.G.T. and R.W.C.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Pawashe, A.; Kalkundri, S.; Chavan, C.; Arunachalam, R. Fault Diagnosis of Engine Lubrication System. In Proceedings of the 2017 International conference on Microelectronic Devices, Circuits and Systems (ICMDCS), Vellore, India, 10–12 August 2017; pp. 1–6. [CrossRef]
2. Daud, S.M.; Najib, M.S.; Zahed, N. Classification of Lubricant Oil Odor-Profile Using Case-Based Reasoning. In Proceedings of the 2016 IEEE Conference on Systems, Process and Control (ICSPC 2016), Melaka, Malaysia, 16–18 December 2016; Institute of Electrical and Electronics Engineers Inc.: Chennai, India, 2017; pp. 207–212.
3. Garud, V.U.; Gavhane, K.; Tiwari, H.U.; Bhoite, S.; Sangale, N.; Patil, S.; Ghadage, S. Integrated Wireless Online Oil Condition Monitoring System for i C Engine. In Proceedings of the International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT 2016), Chennai, India, 3–5 March 2016; pp. 209–214.
4. Sharma, S.; Das, S.; Virmani, J.; Sharma, M.; Singh, S.; Das, A. IoT Based Dipstick Type Engine Oil Level and Impurities Monitoring System: A Portable Online Spectrophotometer. In Proceedings of the 2019 4th International Conference on Internet of Things: Smart Innovation and Usages (IoT-SIU), Ghaziabad, India, 18–19 April 2019; pp. 1–4.
5. Kamal, R.S.; Ahmed, N.S.; Nasser, A.M. Study the Efficiency of Some Compounds as Lubricating Oil Additives. *Appl. Petrochem. Res.* **2013**, *3*, 1–8. [CrossRef]
6. Idros, M.F.M.; Ali, S.; Islam, M.S. Optical Behavior of Transmission Oil Lubricant for Degradation Monitoring. In Proceedings of the 2011 IEEE Student Conference on Research and Development (SCOReD 2011), Cyberjaya, Malaysia, 19–20 December 2011; pp. 225–228.
7. Bravo-Imaz, I.; Garcia-Arribas, A.; Gorritxategi, E.; Arnaiz, A.; Barandiaran, J.M. Magnetoelastic Viscosity Sensor for On-Line Status Assessment of Lubricant Oils. *IEEE Trans. Magn.* **2013**, *49*, 113–116. [CrossRef]
8. Kuzema, O.S.; Kuzema, P.O. Effect of the Duration of Car Engine Operation on the Mechanical Contaminants in Its Lubricant. In Proceedings of the 2017 IEEE 7th International Conference Nanomaterials: Application & Properties (NAP), Odessa, Ukraine, 10–15 September 2017; pp. 01PCSI03-1–01PCSI03-4.
9. Sanga, R.; Sivaramakrishna, M.; Srinivasan, V.S.; Prabhakara Rao, G. Design and Development of Opto-Resistive Type Quasi-Digital Sensor and Instrument to In-Situ Monitoring of the Quality of Lubricant Oil. In Proceedings of the INDICON 2018—15th IEEE India Council International Conference, Coimbatore, India, 16–18 December 2018.
10. Li, Y.; Zuo, Y.; Yi, X.; Liu, H. Research on Engine Lubricant Detection Technology Based on On-Line Visual Technology. In Proceedings of the 2021 IEEE International Conference on Sensing, Diagnostics, Prognostics, and Control (SDPC), Weihai, China, 13–15 August 2021; pp. 87–93.
11. Holmberg, K.; Erdemir, A. The Impact of Tribology on Energy Use and CO_2 Emission Globally and in Combustion Engine and Electric Cars. *Tribol. Int.* **2019**, *135*, 389–396. [CrossRef]
12. Yu, H.-L.; Xu, Y.; Shi, P.-J.; Xu, B.-S.; Wang, X.-L.; Liu, Q. Tribological Properties and Lubricating Mechanisms of Cu Nanoparticles in Lubricant. *Trans. Nonferrous Met. Soc. China* **2008**, *18*, 636–641. [CrossRef]
13. Ghaednia, H.; Hossain, M.S.; Jackson, R.L. Tribological Performance of Silver Nanoparticle–Enhanced Polyethylene Glycol Lubricants. *Tribol. Trans.* **2016**, *59*, 585–592. [CrossRef]
14. Das, L.; Aggarwal, M.; Rajkumar, K.; Aravindan, S.; Gupta, M. Tribological Properties of Magnesium Nano-Alumina Composites under Nano-Graphite Lubrication. *Tribol. Trans.* **2012**, *55*, 334–344. [CrossRef]
15. Laad, M.; Jatti, V.K.S. Titanium Oxide Nanoparticles as Additives in Engine Oil. *J. King Saud. Univ.-Eng. Sci.* **2018**, *30*, 116–122. [CrossRef]
16. Wu, X.; Zhao, G.; Zhao, Q.; Gong, K.; Wang, X.; Liu, W.; Liu, W. Investigating the Tribological Performance of Nanosized MoS2 on Graphene Dispersion in Perfluoropolyether under High Vacuum. *RSC Adv.* **2016**, *6*, 98606–98610. [CrossRef]
17. Sgroi, M.F.; Asti, M.; Gili, F.; Deorsola, F.A.; Bensaid, S.; Fino, D.; Kraft, G.; Garcia, I.; Dassenoy, F. Engine Bench and Road Testing of an Engine Oil Containing MoS2 Particles as Nano-Additive for Friction Reduction. *Tribol. Int.* **2017**, *105*, 317–325. [CrossRef]
18. Rapoport, L.; Leshchinsky, V.; Lapsker, I.; Volovik, Y.; Nepomnyashchy, O.; Lvovsky, M.; Popovitz-Biro, R.; Feldman, Y.; Tenne, R. Tribological Properties of WS2 Nanoparticles under Mixed Lubrication. *Wear* **2003**, *255*, 785–793. [CrossRef]
19. Kedzierski, M.A. Viscosity and Density of Aluminum Oxide Nanolubricant. *Int. J. Refrig.* **2013**, *36*, 1333–1340. [CrossRef]
20. Ingole, S.; Charanpahari, A.; Kakade, A.; Umare, S.S.; Bhatt, D.V.; Menghani, J. Tribological Behavior of Nano TiO_2 as an Additive in Base Oil. *Wear* **2013**, *301*, 776–785. [CrossRef]
21. Koide, T.; Fukami, T.; Hisada, H.; Inoue, M.; Carriere, J.; Heyler, R.; Katori, N.; Okuda, H.; Goda, Y. Identification of Pseudopolymorphism of Magnesium Stearate by Using Low-Frequency Raman Spectroscopy. *Org. Process Res. Dev.* **2016**, *20*, 1906–1910. [CrossRef]
