

Sustainable Nanoparticles in Lubrication System: A Review of Eco-Friendly and Inorganic Additives

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ABSTRACT

The potential of nano-scale additions, such as titanium dioxide (TiO₂), cellulose nanocrystals (CNC), and aluminium oxide (Al₂O₃), for strengthening lubricant efficiency is reviewed in this work. Despite a decreased level of wear, friction, and heat degradation, the nanoparticles strengthen tribological function. CNC is a bio-based, renewable substance that has excellent dispersion and green credentials. TiO₂ and Al₂O₃ NPs promote a protective layer next generation and mechanical strength. Synergistic effects are demonstrated by hybrid CNC and inorganic nanoparticle combinations. Dispersion stability and practical implementation still present difficulties. All things considered, nano-additives offer a viable path toward lubricating systems that are both high-performing and environmentally friendly.

Keywords: Lubricant Oil, Eco-Friendly filler, Inorganic Additives, Viscosity, Tribology

1. INTRODUCTION

Engine oil is an essential component of a diesel engine's running, longevity, and efficiency. As lubricant, it decreases friction between the moving components, permitting them to run without

interruption. By avoiding friction, engine oil contributes to decreasing the impact of wear on elements, expanding the life of the engine, and reducing the likelihood of mechanical breakdowns [1,2]. Furthermore, it functions as a cooling fluid, absorbing heat from the engine, and a filter, preventing sludge and deposits from developing within the system.

The purity and state of the oil directly influence the engine's performance. Correct lubrication contributes to smoother operation, elevated fuel efficiency, and optimized power output [3,4]. Conversely, using low-quality oil or failing to maintain proper oil levels can drastically hinder engine performance. Higher friction due to poor lubrication may result in higher power consumption as the engine works harder to overcome resistance, ultimately leading to poorer fuel economy.

Engine oil also plays a critical part in preventing engine damage. Because lubrication is insufficient, whether due to low oil levels, deteriorated oil, or the use of inappropriate oil, the metal components of the engine can come into direct contact. This leads to higher friction, which generates excessive heat and accelerates wear. Over time, this can cause considerable damage to crucial engine components such as the pistons, cylinders, and bearings. In severe situations, engine failure may occur, necessitating costly repairs or even complete engine replacement.

2. BASE OILS, ADDITIVES AND LUBRICANT FORMULATION

Liquid lubricants are produced from a basic oil and typically incorporate additives to increase performance and function. It may be categorized into two categories mineral oil and synthetic lubricants [5,6]. Lubricating grease, a liquid lubricant with thickening ingredients, is the primary ingredient, with 70-80% of lubricating oil contained in it [7,8]. Solid lubricants, such as graphite, polytetrafluoroethylene (PTFE), and molybdenum disulfide (MoS_2), are used to hold the position of liquid or gas lubricants and minimize friction between surfaces [9]. They are particularly effective in harsh conditions like high heat, vacuum, or chemical presence, and are commonly used in industrial, transportation, and aerospace sectors for performance and dependability. Lubricating oils, also called lubricants in the present research, are utilized in the contemporary manufacturing sector to prevent wear between encountering tribology surfaces in engines and machines. Transferring heat across mediums [10,11]. Furthermore, a lubricant seals the gap between the cylinder liner wall and the piston compression ring in an internal combustion engine. Lubricants serve three further purposes, including helping to clean the internal combustion engine and

suspending matter. It is essential to pick the right base oil and ingredients to produce a lubricant due to the ingredients that give the base oil qualities [12]. The fundamental elements of lubricants, essential for minimizing wear, friction, and heat in equipment, comprise basic oils, ingredients, and lubricant recipes. It can be revealed that understanding the concepts of all components is crucial to formulating effective lubricants for specific applications.

