



BENEFITS AND LIMITATIONS OF NANOMATERIALS AND ADVANCED FRICTION MODIFIERS IN LUBRICANTS AND GREASES

Nanomaterials and other advanced friction modifiers have emerged as promising additives for lubricants and greases due to their increased ability to reduce wear, friction, and overall energy losses in mechanical systems while preserving the lifespan and quality of the base lubricant oil or grease. This paper reviews the current state of research on nanomaterials and other advanced additives, examining their structural classifications, tribological mechanisms, environmental impacts, and ongoing challenges. Nanomaterials that have gained attention, including metals, metal oxides, metal sulfides, carbon-based materials such as graphene, carbon nanotubes, and carbon nano-onions, are evaluated alongside their hybrid nanocomposites. Other prominent advanced friction modifiers, including ionic liquids, organic polymers, and borate-based modifiers, are assessed and compared in addition to nanomaterials. The tribological performance of various additives is analyzed through mechanisms including the rolling effect, polishing, surface repair, and protective tribofilm formation, as well as enhanced thermal and electrical conductivity. Reported studies demonstrate significant reductions in coefficient of friction and wear, indicating the potential of nanolubricants to improve process efficiency, extend machinery lifespan, and reduce energy- and maintenance-related costs. Despite these merits, nanomaterials pose technical complications related to dispersion stability, compatibility with base oils, production costs, and industry-scale commercialization. Toxic waste and other environmental concerns face additive families such as metals and graphene derivatives. Further research developments should continue to focus on optimizing additive concentrations, designing and engineering multifunctional nanocomposites, and integrating artificial intelligence for predictive formulation and smart lubrication systems. As nanomaterials and other advanced additives for lubricants and greases progress, conducting comprehensive life cycle assessments and maximizing environmental sustainability will also be topics for future investigation. Overall, research findings indicate that nanomaterials, especially carbon derivatives such as graphene and carbon dots as well as metal oxides such as titanium dioxide, represent a positive trajectory for current and emerging technology.

1. Introduction

Lubricants and greases are used to improve the operational efficiency of various types of mechanical parts and moving equipment [1]. Lubricants are often composed of mineral-based or synthetic oils and include substances such as motor oils and industrial oils. Greases are similar to lubricants, but they include the addition of a thickener, such as a soap, which allows the grease to exist in a semi-solid to solid state, often operating as a sealing paste [2]. Both greases and lubricants serve to reduce energy losses from friction in machine operations by creating films that separate the surfaces of moving parts. Greases and lubricants further conserve equipment by reducing wear between surfaces in contact, which extends the lifespan of machinery and reduces maintenance costs [3].

Extreme conditions, including high temperatures, high pressure, and shear, can also severely disrupt the typical lubrication quality of a substance [5]. To deal with this problem, additives are mixed into lubricants and greases. Lubricants and greases traditionally have been composed of a base oil

mixed with either soluble additives, such as polymeric viscosity modifiers, dispersants, extreme pressure (EP) additives, and corrosion inhibitors, or insoluble particle additives. While soluble additives completely dissolve in the base oil, modifying the bulk fluid rheology through molecular adsorption, insoluble particle additives alter friction, wear, and other properties through mechanical, as well as chemical, interactions with the base oil. Conventional additive substances often fall short of the standards and regulations set for friction and wear reduction and may raise environmental concerns, pushing researchers to find enhanced additives and pursue nanoparticles as an alternative lubricant ingredient [6]. Because nanoparticles exist on much smaller dimensional levels than do microparticles, nanomaterials have enhanced abilities to interact with both the lubricant or grease solution and the machinery equipment, as demonstrated in studies reported below.

This paper examines the performance advantages and limitations of nanomaterials and other advanced friction modifiers as additives to lubricants and greases. Technical and tribological results, cost effectiveness, environmental benefits and drawbacks, and commercial availability are considered, and future research recommendations are made based on this assessment.

2. Structural Characteristics and Dimensional Classification of Nanomaterials

Nanomaterials are substances that have at least one external dimension that is between 1 and 100 nanometers (see Fig. 1), meaning that their shape can range from minuscule spheres to long, incredibly thin tubes and beyond [8].