22. Lee, C.G.; Hwang, Y.J.; Choi, Y.M.; Lee, J.K.; Choi, C.; Oh, J.M. A Study on the Tribological Characteristics of Graphite Nano Lubricants. *Int. J. Precis. Eng. Manuf.* **2009**, *10*, 85–90. [CrossRef]
23. Ramón-Raygoza, E.D.; Rivera-Solorio, C.I.; Giménez-Torres, E.; Maldonado-Cortés, D.; Cardenas-Alemán, E.; Cué-Sampedro, R. Development of Nanolubricant Based on Impregnated Multilayer Graphene for Automotive Applications: Analysis of Tribological Properties. *Powder Technol.* **2016**, *302*, 363–371. [CrossRef]
24. Hemmat Esfe, M.; Afrand, M.; Rostamian, S.H.; Toghraie, D. Examination of Rheological Behavior of MWCNTs/ZnO-SAE40 Hybrid Nano-Lubricants under Various Temperatures and Solid Volume Fractions. *Exp. Therm. Fluid. Sci.* **2017**, *80*, 384–390. [CrossRef]

25. Afrand, M.; Nazari Najafabadi, K.; Akbari, M. Effects of Temperature and Solid Volume Fraction on Viscosity of SiO_2-MWCNTs/SAE40 Hybrid Nanofluid as a Coolant and Lubricant in Heat Engines. *Appl. Therm. Eng.* **2016**, *102*, 45–54. [CrossRef]
26. Kotia, A.; Chowdary, K.; Srivastava, I.; Ghosh, S.K.; Ali, M.K.A. Carbon Nanomaterials as Friction Modifiers in Automotive Engines: Recent Progress and Perspectives. *J. Mol. Liq.* **2020**, *310*, 113200. [CrossRef]
27. Das, S.K.; Putra, N.; Thiesen, P.; Roetzel, W. Temperature Dependence of Thermal Conductivity Enhancement for Nanofluids. *J. Heat. Transf.* **2003**, *125*, 567–574. [CrossRef]
28. Zawawi, N.N.M.; Azmi, W.H.; Ghazali, M.F. Tribological Performance of Al_2O_3–SiO_2/PAG Composite Nanolubricants for Application in Air-Conditioning Compressor. *Wear* **2022**, *492–493*, 204238. [CrossRef]
29. Singh, S.; Chattopadhyaya, S.; Pramanik, A.; Gupta, N. Influence of Nano-Particle on the Wear Behaviour of Thin Film Coatings A Review. *Int. J. Appl. Eng. Res.* **2018**, *13*, 4053–4058.
30. Igor, U.; Dzhardimalieva, G. The Conjugate Thermolysis—Thermal Polymerization of Metal Chelate Monomers and Thermolysis of Polymers Formed In Situ. In *Nanomaterials Preparation by Thermolysis of Metal Chelates*; Springer: Berlin/Heidelberg, Germany, 2018; pp. 351–423. ISBN 978-3-319-93404-4.
31. Du, F.; Li, C.; Li, D.; Sa, X.; Yu, Y.; Li, C.; Yang, Y.; Wang, J. Research Progress Regarding the Use of Metal and Metal Oxide Nanoparticles as Lubricant Additives. *Lubricants* **2022**, *10*, 196. [CrossRef]
32. Mello, V.S.; Faria, E.A.; Alves, S.M.; Scandian, C. Enhancing Cuo Nanolubricant Performance Using Dispersing Agents. *Tribol. Int.* **2020**, *150*, 106338. [CrossRef]
33. Wang, S.; Chen, D.; Hong, Q.; Gui, Y.; Cao, Y.; Ren, G.; Liang, Z. Surface Functionalization of Metal and Metal Oxide Nanoparticles for Dispersion and Tribological Applications—A Review. *J. Mol. Liq.* **2023**, *389*, 122821. [CrossRef]
34. Nyholm, N.; Espallargas, N. Functionalized Carbon Nanostructures as Lubricant Additives—A Review. *Carbon* **2023**, *201*, 1200–1228. [CrossRef]
35. Zou, J.; Wu, J.; Wang, Y.; Deng, F.; Jiang, J.; Zhang, Y.; Liu, S.; Li, N.; Zhang, H.; Yu, J.; et al. Additive-Mediated Intercalation and Surface Modification of MXenes. *Chem. Soc. Rev.* **2022**, *51*, 2972–2990. [CrossRef] [PubMed]
36. Uflyand, I.E.; Zhinzhilo, V.A.; Burlakova, V.E. Metal-Containing Nanomaterials as Lubricant Additives: State-of-the-Art and Future Development. *Friction* **2019**, *7*, 93–116. [CrossRef]
37. Guaregua M., J.A.; Squitieri, E.; Mujica, V. A Computational Study of the Stability Ratios of Spherical Coloidal Particles. *J. Mol. Struct. THEOCHEM* **2006**, *769*, 165–170. [CrossRef]
38. Yang, L.; Ji, W.; Mao, M.; Huang, J.N. An Updated Review on the Properties, Fabrication and Application of Hybrid-Nanofluids along with Their Environmental Effects. *J. Clean. Prod.* **2020**, *257*, 120408. [CrossRef]
39. Chen, Y.; Renner, P.; Liang, H. Dispersion of Nanoparticles in Lubricating Oil: A Critical Review. *Lubricants* **2019**, *7*, 7. [CrossRef]
40. Azman, N.F.; Samion, S. Dispersion Stability and Lubrication Mechanism of Nanolubricants: A Review. *Int. J. Precis. Eng. Manuf.-Green. Technol.* **2019**, *6*, 393–414. [CrossRef]
41. Jamal-Abad, M.T.; Zamzamian, A.; Dehghan, M. Experimental Studies on the Heat Transfer and Pressure Drop Characteristics of Cu-Water and Al-Water Nanofluids in a Spiral Coil. *Exp. Therm. Fluid. Sci.* **2013**, *47*, 206–212. [CrossRef]
42. Zhang, J.; Cao, R.; Song, W.; Liu, L.; Li, J. One-Step Method to Prepare Core-Shell Magnetic Nanocomposite Encapsulating Silver Nanoparticles with Superior Catalytic and Antibacterial Activity. *J. Colloid. Interface Sci.* **2022**, *607*, 1730–1740. [CrossRef] [PubMed]
43. Xu, L.; Liu, H.; Zhou, H.; Hong, M. One-Step Fabrication of Metal Nanoparticles on Polymer Film by Femtosecond LIPAA Method for SERS Detection. *Talanta* **2021**, *228*, 122204. [CrossRef]
44. Yu, W.; France, D.M.; Routbort, J.L.; Choi, S.U.S. Review and Comparison of Nanofluid Thermal Conductivity and Heat Transfer Enhancements. *Heat. Transf. Eng.* **2008**, *29*, 432–460. [CrossRef]
45. Lo, C.H.; Tsung, T.T.; Chen, L.C.; Su, C.H.; Lin, H.M. Fabrication of Copper Oxide Nanofluid Using Submerged Arc Nanoparticle Synthesis System (SANSS). *J. Nanoparticle Res.* **2005**, *7*, 313–320. [CrossRef]
46. Lo, C.H.; Tsung, T.T.; Chen, L.C. Shape-Controlled Synthesis of Cu-Based Nanofluid Using Submerged Arc Nanoparticle Synthesis System (SANSS). *J. Cryst. Growth* **2005**, *277*, 636–642. [CrossRef]