Base oils make up 70-99% of all lubricants, providing essential lubricating qualities to reduce wear and friction between moving parts in machines [13]. The lubricant's performance is largely determined by its properties and quality. Modifiers, which are dissolved or distributed using base oils as carriers, improve the lubricant's properties, such as less oxidation, better wear protection, or resistance to corrosion [14]. The viscosity of a base oil impacts its capacity to flow at varied temperatures, forming a protective layer during interfacing contact. High thermal stability guarantees the oil maintains its effectiveness at both high and low temperatures [15]. Based on their chemical composition, performance characteristics, and refining processes, base oils are divided into a wide variety. Category I oils are purified by solvent extraction, while Category II oils undergo hydrocracking for superior performance [16]. Category III oils are highly refined and resemble synthetic oils, while Category IV oils are synthetic and ideal for extreme protection and longevity. The choice of base oil depends on the lubricant's demands and intended purpose [17–19]. Modifiers are chemical ingredients used in base oils to boost their efficiency and provide extra features. Therefore, the ingredients adopt the physical qualities of the lubricants to fit diverse operational criteria under various scenarios [20].

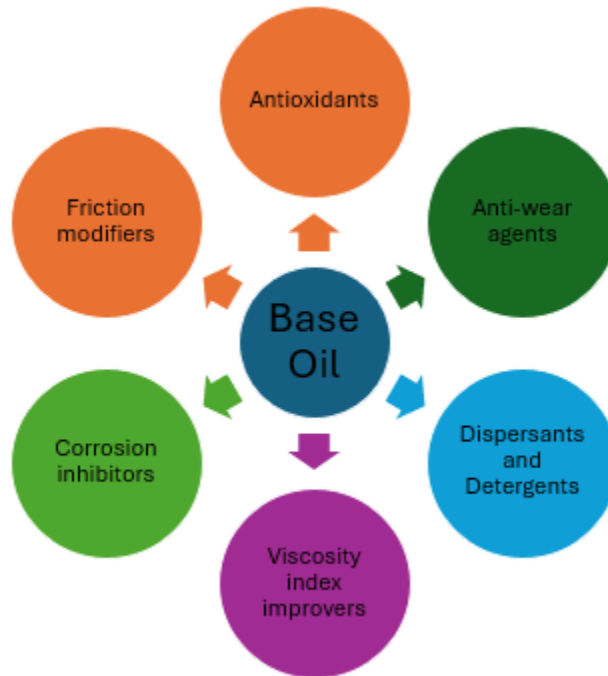


Fig.1. Frequent Classes of Additive Chemicals

Antioxidants inhibit oxygen from interacting with the foundation oil that contributes to minimizing degradation and extending the lubricant's lifespan [21]. Anti-wear agents provide protective coating on metal surfaces, increasing machinery's lifespan and reducing the need for replacements or repairs [22]. Viscosity index improvers help maintain constant viscosity across different temperatures [22]. Lubricants also contain detergents to maintain clean surfaces, neutralize acidic byproducts, and prevent impurities from clumping together [23,24]. Corrosion inhibitors protect metal surfaces from rust and corrosion, while friction modifiers increase mechanical efficiency and reduce energy consumption [25]. Each type of additive has a distinct function to improve the base oil's characteristics and withstand machinery demands [26].

3. LUBRICATION SCENARIOS AND OPERATING REGIMES

Lubrication parameters refer to the conditions where two surfaces slide relative to each other, influenced by factors like lubricant qualities, temperature, load, and speed. These parameters affect machinery efficiency and determine the appropriate lubricant. Therefore, various lubrication conditions affect the working efficiency of machinery and determine the category of lubricant that should be utilized, as demonstrated in Figure 2. The term "hydrodynamic lubrication" describes a

situation in which two sliding surfaces are separated from one another by a full lubricant coating, preventing direct contact [27]. The lubricant's viscosity and the surfaces' relative motion cause this separation, which leaves a stable film in its wake. By keeping surfaces apart, this lubricant coating reduces wear and friction that would otherwise result from direct metal-to-metal contact [28]. In most cases, hydrodynamic lubrication happens when there is relatively modest stress and high speeds of motion. Reduced loads stop the surfaces from piercing the stable and thick lubricating coating that is facilitated by the motion [29]. In conclusion, hydrodynamic lubrication creates ideal conditions for machinery by using motion and the lubricant's properties to maintain surface separation, reducing wear and friction, and extending the life of mechanical parts [28,29].