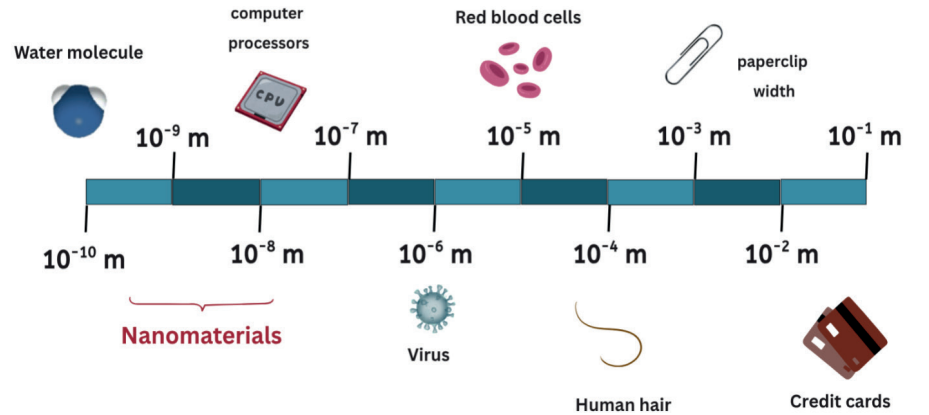


Figure 1: Size of Nanomaterials Relative to Common Objects
Source: [7]

Nanomaterials may be zero-dimensional, a term indicating that these objects hold zero outer dimensions larger than the nanoscale specifications, and instead possess all three external dimensions in the nanoscale, as in spheres, polyhedra, and clusters [9]. They may be one-dimensional, meaning that only two dimensions fit in the nanoscale, as with nanotubes or nanofibers; two-dimensional, with just one dimension that fits in the nanoscale, as with a graphene nanosheet or nanofilms; or three-dimensional, where nanomaterials exist in the bulk, dispersed in a substance (see Fig. 2) [9]. The dimensional classification of a nanomaterial is often directly related to its functional use within a nanolubricant, as the form of the additive determines which mechanism, or combination of mechanisms, a material can exhibit, as described below. These materials may be synthetically engineered or occur naturally, and they may be composed of several elements. Since they have a high surface-to-volume ratio, their chemical and physical properties can often vary from those typical of the substances they represent [10]. Thus, the characteristics of a material in bulk form may vary widely from those of the same material in nanodimensional form, giving nanomaterials the unique qualities that make these additives increasingly useful in industrial fields.