47. Kim, M.; Osone, S.; Kim, T.; Higashi, H.; Seto, T. Synthesis of Nanoparticles by Laser Ablation: A Review. *KONA Powder Part. J.* **2017**, *2017*, 80–90. [CrossRef]
48. Liu, P.S.; Cai, W.P.; Wan, L.X.; Shi, M.D.; Luo, X.D.; Jing, W.P. Fabrication and Characteristics of Rutile TiO_2 Nanoparticles Induced by Laser Ablation. *Trans. Nonferrous Met. Soc. China (Engl. Ed.)* **2009**, *19*, s743–s747. [CrossRef]
49. Liang, C.H.; Shimizu, Y.; Sasaki, T.; Koshizaki, N. Preparation of Ultrafine TiO_2 Nanocrystals via Pulsed-Laser Ablation of Titanium Metal in Surfactant Solution. *Appl. Phys. A Mater. Sci. Process* **2005**, *80*, 819–822. [CrossRef]
50. Cao, J.; Du, B.; Wu, L.; Zhang, W.; Pan, Y.; Ye, Y.; Shen, R.; Zhou, B. The Influence of Aluminum Nanoparticles on the Laser Ablation Characteristics of Hydroxylamine Nitrate-Based Liquid Propellants. *Acta Astronaut.* **2022**, *197*, 169–178. [CrossRef]
51. Chang, H.; Jwo, C.S.; Lo, C.H.; Kao, M.J.; Pai, S.H. A Study of Process Optimization Using the Combined Submerged Arc Nanoparticle Synthesis System for Preparing TiO_2 Nanoparticle Suspension. *J. Alloys Compd.* **2007**, *434–435*, 668–671. [CrossRef]
52. Chen, L.C. Preparation of TiO_2 Nanoparticles by Submerged Arc Nanoparticle Synthesis System. *J. Alloys Compd.* **2010**, *495*, 476–480. [CrossRef]
53. Chang, H.; Liu, M.K. Fabrication and Process Analysis of Anatase Type TiO_2 Nanofluid by an Arc Spray Nanofluid Synthesis System. *J. Cryst. Growth* **2007**, *304*, 244–252. [CrossRef]

54. Chang, H.; Jwo, C.; Fan, P.; Pai, S. Process Optimization and Material Properties for Nanofluid Manufacturing. *Int. J. Adv. Manuf. Technol.* **2007**, *34*, 300–306. [CrossRef]
55. Khan, M.A.; Nayan, N.; Ahmad, M.K.; Fhong, S.C.; Mohamed Ali, M.S.; Mustafa, M.K.; Tahir, M. Interface Study of Hybrid CuO Nanoparticles Embedded ZnO Nanowires Heterojunction Synthesized by Controlled Vapor Deposition Approach for Optoelectronic Devices. *Opt. Mater.* **2021**, *117*, 111132. [CrossRef]
56. Hoyos-Palacio, L.M.; Cuesta Castro, D.P.; Ortiz-Trujillo, I.C.; Botero Palacio, L.E.; Galeano Upegui, B.J.; Escobar Mora, N.J.; Carlos Cornelio, J.A. Compounds of Carbon Nanotubes Decorated with Silver Nanoparticles via In-Situ by Chemical Vapor Deposition (CVD). *J. Mater. Res. Technol.* **2019**, *8*, 5893–5898. [CrossRef]
57. Ali, H.M.; Babar, H.; Shah, T.R.; Sajid, M.U.; Qasim, M.A.; Javed, S. Preparation Techniques of TiO_2 Nanofluids and Challenges: A Review. *Appl. Sci.* **2018**, *8*, 587. [CrossRef]
58. Chen, J.; Zhao, C.Y.; Wang, B.X. Effect of Nanoparticle Aggregation on the Thermal Radiation Properties of Nanofluids: An Experimental and Theoretical Study. *Int. J. Heat Mass Transf.* **2020**, *154*, 119690. [CrossRef]
59. Tarafdar, A.; Sirohi, R.; Negi, T.; Singh, S.; Badgujar, P.C.; Shahi, N.C.; Kumar, S.; Sim, S.J.; Pandey, A. Nanofluid research advances: Preparation, characteristics and applications in food processing. *Food Res. Int.* **2021**, *150*, 110751. [CrossRef]
60. Yu, W.; Xie, H. A Review on Nanofluids: Preparation, Stability Mechanisms, and Applications. *J. Nanomater.* **2011**, *2012*, 1–17. [CrossRef]
61. Supiyani; Agusnar, H.; Sugita, P.; Nainggolan, I. Preparation sodium silicate from rice husk to synthesize silica nanoparticles by sol-gel method for adsorption water in analysis of methamphetamine. *S. Afr. J. Chem. Eng.* **2022**, *40*, 80–86. [CrossRef]
62. Khan, S.A.; Zahera, M.; Khan, I.A.; Khan, M.S.; Azam, A.; Arshad, M.; Syed, A.; Nasif, O.; Elgorban, A.M. Photocatalytic degradation of methyl orange by cadmium oxide nanoparticles synthesized by the sol-gel method. *Optik* **2022**, *251*, 168401. [CrossRef]
63. Shojaei, B.; Miri, R.; Bazyari, A.; Thompson, L.T. Asphaltene adsorption on MgO, CaO, SiO_2, and Al_2O_3 nanoparticles synthesized via the Pechini-type Sol−Gel method. *Fuel* **2022**, *321*, 124136. [CrossRef]
64. Behnajady, M.A.; Eskandarloo, H.; Modirshahla, N.; Shokri, M. Investigation of the effect of sol-gel synthesis variables on structural and photocatalytic properties of TiO_2 nanoparticles. *Desalination* **2011**, *278*, 10–17. [CrossRef]
65. Sadetskaya, A.V.; Bobrysheva, N.P.; Osmolowsky, M.G.; Osmolovskaya, O.M.; Voznesenskiy, M.A. Correlative experimental and theoretical characterization of transition metal doped hydroxyapatite nanoparticles fabricated by hydrothermal method. *Mater. Charact.* **2021**, *173*, 110911. [CrossRef]
66. Zhang, Y.X.; Li, G.H.; Jin, Y.X.; Zhang, J.; Zhang, L.D. Hydrothermal synthesis and photoluminescence of TiO_2 nanowires. *Chem. Phys. Lett.* **2002**, *365*, 300–304. [CrossRef]
67. Suzuki, Y.; Yoshikawa, S. Synthesis and Thermal Analyses of TiO_2-Derived Nanotubes Prepared by the Hydrothermal Method. *J. Mater. Res.* **2004**, *19*, 982–985. [CrossRef]
68. Gan, Y.X.; Jayatissa, A.H.; Yu, Z.; Chen, X.; Li, M. Hydrothermal Synthesis of Nanomaterials. *J. Nanomater.* **2020**, *2020*, 1–3. [CrossRef]
69. Duangthongsuk, W.; Wongwises, S. Heat transfer enhancement and pressure drop characteristics of TiO_2-water nanofluid in a double-tube counter flow heat exchanger. *Int. J. Heat Mass Transf.* **2009**, *52*, 2059–2067. [CrossRef]