A mixed lubrication occurs when boundary and hydrodynamic lubrication are present simultaneously. In this case, certain surfaces are completely isolated from one another by a lubricant coating, while the others are in direct contact with one another due to surface asperities [30]. In mixed lubrication, the friction levels are lower than in boundary lubrication, where the surfaces come into more direct contact, but higher than in hydrodynamic lubrication, where a complete lubricant layer is present [31]. Because these parts work in different environments, they are more likely to encounter both boundary lubrication and hydrodynamic lubrication at the same time [32]. In conclusion, mixed lubrication produces mild friction and wear by combining elements of boundary and hydrodynamic lubrication. In boundary lubrication, the film of oil is too thin to separate the two surfaces in contact, allowing microscopic surface roughness (called asperities) to come into direct contact. This state commonly develops during scenarios where there are large loads, low speeds, or extreme pressure, preventing the lubricant from developing a thick protective film as it does in hydrodynamic lubrication [33].

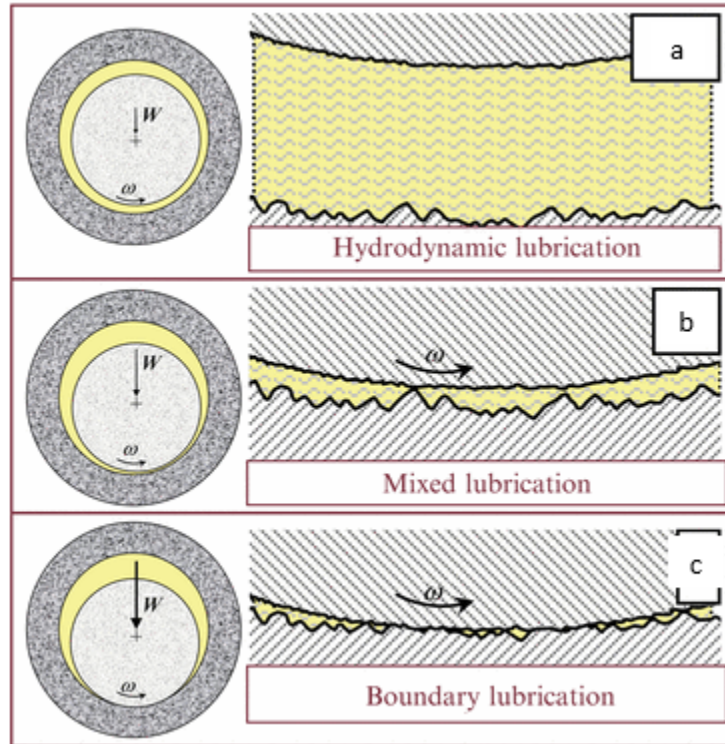


Fig.2. Scenarios of lubrication regimes: a) Hydrodynamic b) Mixed c) Boundary

Boundary lubrication is common when machinery is operating under conditions where there isn't enough relative motion between the parts to maintain a complete layer of lubricant [34]. In boundary lubrication, additives like anti-wear agents and friction modifiers are crucial [35]. These additives provide a protective barrier on the metal surfaces, lessening wear and minimizing friction despite the lack of a full lubricating coating. For instance: Anti-wear chemicals create a chemical barrier on surfaces to prevent direct contact damage [36]. Friction modifiers can reduce friction, even when the lubricant layer is thin. In slow-moving machinery, the relative speed is insufficient to maintain a hydrodynamic lubrication layer. High-pressure situations in bearings can cause the lubricant coating to collapse, leading to boundary lubrication [37]. In summary, boundary lubrication occurs when conditions prevent a full lubricant layer from developing. Ingredients minimize friction and wear in machinery working under high conditions or during start-up phases, which makes it a common challenge.

4.ROLE OF NANOMATERIALS AS LUBRICANT ADDITIVES

The purpose of adding nanomaterials to engine oil is to improve wear resistance, lower friction, boost fuel efficiency, and improve engine performance [38,39]. Nanoparticles are very small

particles that are usually less than 100 nanometers across. These additives make engine oil able to interact closely with surfaces and provide unique tribological benefits [40]. Silver, zinc, copper, these metal nanoparticles lower friction by coating the engine's metal surfaces with a protective layer and reducing direct contact between metal elements. prolongs engine life, lowers wear, and enhances engine lubrication [41–46]. Fullerene is a spherically shaped nanoparticle based on carbon. At the nanoscale, it functions as a ball bearing to lessen friction between moving engine parts. reduces wear, improves lubrication, and, by lowering frictional energy loss, may increase fuel economy [47,48]. A single sheet of carbon atoms organized in a hexagonal lattice is called graphene. It has a low friction coefficient, remarkable conductivity, and strength. enhances wear resistance, boosts engine oil's thermal stability, and offers excellent lubrication efficiency at high pressure [49–51]. Metal oxide nanoparticles, such as cerium oxide (CeO_2) [52,53], zinc oxide (ZnO) [54,55], aluminium oxide (Al_2O_3) and titanium dioxide (TiO_2) [56–58]. These nanoparticles function as wear additives by lowering the oil's oxidative deterioration and creating protective coatings on engine components. prolongs the life of engine oil, decreases wear and friction, and improves thermal and oxidative stability. h-BN, or hexagonal boron nitride, is a typical additive. helps to maintain a steady engine temperature by reducing friction, providing good anti-wear qualities, and having high thermal conductivity [59,60]. A substance called MoS_2 creates layered structures that make it easier for sheets to slide over one another and lower friction. provides robust anti-friction qualities, lowers wear, and keeps working well under heavy loads [59,60]. Because of their special structure, carbon nanotubes are cylinder-shaped molecules with remarkable strength and thermal capabilities. boosts wear resistance, lubrication, and load-bearing capability of oil, especially in high-stress engine settings [61,62]. Oil's viscosity index can be raised by using silica SiO_2 NPs. enhances thermal stability and guards against high-temperature oil deterioration [63–65]. The overall advantages of nano additives are nanoparticles produce smoother surface contacts, reducing friction between engine parts. Engine life can be increased by reducing wear and tear thanks to the protective layers that nanoparticles generate [59,60]. The ability of the oil to tolerate high temperatures without degrading is improved by several nano additions. Fuel economy can be increased by enhanced lubrication and less friction. Certain nanoparticles provide long-term dependability by shielding engine components from oxidation and corrosion [66]. The application of nano additives is still in its infancy, and different engine types and operating environments may have different effects on how well they work [41,47,66]. Ensuring conformity with engine

requirements and being cognizant of potential long-term impacts on engine materials or oil systems are crucial.

Due to their potential tribological qualities, Al_2O_3 NPs dispersion in lubricants has attracted a lot of attention. The well-known ceramic substance Al_3O_4 is prized for its high melting point, hardness, and thermal stability [67]. Al_2O_3 NPs are very helpful in engine and equipment applications because they can increase wear resistance, decrease friction, and improve thermal conductivity when correctly dispersed in lubricants. Getting a stable and homogenous dispersion of Al_2O_3 NPs in lubricants is a major difficulty [68]. Because of their strong van der Waals forces and high surface energy, nanoparticles tend to aggregate. This agglomeration may cause the lubricant to become unevenly distributed, which could reduce the efficiency of the nanoparticles and possibly clog the system. Furthermore, if nanoparticles are not properly dispersed, they may silt and lose their tribological benefits as they sink to the bottom of the lubricant reservoir.