70. Murshed, S.M.S.; Leong, K.C.; Yang, C. Enhanced thermal conductivity of TiO_2—Water based nanofluids. *Int. J. Therm. Sci.* **2005**, *44*, 367–373. [CrossRef]
71. Mo, S.; Chen, Y.; Jia, L.; Luo, X. Investigation on crystallization of TiO_2–water nanofluids and deionized water. *Appl. Energy* **2012**, *93*, 65–70. [CrossRef]
72. Tajik, B.; Abbassi, A.; Saffar-Avval, M.; Najafabadi, M.A. Ultrasonic properties of suspensions of TiO_2 and Al_2O_3 nanoparticles in water. *Powder Technol.* **2012**, *217*, 171–176. [CrossRef]
73. Leena, M.; Srinivasan, S. Synthesis and ultrasonic investigations of titanium oxide nanofluids. *J. Mol. Liq.* **2015**, *206*, 103–109. [CrossRef]
74. Sandhya, M.; Ramasamy, D.; Sudhakar, K.; Kadirgama, K.; Harun, W.S.W. Ultrasonication an intensifying tool for preparation of stable nanofluids and study the time influence on distinct properties of graphene nanofluids—A systematic overview. *Ultrason. Sonochem.* **2021**, *73*, 105479. [CrossRef] [PubMed]
75. Imarah, A.O.; Csuka, P.; Bataa, N.; Decsi, B.; Sánta-Bell, E.; Molnár, Z.; Balogh-Weiser, D.; Poppe, L. Magnetically Agitated Nanoparticle-Based Batch Reactors for Biocatalysis with Immobilized Aspartate Ammonia-Lyase. *Catalysts* **2021**, *11*, 483. [CrossRef]
76. Kim, S.H.; Choi, S.R.; Kim, D. Thermal Conductivity of Metal-Oxide Nanofluids: Particle Size Dependence and Effect of Laser Irradiation. *J. Heat Transf.* **2007**, *129*, 298–307. [CrossRef]
77. Saleh, R.; Putra, N.; Wibowo, R.E.; Septiadi, W.N.; Prakoso, S.P. Titanium dioxide nanofluids for heat transfer applications. *Exp. Therm. Fluid Sci.* **2014**, *52*, 19–29. [CrossRef]
78. Chakraborty, S.; Sarkar, I.; Behera, D.K.; Pal, S.K.; Chakraborty, S. Experimental investigation on the effect of dispersant addition on thermal and rheological characteristics of TiO_2 nanofluid. *Powder Technol.* **2017**, *307*, 10–24. [CrossRef]
79. Wen, D.; Ding, Y. Formulation of nanofluids for natural convective heat transfer applications. *Int. J. Heat Fluid Flow* **2005**, *26*, 855–864. [CrossRef]

80. Bhambi, S.; Agarwal, V.K. Sub Atmospheric Pool Boiling and Experimental Heat Transferof Alumina Nanofluids. *Mater. Today Proc.* **2019**, *18*, 1495–1509. [CrossRef]
81. Wang, X.-Q.; Mujumdar, A.S. Heat transfer characteristics of nanofluids: A review. *Int. J. Therm. Sci.* **2007**, *46*, 1–19. [CrossRef]
82. Khanafer, K.; Vafai, K.; Lightstone, M. Buoyancy-driven heat transfer enhancement in a two-dimensional enclosure utilizing nanofluids. *Int. J. Heat Mass Transf.* **2003**, *46*, 3639–3653. [CrossRef]
83. Wei, B.; Zou, C.; Li, X. Experimental investigation on stability and thermal conductivity of diathermic oil based TiO_2 nanofluids. *Int. J. Heat Mass Transf.* **2017**, *104*, 537–543. [CrossRef]
84. Shao, X.; Chen, Y.; Mo, S.; Cheng, Z.; Yin, T. Dispersion Stability of TiO_2-H_2O Nanofluids Containing Mixed Nanotubes and Nanosheets. *Energy Procedia* **2015**, *75*, 2049–2054. [CrossRef]
85. Ghadimi, A.; Saidur, R.; Metselaar, H.S.C. A review of nanofluid stability properties and characterization in stationary conditions. *Int. J. Heat Mass Transf.* **2011**, *54*, 4051–4068. [CrossRef]
86. Hwang, Y.; Lee, J.K.; Lee, C.H.; Jung, Y.M.; Cheong, S.I.; Lee, C.G.; Ku, B.C.; Jang, S.P. Stability and thermal conductivity characteristics of nanofluids. *Thermochim. Acta* **2007**, *455*, 70–74. [CrossRef]
87. Liu, Z.-Q.; Ma, J.; Cui, Y.-H. Carbon nanotube supported platinum catalysts for the ozonation of oxalic acid in aqueous solutions. *Carbon* **2008**, *46*, 890–897. [CrossRef]
88. Deng, K.; Chen, S.; Song, H. Chiral recognition of tryptophan enantiomers with UV–Vis spectrophotometry approach by using L-cysteine modified $ZnFe_2O_4$ nanoparticles in the presence of Cu^{2+}. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* **2022**, *270*, 120847. [CrossRef]
89. Lee, K.; Hwang, Y.; Cheong, S.; Kwon, L.; Kim, S.; Lee, J. Performance evaluation of nano-lubricants of fullerene nanoparticles in refrigeration mineral oil. *Curr. Appl. Phys.* **2009**, *9*, e128–e131. [CrossRef]
90. Jiang, L.; Gao, L.; Sun, J. Production of aqueous colloidal dispersions of carbon nanotubes. *J. Colloid Interface Sci.* **2003**, *260*, 89–94. [CrossRef] [PubMed]
91. Lee, D.; Kim, J.-W.; Kim, B.G. A New Parameter to Control Heat Transport in Nanofluids: Surface Charge State of the Particle in Suspension. *J. Phys. Chem. B* **2006**, *110*, 4323–4328. [CrossRef] [PubMed]
92. Wang, X.-J.; Zhu, D.-S.; Yang, S. Investigation of pH and SDBS on enhancement of thermal conductivity in nanofluids. *Chem. Phys. Lett.* **2009**, *470*, 107–111. [CrossRef]
93. Lee, J.-H.; Hwang, K.S.; Jang, S.P.; Lee, B.H.; Kim, J.H.; Choi, S.U.S.; Choi, C.J. Effective viscosities and thermal conductivities of aqueous nanofluids containing low volume concentrations of Al_2O_3 nanoparticles. *Int. J. Heat Mass Transf.* **2008**, *51*, 2651–2656. [CrossRef]
94. Keblinski, P.; Eastman, J.A.; Cahill, D.G. Nanofluids for Thermal Transport. *Mater. Today* **2005**, *8*, 36–44. [CrossRef]
95. Wei, X.; Zhu, H.; Kong, T.; Wang, L. Synthesis and thermal conductivity of Cu_2O nanofluids. *Int. J. Heat Mass Transf.* **2009**, *52*, 4371–4374. [CrossRef]
96. Wang, X.-J.; Li, X.-F. Influence of PH on Nanofluids' Viscosity and Thermal Conductivity. *Chin. Phys. Lett.* **2009**, *26*, 056601.