Several methods are used to guarantee uniform and stable dispersion of Al_2O_3 NPs in lubricants. One of the most popular ways to stabilize nanoparticles in lubricants is to add surfactants or dispersants. By lowering the surface tension that exists between the lubricant and the nanoparticles, surfactants help to maintain uniform dispersion and avoid agglomeration [5]. Dispersants have the capacity to improve the nanoparticles' compatibility with base oil, which improves stability [62]. Clusters of nanoparticles are broken up by mechanical agitation, such as high-speed stirring or ultrasonication. Ultrasonication works very well because the high-frequency sound waves create cavitation and strong enough forces to separate the particles and distribute them evenly throughout the lubricant [62]. To improve Al_2O_3 NPs' affinity for the lubricant, their surfaces can be modified by covering them with polymers or functional groups. By using this method, wear resistance and friction reduction are improved, as well as the interface between the nanoparticles and engine component surfaces [69]. Al_2O_3 NPs have the potential to greatly enhance lubricant performance when they are evenly distributed. Engine parts' metal surfaces are covered in a protective layer formed by the hard ceramic nanoparticles, which lessens direct metal-to-metal contact. This layer reduces wear and tear, which increases the lifespan of engine parts. Furthermore, by functioning as a rolling element at the nanoscale, the spherical size and form of Al_2O_3 NPs can lower friction and increase lubricating efficiency. Al_2O_3 NPs also improve lubricants' heat stability. These particles' high thermal conductivity aids in the dissipation of heat produced during engine running, guaranteeing the lubricant's effectiveness even at greater temperatures. Thus, the likelihood of

lubricant breakdown is decreased, and the lubricant's service life is increased. The addition of Al_2O_3 NPs to lubricants provides notable benefits in terms of thermal stability, friction reduction, and wear resistance. To realize these advantages, though, a steady dispersion must be achieved and maintained. The dispersion issues can be successfully handled by using methods including surface modification, ultrasonication, and surfactant addition, which will improve lubricant performance and lengthen the life of machinery. Lubricating oil can effectively disperse hydrothermally prepared silane coupling agent-modified spherical Al_2O_3 NPs. The four-ball and thrust-ring friction tests were used to examine the tribology characteristics of Al_2O_3 NPs as lubricating oil additives [70]. The results show that the modified Al_2O_3 NPs may significantly improve the lubricating behaviors when compared to the base oil. Both the wear mark width and the friction coefficient are at their smallest levels when the additional level is 0.1 weight percent. The friction surface forms a protective film that self-laminates, causing the wear behavior to shift from sliding to rolling friction. This is the lubrication process. Employing a four-ball tester, the present investigation examines the effects of lubricant additives such as Al_2O_3 NPs on the tribological performance of basic lubricant oil (SAE10W40) [71]. The impact of the additive on wear-preventive properties and COF is assessed in this study. An Integrated Taguchi-Grey relationship technique is employed to determine the ideal load and Al_2O_3 NPs addition ratio. The findings indicate that adding 0.5 % by weight of Al_2O_3 NPs to base lubricating oil reduces the scar diameter and coefficient of friction by 20.75% and 22.67%, respectively. On the friction surface, the nanoparticles also create a layer that shields itself.

Using pin-on-disc equipment, the tribological qualities of lithium grease specimens with varying Al_2O_3 NPs levels were examined under various sliding velocities and conventional loads [72]. The findings demonstrated that Al_2O_3 NPs improved the tribological characteristics of lithium grease and decreased wear scar width and COF by roughly 47.5% and 57.9%, respectively. The dispersion stability in lubricating oil was enhanced by $\text{Al}_2\text{O}_3/\text{TiO}_2$ NPs being created by grafting monomers onto their surface, according to the results [73]. Containing the anti-friction mechanism producing a protective covering on the worn surface and a shift in wear behavior from sliding to rolling friction, the friction and wear properties of the oil containing the nanocomposites were also enhanced. Al_2O_3 NPs are added to the jojoba oil based on weight in percentage. The tribological properties of the Al_2O_3 NPs were assessed in relation to their concentration fluctuation in jojoba oil [74]. The concentration of 0.1% yielded the lowest friction coefficient and wear, while 0.2%

concentration produced the most wear. At 0.15% amount, wear increases even further. In comparison to base jojoba oil, the smooth surface of the pin was noticed at a concentration of 0.1% Al_2O_3 NPs. The amount of 0.2% yielded the highest overall acid number alterations when compared to other nanoparticle concentrations. The impact of adding Al_2O_3 and hexagonal boron nitride (hBN) NPs to SAE 15W40 diesel engine oil was investigated [75]. A four-ball tribo-tester was used for a tribological test. At hBN NPs additions were added to SAE 15W40 diesel engine oil, as opposed to either Al_2O_3 or no additives, the results demonstrated a considerable reduction in both COF and wear rate of the ball. This is consistent with the ball's smoother worn surfaces and noticeably smaller wear scar diameters. The impact of Al_2O_3 NPs and multi-walled carbon nanotubes (MWCNTs) as lubricant nano additives. To compare with conventional oil, several engine oil samples were loaded with 0.5–2.0 wt.% Al_2O_3 NPs and 0.5–1.0 wt.% MWCNTs. The four-ball test method was used to examine the Nano lubricants' function. Moreover, SEM and 3D micrographs were used to assess the wear scar in the engine [62]. The durability of wear and sliding performance of the sliding surfaces utilizing hybrid MWCNTs/ Al_2O_3 NPs were superior. When compared to unmodified oil, the wear scar width and COF improved by 51.5% and 47.9%, respectively.

Because of their high surface energy, SiO_2 nanoparticles tend to agglomerate, which is one of the main challenges in using them as lubricants [67]. Due to their strong reactivity and propensity to cluster, these particles lose some of their tribological advantages and have less surface area available for contact with metal surfaces. Agglomeration can also result in uneven lubricant distribution, which can impair the oil's overall performance. Another issue is the gradual sedimentation of particles, which can cause the nanoparticles to settle and lose some of their potency [76,77]. Several tactics are used to get over these obstacles and guarantee a steady and uniform dispersion of SiO_2 NPs in lubricants

The addition of dispersants or surfactants is one of the most popular techniques for improving SiO_2 NPs dispersion. Surfactants facilitate a more uniform distribution by lowering the surface tension that exists between the lubricant and the nanoparticles, thus preventing agglomeration. Long-term efficacy is ensured by dispersants, which stabilize the nanoparticles and aid in maintaining their uniform dispersion in the lubricant. [78,79]. Ultrasonic treatment is an effective technique for spreading nanoparticles in fluids. Ultrasonic wave applications result in cavitation, which generates strong shear forces that disintegrate aggregated nanoparticles. By distributing SiO_2 NPs uniformly

throughout the lubricant, this method helps to improve stability and inhibit sedimentation [62]. To improve SiO₂ nanoparticles' compatibility with lubricant base oils, surface modification can be carried out. The surface of the nanoparticles can be modified to maximize their contact with the lubricant molecules by adding polymers or functional groups. This alteration keeps SiO₂ NPs from clumping together and improves their dispersion stability in the fluid. Mechanical stirring, such as high-speed stirring or milling, is another technique for dispersing nanoparticles. The nanoparticles are kept in motion by constant mechanical force application, which lowers the likelihood of settling and aggregating. However, as compared to surfactants or ultrasonication, this technique might not be able to give stability over the long run.