97. Liu, M.-S.; Lin, M.C.-C.; Huang, I.-T.; Wang, C.-C. Enhancement of thermal conductivity with carbon nanotube for nanofluids. *Int. Commun. Heat Mass Transf.* **2005**, *32*, 1202–1210. [CrossRef]
98. Liu, M.-S.; Lin, M.C.-C.; Tsai, C.Y.; Wang, C.-C. Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method. *Int. J. Heat Mass Transf.* **2006**, *49*, 3028–3033. [CrossRef]
99. Hong, K.S.; Hong, T.-K.; Yang, H.-S. Thermal conductivity of Fe nanofluids depending on the cluster size of nanoparticles. *Appl. Phys. Lett.* **2006**, *88*, 031901. [CrossRef]
100. Chan, Y.; Steckel, J.S.; Snee, P.T.; Caruge, J.-M.; Hodgkiss, J.M.; Nocera, D.G.; Bawendi, M.G. Blue semiconductor nanocrystal laser. *Appl. Phys. Lett.* **2005**, *86*, 1–3. [CrossRef]
101. Hajjar, Z.; Rashidi, A.M.; Ghozatloo, A. Enhanced thermal conductivities of graphene oxide nanofluids. *Int. Commun. Heat Mass Transf.* **2014**, *57*, 128–131. [CrossRef]
102. Wei, X.; Wang, L. Synthesis and thermal conductivity of microfluidic copper nanofluids. *Particuology* **2010**, *8*, 262–271. [CrossRef]
103. Zhu, H.; Zhang, C.; Tang, Y.; Wang, J.; Ren, B.; Yin, Y. Preparation and thermal conductivity of suspensions of graphite nanoparticles. *Carbon* **2007**, *45*, 226–228. [CrossRef]
104. Oh, D.-W.; Jain, A.; Eaton, J.K.; Goodson, K.E.; Lee, J.S. Thermal conductivity measurement and sedimentation detection of aluminum oxide nanofluids by using the 3ω method. *Int. J. Heat Fluid Flow* **2008**, *29*, 1456–1461. [CrossRef]
105. Wang, H.; Sen, M. Analysis of the 3-omega method for thermal conductivity measurement. *Int. J. Heat Mass Transf.* **2009**, *52*, 2102–2109. [CrossRef]
106. Ali, M.K.A.; Xianjun, H.; Essa, F.A.; Abdelkareem, M.A.A.; Elagouz, A.; Sharshir, S.W. Friction and Wear Reduction Mechanisms of the Reciprocating Contact Interfaces Using Nanolubricant Under Different Loads and Speeds. *J. Tribol.* **2018**, *140*, 127862. [CrossRef]
107. Fei, J.; Zhao, B.; Li, C.; Liu, T.; Zhou, M. Carbon spheres wrapped with 2D covalent organic polymer as lubricant additives for enhancing tribological properties. *Colloids Surfaces A Physicochem. Eng. Asp.* **2022**, *633*, 127862. [CrossRef]
108. Alazemi, A.A. Experimental Study of the Lubrication Mechanism of Micro-Spherical Solid Particles between Flat Surfaces. *Lubricants* **2021**, *9*, 81. [CrossRef]
109. Gu, Y.; Fei, J.; Huang, J.; Zhang, L.; Qu, M.; Zheng, X. Carbon microspheres coated with graphene oxide nanosheets as oil-based additives for tribological applications. *Mater. Today Commun.* **2020**, *25*, 101271. [CrossRef]

110. Shen, Y.; Lei, W.; Tang, W.; Ouyang, T.; Liang, L.; Tian, Z.Q.; Shen, P.K. Synergistic friction-reduction and wear-resistance mechanism of 3D graphene and SiO_2 nanoblend at harsh friction interface. *Wear* **2022**, *488–489*, 204175. [CrossRef]
111. Wang, Y.; Cui, L.; Cheng, G.; Yuan, N.; Ding, J.; Pesika, N.S. Water-Based Lubrication of Hard Carbon Microspheres as Lubricating Additives. *Tribol. Lett.* **2018**, *66*, 148. [CrossRef]
112. Liu, Y.; Ge, X.; Li, J. Graphene Lubrication. *Appl. Mater. Today* **2020**, *20*, 100662. [CrossRef]
113. Rabaso, P.; Ville, F.; Dassenoy, F.; Diaby, M.; Afanasiev, P.; Cavoret, J.; Vacher, B.; Le Mogne, T. Boundary lubrication: Influence of the size and structure of inorganic fullerene-like MoS2 nanoparticles on friction and wear reduction. *Wear* **2014**, *320*, 161–178. [CrossRef]
114. Greco, A.; Mistry, K.; Sista, V.; Eryilmaz, O.; Erdemir, A. Friction and wear behaviour of boron based surface treatment and nano-particle lubricant additives for wind turbine gearbox applications. *Wear* **2011**, *271*, 1754–1760. [CrossRef]
115. Battez, A.H.; Rico, J.F.; Arias, A.N.; Rodriguez, J.V.; Rodriguez, R.C.; Fernandez, J.D. The tribological behaviour of ZnO nanoparticles as an additive to PAO6. *Wear* **2006**, *261*, 256–263. [CrossRef]
116. Battez, A.H.; González, R.; Felgueroso, D.; Fernández, J.E.; Fernández, M.d.R.; García, M.A.; Peñuelas, I. Wear prevention behaviour of nanoparticle suspension under extreme pressure conditions. *Wear* **2007**, *263*, 1568–1574. [CrossRef]
117. Hernández Battez, A.; González, R.; Viesca, J.L.; Fernández, J.E.; Díaz Fernández, J.M.; Machado, A.; Chou, R.; Riba, J. CuO, ZrO_2 and ZnO nanoparticles as antiwear additive in oil lubricants. *Wear* **2008**, *265*, 422–428. [CrossRef]
118. Cho, Y.; Park, J.; Ku, B.; Lee, J.; Park, W.-G.; Lee, J.; Kim, S.H. Synergistic effect of a coating and nano-oil lubricant on the tribological properties of friction surfaces. *Int. J. Precis. Eng. Manuf.* **2012**, *13*, 97–102. [CrossRef]
119. Sui, T.; Song, B.; Zhang, F.; Yang, Q. Effect of Particle Size and Ligand on the Tribological Properties of Amino Functionalized Hairy Silica Nanoparticles as an Additive to Polyalphaolefin. *J. Nanomater.* **2015**, *2015*, 492401. [CrossRef]
120. Koshy, C.P.; Rajendrakumar, P.K.; Thottackkad, M.V. Evaluation of the tribological and thermo-physical properties of coconut oil added with MoS 2 nanoparticles at elevated temperatures. *Wear* **2015**, *330–331*, 288–308. [CrossRef]
121. Luo, T.; Wei, X.; Huang, X.; Huang, L.; Yang, F. Tribological properties of Al_2O_3 nanoparticles as lubricating oil additives. *Ceram. Int.* **2014**, *40*, 7143–7149. [CrossRef]
122. Thottackkad, M.V.; Perikinalil, R.K.; Kumarapillai, P.N. Experimental evaluation on the tribological properties of coconut oil by the addition of CuO nanoparticles. *Int. J. Precis. Eng. Manuf.* **2012**, *13*, 111–116. [CrossRef]