At the nanoscale, SiO₂ NPs function as rolling elements, assisting in the reduction of friction between moving metal surfaces. This is especially helpful under heavy load situations, where lowering friction can greatly increase energy efficiency. Wear is minimized when SiO₂ NPs form a thin tribo-film on engine components, reducing direct contact between metal surfaces. The longevity of mechanical parts is increased by this protective layer, which also lessens the need for regular maintenance. The exceptional thermal stability of SiO₂ NPs improves the lubricant's performance at high temperatures. They aid in heat dissipation, halt lubricant deterioration, and preserve lubrication even at high temperatures. Additionally, lubricants' oxidation stability can be enhanced by SiO₂ NPs. For extended periods, the lubricant remains clean and effective due to the nanoparticles' ability to slow down the oxidation process, which helps avoid the production of varnish and sludge [10]. Optimizing lubricant performance greatly depends on the dispersion of SiO₂ NPs. The problems of agglomeration and sedimentation can be successfully handled by using techniques such as surface modification, ultrasonication, and the application of dispersants. The lubricant's capacity to lower friction, increase wear resistance, and preserve thermal stability is improved by properly distributed SiO₂ NPs, which results in mechanical systems that are more reliable and efficient [6,13]. Stearic acid-modified SiO₂ nanoparticles (SiO₂-SA) were added at weight percentages of 0.05, 0.10, 0.20, and 0.30, and the same quantity of SA was used as a dispersant. Tribological tests were carried out in rolling-sliding and pure sliding scenarios with a 5% slide-to-roll ratio at 120 °C. All nano lubricants have superior anti-friction properties [80]. For both tribological circumstances, the optimal concentration for reducing friction was 0.30 weight percent. The samples evaluated in pure sliding conditions yielded the highest anti-wear results at loading level of 0.20 wt. % SiO₂-SA was used. Wear track width, track depth, and wear area were

reduced by 55%, 86%, and 92%, respectively. A paraffinic base oil's tribological nature is investigated in relation to SiO_2 and SiO_2 -SA NPs [81]. Using a traditional two-step process including ultrasonic agitation, eight nano lubricants were synthesized, including paraffinic base oil + SiO_2 -SA and paraffinic oil + SiO_2 . The nanofiller contained 0.15 to 0.60 weight percent. Experimental investigations were conducted on several factors, such as density, viscosity index, wear, friction coefficient, and viscosity. At 393.15 K, a 3D optical profilometer was used to evaluate wear, and friction assessments were carried out in pure sliding contacts. According to the friction tests' results, the SiO_2 -SA nano lubricants outperformed the neat paraffinic base oil with much lower friction coefficients. A friction coefficient reduction of about 43% was achieved with an optimal concentration of nanoparticles of 0.60 weight percent SiO_2 -SA. When compared to the pure paraffinic base oil, the addition of 0.60 weight percent SiO_2 -SA caused the highest reductions in breadth, depth, and area, with reductions of 21, 22, and 54% achieved, respectively, when it came to wear. The tribological response of SiO_2 NPs incorporated into paraffin-based SN-500 base oil was examined [82]. Each experiment was conducted with varying loads and nanoparticle levels in lubricating oil. Pin-on-disk equipment was employed for the friction and wear examinations. The outcomes of the experiment demonstrate that adding nanoparticles, like SiO_2 , to base oil has a positive impact on wear resistance and friction reduction. Additionally, compared to standard base oil without SiO_2 NPs, the SN-500 base oil with SiO_2 NPs reduced the friction coefficient by 61%, 55%, and 43% at 0.5 wt. % concentration and 36%, 76%, and 17% at 0.75 wt. % concentration, respectively. The behavior of tribology is closely related to the deposit of nanoparticles on surfaces that rub against each other. At different levels of concentration, the rheological and tribological properties of sunflower oil modified with SiO_2 and TiO_2 NPs as additives to lube were assessed. The impacts of level and shear rate on the shear viscosity have been examined using a parallel plate rheometer, and the experimental results were compared with traditional models. Block-on-ring sliding experiments were used to assess the oil compositions' wear prevention and friction properties. Surface evaluation instruments such as profilometry, EDS, and SEM were utilized to describe the worn surfaces' shape and structure. In comparison to base sunflower oil, the experiments conducted demonstrated that the inclusion of SiO_2 and TiO_2 NPs reduced the coefficient of friction by 77.7% and 93.7%, respectively. Moreover, the inclusion of SiO_2 and TiO_2 nanoparticles reduced the volume loss by 74.1% and 70.1%, respectively [83]. The authors draw

the conclusion that modified sunflower oil augmented with nanoparticles has the potential to be used as a helpful sustainable lubricant considering the findings from the experiments.

Cellulose is currently proved as a creative, sustainable, and ecologically beneficial ingredient in several types of lubricants. The usefulness of nanocellulose as a lubricant in liquid paraffin base oil has been established, displaying higher wear resistance and endurance characteristics as opposed to liquid paraffin without adjustments [84–87]. Experiments were carried out to evaluate the frictional and rheological features of lubricants supplemented with CNCs, which vary from 0.005% to 5.0% by content. Observations demonstrated a gradual decrease of wear scar and coefficient of friction as the CNCs concentration got higher, with optimal effectiveness seen up to a 2% concentration. Nevertheless, reaching this barrier resulted in diminishing benefits due to the emergence of much bigger CNCs agglomerates [88]. Ultrasonic technology is currently employed to boost the functionality of CNCs in water-based lubricants. In contrast to materials that were not exposed to this procedure, examinations indicated that lubricants containing 1% CNCs and exposed to ultrasonic waves exhibited a 30% and 25% decrease in the wear and the coefficient of friction, respectively [89]. Furthermore, it has been verified that cellulose nanocrystals infused with castor oil and utilized in CNCs are promising fillers for cutting fluids. This may be leading to offering superior lubricating qualities and combination stability. It can be indicated that using 0.5% by weight of CNCs or CO-CNCs significantly boosts the frictional characteristics of nanofluids [90]. Moreover, the utilization of cotton-derived CNCs as an addition in poly-alpha olefin (PAO) base oil was assessed at weight percentages varying from 0.1% to 2.0%. The research results demonstrated that incorporating 2.0% of CNCs by weight lowers the coefficient of friction by roughly 30%, showing high viscosity and a consistent, uniform dispersion of nano oil [91]. A study evaluated the efficiency of mixing SAE 40 base oil with CNCs at weight concentrations between 0.1% and 0.9%, paying particular attention to the oil's tribological properties and wear resistance. It can claim that adding 0.1 % weight percent to their CNCs led to a noteworthy 69% reduction in the wear rate and coefficient of friction [92]. Furthermore, it was discovered that the viscosity index of the SAE 40 base oil increased when 1% CNCs were added, indicating an important boost in the oil's viscosity index at this level [93]. The utilization of CNCs as a sustainability ingredient in lubricants has been rigorously examined, and the results have demonstrated that even the lowest quantities of the additive are effective. In particular, the focus is on boosting gear oil's qualities, which includes eliminating friction, strengthening wear resistance, and boosting overall lubrication

efficiency. Despite environmental rules growing increasingly rigorous, there is a rising need to design lubricants that can be extensively used in numerous applications, making our research highly useful for solving these difficulties.

6. CONCLUSIONS

The incorporation of nanocomponents such as Al_2O_3 NPs, cellulose nanocrystals (CNC), and TiO_2 NPs into lubricant formulations. This technology is now applicable to enhance frictional performance, energy efficiency and recognized environmental sustainability. According to this review, these nanoparticles play a major role in lowering wear and friction, increasing load carrying capacity, and stabilizing the lubricant's oxidative and thermal behavior throughout a range of operating circumstances. As inorganic nanoparticles, Al_2O_3 and TiO_2 NPs offer superior surface protection and mechanical reinforcement because of their hardness, thermal stability, and capacity to build protective tribo-films. CNC, on the other hand, provides a bio-based, environmentally benign substitute with good dispersibility and surface reactivity, making it a viable choice for more environmentally responsible lubricating systems. To further optimize lubricating performance, hybrid formulations that blend CNC and inorganic nanoparticles have shown synergistic effects.

Nevertheless, despite encouraging evaluations, issues including compatibility with various base oils, long-term stability, and ideal dispersion methods still pose significant obstacles to practical application. Large-scale testing, life-cycle analyses, and the creation of multipurpose hybrid additives that strike a balance between environmental impact and performance should be the main areas of future research. Whenever considered, nano-scale additives, especially Al_2O_3 , CNC, and TiO_2 NPs, mark a new development in the creation of sustainable and high-performing lubricants appropriate for cutting-edge technological tasks.

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