123. Azman, S.S.N.; Zulkifli, N.W.M.; Masjuki, H.; Gulzar, M.; Zahid, R. Study of tribological properties of lubricating oil blend added with graphene nanoplatelets. *J. Mater. Res.* **2016**, *31*, 1932–1938. [CrossRef]
124. Schiøtz, J.; Jacobsen, K.W. A Maximum in the Strength of Nanocrystalline Copper. *Science* **2003**, *301*, 1357–1359. [CrossRef] [PubMed]
125. Peña-Parás, L.; Taha-Tijerina, J.; Garza, L.; Maldonado-Cortés, D.; Michalczewski, R.; Lapray, C. Effect of CuO and Al_2O_3 nanoparticle additives on the tribological behavior of fully formulated oils. *Wear* **2015**, *332–333*, 1256–1261. [CrossRef]
126. Joly-Pottuz, L.; Vacher, B.; Ohmae, N.; Martin, J.M.; Epicier, T. Anti-wear and Friction Reducing Mechanisms of Carbon Nano-onions as Lubricant Additives. *Tribol. Lett.* **2008**, *30*, 69–80. [CrossRef]
127. Kolodziejczyk, L.; Martínez-Martínez, D.; Rojas, T.C.; Fernández, A.; Sánchez-López, J.C. Surface-modified Pd nanoparticles as a superior additive for lubrication. *J. Nanoparticle Res.* **2007**, *9*, 639–645. [CrossRef]
128. Peng, D.X.; Chen, C.H.; Kang, Y.; Chang, Y.P.; Chang, S.Y. Size effects of SiO_2 nanoparticles as oil additives on tribology of lubricant. *Ind. Lubr. Tribol.* **2010**, *62*, 111–120. [CrossRef]
129. Peng, D.X.; Kang, Y.; Chen, S.K.; Shu, F.; Chang, Y.P. Dispersion and tribological properties of liquid paraffin with added aluminum nanoparticles. *Ind. Lubr. Tribol.* **2010**, *62*, 341–348. [CrossRef]
130. Akbulut, M. Nanoparticle-Based Lubrication Systems. *J. Powder Met. Min.* **2012**, *1*, 1–3. [CrossRef]
131. Chou, R.; Battez, A.H.; Cabello, J.J.; Viesca, J.L.; Osorio, A.; Sagastume, A. Tribological behavior of polyalphaolefin with the addition of nickel nanoparticles. *Tribol. Int.* **2010**, *43*, 2327–2332. [CrossRef]
132. Viesca, J.L.; Hernández Battez, A.; González, R.; Chou, R.; Cabello, J.J. Antiwear properties of carbon-coated copper nanoparticles used as an additive to a polyalphaolefin. *Tribol. Int.* **2011**, *44*, 829–833. [CrossRef]
133. La, D.D.; Truong, T.N.; Pham, T.Q.; Vo, H.T.; Tran, N.T.; Nguyen, T.A.; Nadda, A.K.; Nguyen, T.T.; Chang, S.W.; Chung, W.J.; et al. Scalable Fabrication of Modified Graphene Nanoplatelets as an Effective Additive for Engine Lubricant Oil. *Nanomaterials* **2020**, *10*, 877. [CrossRef] [PubMed]
134. Ali, M.K.A.; Xianjun, H. Role of bis(2-ethylhexyl) phosphate and Al_2O_3/TiO_2 hybrid nanomaterials in improving the dispersion stability of nanolubricants. *Tribol. Int.* **2021**, *155*, 106767. [CrossRef]
135. Liu, K.N.; Zhang, Y.; Dai, F.; Sun, W. Improved heat transfer of the engine oil by changing it to hybrid nanofluid: Adding hybrid nano-powders. *Powder Technol.* **2021**, *383*, 56–64. [CrossRef]
136. Singh, J.P.; Singh, S.; Nandi, T.; Ghosh, S.K. Development of graphitic lubricant nanoparticles based nanolubricant for automotive applications: Thermophysical and tribological properties followed by IC engine performance. *Powder Technol.* **2021**, *387*, 31–47. [CrossRef]
137. Guo, J.; Peng, R.; Du, H.; Shen, Y.; Li, Y.; Li, J.; Dong, G. The Application of Nano-MoS_2 Quantum Dots as Liquid Lubricant Additive for Tribological Behavior Improvement. *Nanomaterials* **2020**, *10*, 200. [CrossRef]
138. Chouhan, A.; Sarkar, T.K.; Kumari, S.; Vemuluri, S.; Khatri, O.P. Synergistic lubrication performance by incommensurately stacked ZnO-decorated reduced graphene oxide/MoS2 heterostructure. *J. Colloid Interface Sci.* **2020**, *580*, 730–739. [CrossRef]

139. Vardhaman, B.S.A.; Amarnath, M.; Ramkumar, J.; Mondal, K. Enhanced tribological performances of zinc oxide/MWCNTs hybrid nanomaterials as the effective lubricant additive in engine oil. *Mater. Chem. Phys.* **2020**, *253*, 123447. [CrossRef]
140. Mousavi, S.B.; Heris, S.Z.; Estellé, P. Experimental comparison between ZnO and MoS2 nanoparticles as additives on performance of diesel oil-based nano lubricant. *Sci. Rep.* **2020**, *10*, 5813. [CrossRef]
141. Kałużny, J.; Waligórski, M.; Szymański, G.M.; Merkisz, J.; Różański, J.; Nowicki, M.; Al Karawi, M.; Kempa, K. Reducing friction and engine vibrations with trace amounts of carbon nanotubes in the lubricating oil. *Tribol. Int.* **2020**, *151*, 106484. [CrossRef]
142. Wu, B.; Song, H.; Li, C.; Song, R.; Zhang, T.; Hu, X. Enhanced tribological properties of diesel engine oil with Nano-Lanthanum hydroxide/reduced graphene oxide composites. *Tribol. Int.* **2020**, *141*, 105951. [CrossRef]
143. Ali, M.K.A.; Hou, X.; Abdelkareem, M.A.A. Anti-wear properties evaluation of frictional sliding interfaces in automobile engines lubricated by copper/graphene nanolubricants. *Friction* **2020**, *8*, 905–916. [CrossRef]
144. Wang, W.; Zhang, G.; Xie, G. Ultralow concentration of graphene oxide nanosheets as oil-based lubricant additives. *Appl. Surf. Sci.* **2019**, *498*, 143683. [CrossRef]
145. Paul, G.; Shit, S.; Hirani, H.; Kuila, T.; Murmu, N.C. Tribological behavior of dodecylamine functionalized graphene nanosheets dispersed engine oil nanolubricants. *Tribol. Int.* **2018**, *131*, 605–619. [CrossRef]
146. Ghasemi, R.; Fazlali, A.; Mohammadi, A.H. Effects of TiO_2 nanoparticles and oleic acid surfactant on the rheological behavior of engine lubricant oil. *J. Mol. Liq.* **2018**, *268*, 925–930. [CrossRef]
147. Ali, M.K.A.; Xianjun, H.; Abdelkareem, M.A.A.; Gulzar, M.; Elsheikh, A.H. Novel approach of the graphene nanolubricant for energy saving via anti-friction/wear in automobile engines. *Tribol. Int.* **2018**, *124*, 209–229. [CrossRef]
148. Ali, M.K.A.; Fuming, P.; Younus, H.A.; Abdelkareem, M.A.A.; Essa, F.A.; Elagouz, A.; Xianjun, H. Fuel economy in gasoline engines using Al_2O_3/TiO_2 nanomaterials as nanolubricant additives. *Appl. Energy* **2018**, *211*, 461–478. [CrossRef]
149. Esfe, M.H.; Saedodin, S.; Rejvani, M.; Shahram, J. Experimental investigation, model development and sensitivity analysis of rheological behavior of ZnO/10W40 nano-lubricants for automotive applications. *Phys. E Low-Dimens. Syst. Nanostruct.* **2017**, *90*, 194–203. [CrossRef]
150. Sepyani, K.; Afrand, M.; Esfe, M.H. An experimental evaluation of the effect of ZnO nanoparticles on the rheological behavior of engine oil. *J. Mol. Liq.* **2017**, *236*, 198–204. [CrossRef]
151. Ran, X.; Yu, X.; Zou, Q. Effect of Particle Concentration on Tribological Properties of ZnO Nanofluids. *Tribol. Trans.* **2016**, *60*, 154–158. [CrossRef]
152. Moghaddam, M.A.; Motahari, K. Experimental investigation, sensitivity analysis and modeling of rheological behavior of MWCNT-CuO (30–70)/SAE40 hybrid nano-lubricant. *Appl. Therm. Eng.* **2017**, *123*, 1419–1433. [CrossRef]
153. Wu, H.; Qin, L.; Dong, G.; Hua, M.; Yang, S.; Zhang, J. An investigation on the lubrication mechanism of MoS2 nano sheet in point contact: The manner of particle entering the contact area. *Tribol. Int.* **2017**, *107*, 48–55. [CrossRef]
154. Esfe, M.H.; Afrand, M.; Yan, W.-M.; Yarmand, H.; Toghraie, D.; Dahari, M. Effects of temperature and concentration on rheological behavior of MWCNTs/SiO 2 (20–80)-SAE40 hybrid nano-lubricant. *Int. Commun. Heat Mass Transf.* **2016**, *76*, 133–138. [CrossRef]
155. Ali, M.K.A.; Xianjun, H.; Mai, L.; Bicheng, C.; Turkson, R.F.; Qingping, C. Reducing frictional power losses and improving the scuffing resistance in automotive engines using hybrid nanomaterials as nano-lubricant additives. *Wear* **2016**, *364–365*, 270–281. [CrossRef]
156. Asadi, M.; Asadi, A. Dynamic viscosity of MWCNT/ZnO–engine oil hybrid nanofluid: An experimental investigation and new correlation in different temperatures and solid concentrations. *Int. Commun. Heat Mass Transf.* **2016**, *76*, 41–45. [CrossRef]
157. Wu, L.; Zhang, Y.; Yang, G.; Zhang, S.; Yu, L.; Zhang, P. Tribological properties of oleic acid-modified zinc oxide nanoparticles as the lubricant additive in poly-alpha olefin and diisooctyl sebacate base oils. *RSC Adv.* **2016**, *6*, 69836–69844. [CrossRef]
158. Zheng, D.; Cai, Z.-B.; Shen, M.-X.; Li, Z.-Y.; Zhu, M.-H. Investigation of the tribology behaviour of the graphene nanosheets as oil additives on textured alloy cast iron surface. *Appl. Surf. Sci.* **2016**, *387*, 66–75. [CrossRef]
159. Meng, Y.; Su, F.; Chen, Y. Supercritical Fluid Synthesis and Tribological Applications of Silver Nanoparticle-decorated Graphene in Engine Oil Nanofluid. *Sci. Rep.* **2016**, *6*, 31246. [CrossRef]
160. Mungse, H.P.; Kumar, N.; Khatri, O.P. Synthesis, dispersion and lubrication potential of basal plane functionalized alkylated graphene nanosheets. *RSC Adv.* **2015**, *5*, 25565–25571. [CrossRef]
161. Jia, Z.; Chen, T.; Wang, J.; Ni, J.; Li, H.; Shao, X. Synthesis, characterization and tribological properties of Cu/reduced graphene oxide composites. *Tribol. Int.* **2015**, *88*, 17–24. [CrossRef]
162. Zin, V.; Agresti, F.; Barison, S.; Colla, L.; Mercadelli, E.; Fabrizio, M.; Pagura, C. Tribological Properties of Engine Oil with Carbon Nano-horns as Nano-additives. *Tribol. Lett.* **2014**, *55*, 45–53. [CrossRef]
163. Arumugam, S.; Sriram, G.; Ellappan, R. Bio-lubricant-biodiesel combination of rapeseed oil: An experimental investigation on engine oil tribology, performance, and emissions of variable compression engine. *Energy* **2014**, *72*, 618–627. [CrossRef]
164. Wan, Q.; Jin, Y.; Sun, P.; Ding, Y. Rheological and tribological behaviour of lubricating oils containing platelet MoS2 nanoparticles. *J. Nanoparticle Res.* **2014**, *16*, 2386. [CrossRef]
165. Ettefaghi, E.-O.; Ahmadi, H.; Rashidi, A.; Nouralishahi, A.; Mohtasebi, S.S. Preparation and thermal properties of oil-based nanofluid from multi-walled carbon nanotubes and engine oil as nano-lubricant. *Int. Commun. Heat Mass Transf.* **2013**, *46*, 142–147. [CrossRef]
166. Ettefaghi, E.-O.; Rashidi, A.; Ahmadi, H.; Mohtasebi, S.S.; Pourkhalil, M. Thermal and rheological properties of oil-based nanofluids from different carbon nanostructures. *Int. Commun. Heat Mass Transf.* **2013**, *48*, 178–182. [CrossRef]

167. Demas, N.G.; Timofeeva, E.V.; Routbort, J.L.; Fenske, G.R. Tribological Effects of BN and MoS2 Nanoparticles Added to Polyalphaolefin Oil in Piston Skirt/Cylinder Liner Tests. *Tribol. Lett.* **2012**, *47*, 91–102. [CrossRef]
168. Eswaraiah, V.; Sankaranarayanan, V.; Ramaprabhu, S. Graphene-Based Engine Oil Nanofluids for Tribological Applications. *ACS Appl. Mater. Interfaces* **2011**, *3*, 4221–4227. [CrossRef]
169. Thachnatharen, N.; Khalid, M.; Arulraj, A.; Sridewi, N. Tribological performance of hexagonal boron nitride (hBN) as nano-additives in military grade diesel engine oil. *Mater. Today Proc.* **2021**, *50*, 70–73. [CrossRef]
170. Charoo, M.S.; Hanief, M. Improving the tribological characteristics of a lubricating oil by nano sized additives. *Mater. Today Proc.* **2020**, *28*, 1205–1209. [CrossRef]
171. Rasheed, A.K.; Khalid, M.; Javeed, A.; Rashmi, W.; Gupta, T.C.S.M.; Chan, A. Heat transfer and tribological performance of graphene nanolubricant in an internal combustion engine. *Tribol. Int.* **2016**, *103*, 504–515. [CrossRef]
172. Vyavhare, K.; Timmons, R.B.; Erdemir, A.; Edwards, B.L.; Aswath, P.B. Tribochemistry of fluorinated ZnO nanoparticles and ZDDP lubricated interface and implications for enhanced anti-wear performance at boundary lubricated contacts. *Wear* **2021**, *474–475*, 203717. [CrossRef]
173. Avilés, M.-D.; Pamies, R.; Sanes, J.; Bermúdez, M.-D. Graphene-Ionic Liquid Thin Film Nanolubricant. *Nanomaterials* **2020**, *10*, 535. [CrossRef] [PubMed]
174. Mello, V.S.; Trajano, M.F.; Guedes, A.E.D.S.; Alves, S.M. Comparison between the Action of Nano-Oxides and Conventional EP Additives in Boundary Lubrication. *Lubricants* **2020**, *8*, 54. [CrossRef]
175. Cheng, Z.-L.; Li, W.; Wu, P.-R.; Liu, Z. Study on structure-activity relationship between size and tribological properties of graphene oxide nanosheets in oil. *J. Alloys Compd.* **2017**, *722*, 778–784. [CrossRef]
176. Ivanov, M.; Shenderova, O. Nanodiamond-based nanolubricants for motor oils. *Curr. Opin. Solid State Mater. Sci.* **2017**, *21*, 17–24. [CrossRef]
177. Ali, M.K.A.; Xianjun, H.; Elagouz, A.; Essa, F.A.; Abdelkareem, M.A.A. Minimizing of the boundary friction coefficient in automotive engines using Al_2O_3 and TiO_2 nanoparticles. *J. Nanoparticle Res.* **2016**, *18*, 377. [CrossRef]
178. Padgurskas, J.; Rukuiza, R.; Prosyčevas, I.; Kreivaitis, R. Tribological properties of lubricant additives of Fe, Cu and Co nanoparticles. *Tribol. Int.* **2013**, *60*, 224–232. [CrossRef]
179. Mousavi, S.B.; Heris, S.Z.; Estellé, P. Viscosity, tribological and physicochemical features of ZnO and MoS_2 diesel oil-based nanofluids: An experimental study. *Fuel* **2021**, *293*, 120481. [CrossRef]
180. Tóth, D.; Szabó, Á.I.; Kuti, R. Tribological properties of nano-sized ZrO_2 ceramic particles in automotive lubricants. *FME Trans.* **2021**, *49*, 36–43. [CrossRef]
181. Beheshti, A.; Huang, Y.; Ohno, K.; Blakey, I.; Stokes, J.R. Improving tribological properties of oil-based lubricants using hybrid colloidal additives. *Tribol. Int.* **2020**, *144*, 106130. [CrossRef]
182. Mousavi, S.B.; Heris, S.Z. Experimental investigation of ZnO nanoparticles effects on thermophysical and tribological properties of diesel oil. *Int. J. Hydrog. Energy* **2020**, *45*, 23603–23614. [CrossRef]
183. Xue, C.Y.; Wang, S.R.; Wang, Y.; Wang, G.Q.; Yan, X.Y. The Influence of Nanocomposite Carbon Additive on Tribological Behavior of Cylinder Liner/Piston Ring. In *IOP Conference Series: Materials Science and Engineering, Proceedings of the International Conference on Mechanical and Aeronautical Engineering (ICMAE 2018), Bangkok, Thailand, 13–16 December 2018*; Institute of Physics Publishing: Beijing, China, 2019; Volume 491.
184. Scherge, M.; Böttcher, R.; Kürten, D.; Linsler, D. Multi-Phase Friction and Wear Reduction by Copper Nanopartices. *Lubricants* **2016**, *4*, 36. [CrossRef]
185. Asnida, M.; Hisham, S.; Awang, N.W.; Amirruddin, A.K.; Noor, M.M.; Kadirgama, K.; Ramasamy, D.; Najafi, G.; Tarlochan, F. Copper (II) oxide nanoparticles as additve in engine oil to increase the durability of piston-liner contact. *Fuel* **2018**, *212*, 656–667. [CrossRef]
186. Rajendhran, N.; Palanisamy, S.; Periyasamy, P.; Venkatachalam, R. Enhancing of the tribological characteristics of the lubricant oils using Ni-promoted MoS2 nanosheets as nano-additives. *Tribol. Int.* **2018**, *118*, 314–328. [CrossRef]
187. Borda, F.L.G.; de Oliveira, S.J.R.; Lazaro, L.M.S.M.; Leiróz, A.J.K. Experimental investigation of the tribological behavior of lubricants with additive containing copper nanoparticles. *Tribol. Int.* **2018**, *117*, 52–58. [CrossRef]
188. Ali, M.K.A.; Xianjun, H.; Mai, L.; Qingping, C.; Turkson, R.F.; Bicheng, C. Improving the tribological characteristics of piston ring assembly in automotive engines using Al_2O_3 and TiO_2 nanomaterials as nano-lubricant additives. *Tribol. Int.* **2016**, *103*, 540–554. [CrossRef]
189. Jeng, Y.-R.; Huang, Y.-H.; Tsai, P.-C.; Hwang, G.-L. Tribological Performance of Oil-Based Lubricants with Carbon-Fe Nanocapsules Additive. *Tribol. Trans.* **2015**, *58*, 924–929. [CrossRef]
190. Zhang, B.-S.; Xu, B.-S.; Xu, Y.; Gao, F.; Shi, P.-J.; Wu, Y.-X. CU nanoparticles effect on the tribological properties of hydrosilicate powders as lubricant additive for steel–steel contacts. *Tribol. Int.* **2011**, *44*, 878–886. [CrossRef]
191. Nurchi, C.; Buonvino, S.; Arciero, I.; Melino, S. Sustainable Vegetable Oil-Based Biomaterials: Synthesis and Biomedical Applications. *Int. J. Mol. Sci.* **2023**, *24*, 2153. [CrossRef] [PubMed]
192. Taha-Tijerina, J.J.; Aviña, K.; Padilla-Gainza, V.; Akundi, A. Halloysite Reinforced Natural Esters for Energy Applications. *Lubricants* **2023**, *11*, 65. [CrossRef]

193. Gupta, H.S.; Sehgal, R.; Wani, M.F. Formulation and characterization of eco-friendly Mahua and Linseed oil-based nanolubricants by incorporating h-BN nano-additives. *Environ. Dev. Sustain.* **2024**, 1–21. [CrossRef]
194. Hameed, A.Z.; Muralidharan, K. Performance, Emission, and Catalytic Activity Analysis of AL_2O_3 and CEO_2 Nano-Additives on Diesel Engines Using Mahua Biofuel for a Sustainable Environment. *ACS Omega* **2023**, *8*, 5692–5701. [CrossRef] [PubMed]