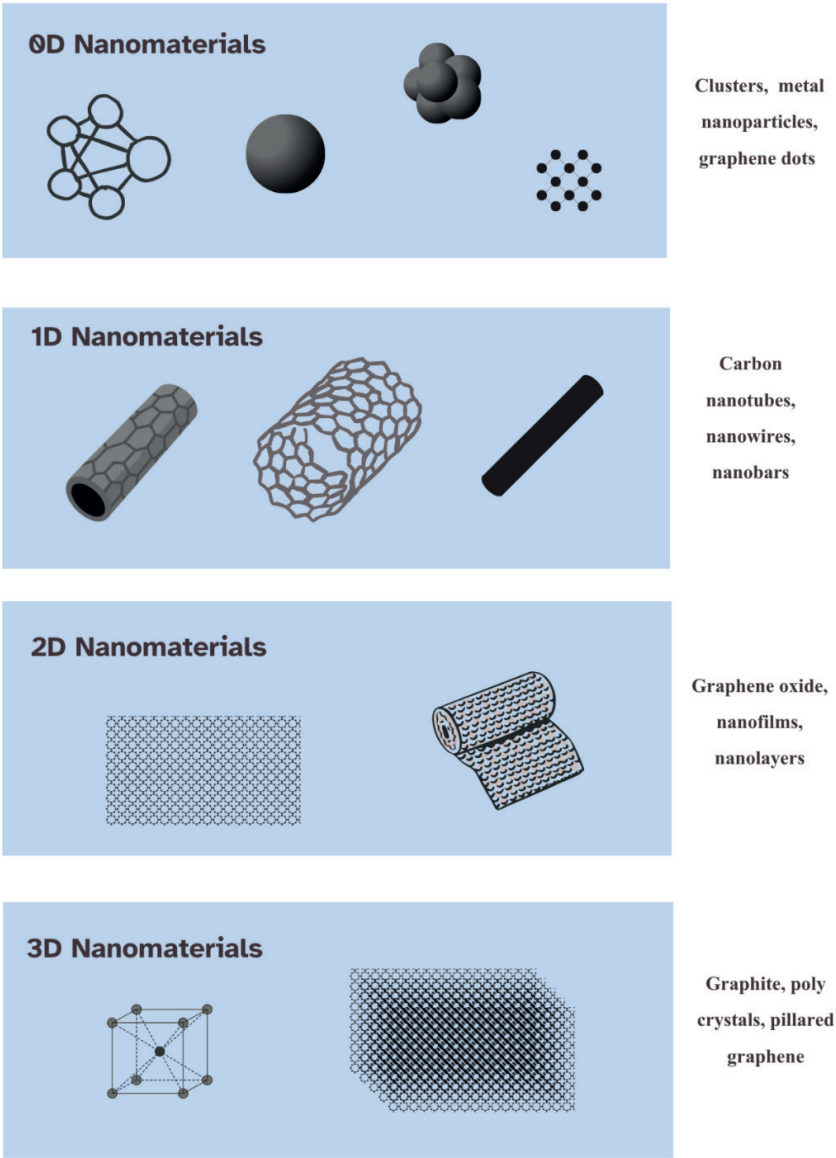


Figure 2: Dimensional Classifications of Nanomaterials
Source: [9]

3. Representative Nanomaterial Systems Explored in Current Research

The primary categories of nanomaterial additives to lubricants and greases are inorganics (including metals, metal oxides, and metal sulfides) and carbon derivatives [11]. Table 1 summarizes the principal classes of nanomaterials investigated as lubricant additives and reveals the breadth of materials currently explored in tribological research. Metallic nanoparticles are primarily valued for their load-carrying capability and thermal conductivity, while metal oxides are beneficial for their chemical stability and potential to form protective surface interactions, and metal sulfides are used for their low shear strength caused by layered crystal structures, a structure that underlies both their interlayer sliding behavior and their tendency to form protective tribofilms, as described in Section 5. Carbon derivatives, on the other hand, are reported to have exceptional mechanical properties, sliding abilities, and environmental compatibility. Other categories include organic nanoparticles and ceramics, also known as non-metal solids [11]. Beyond simple substance additions, experiments have been made regarding composite additives, with varying amounts and ratios of each material [12]. Prevalent metallic nanoparticle additives are copper (Cu), silver (Ag), nickel (Ni), and zinc (Zn). Examples of metal oxides currently used and studied as nanoparticle additives include copper oxide (CuO), zinc oxide (ZnO), titanium dioxide (TiO₂), and aluminum oxide (Al₂O₃) [12]. Metal sulfides that have gained attention include copper sulfide (CuS), tungsten disulfide (WS₂), and molybdenum disulfide (MoS₂) [12]. Other nanomaterial additives may be composites of metals, other inorganics, and organic substances. Another category of nanomaterials that has drawn positive attention for accessibility and lower toxicity than some metallic materials is carbon derivatives, including carbon nanotubes (CNTs), carbon nano-onions (CNOs), and graphene, which consists of a single layer of carbon atoms that are arranged in a hexagonal lattice and exhibit extreme mechanical strength [13,14]. Thus, each category offers its own benefits and drawbacks while some aspects stay constant across classifications; overall, specific nanomaterials and nanocomposites, rather than complete categories, have risen to prominence for lubricant and mechanical transformation.

Composites of nanomaterial additives are engineered to synergistically combine the special properties of individual additives, designed to maximize tribological performance benefits while minimizing cost and toxicity [3,13]. Nanocomposites often have the additional benefit of chemically forming enhanced tribofilm layers through interactions among their components [5]. Examples that have gained attention include composites of graphene (Gr) and derivatives of graphene, such as graphene oxide (GO), reduced graphene oxide (rGO), or graphene nanoplatelets (GnPs) modified with metallic or metal-oxide nanoparticles to maximize chemical synergy and film-forming ability [13]. Research found silver nanoparticles improved agglomeration resistance in graphene-derived nanolubricants, and copper with GO nanocomposites in polyethylene glycol improved wear resistance up to 47% [13].

4. Other Advanced Friction Modifiers as Additives

Beyond nanomaterials, other advanced friction modifiers are currently employed and analyzed as lubricant and grease additives. These include ionic liquids (ILs), borate-based friction modifiers, soluble organo-molybdenum compounds, and other organic friction modifiers (see Table 2) [15].

ILs are salts composed entirely of ions that remain liquid while at or below 100 °C, and they have attracted attention as lubricant additives due to their negligible volatility, high thermal and chemical stability, low melting point, and tunable miscibility with organic compounds [15,16]. At 1 wt%

concentration, imidazolium-based ILs were found to significantly improve the friction-reducing and anti-wear performance of base oils and greases [15]. ILs operate in the boundary lubrication regime, and their polar nature allows them to form strong adsorbed films on the moving surfaces, which reduces wear and the coefficient of friction. Longer alkyl chains allow ILs to create even thicker, ordered films, and under high loads, ILs can decompose and react with metal surfaces to generate further protective tribofilms [15,16].

Borate-based friction modifiers are reported to show a variety of benefits in lubricants due to chemical properties and functional group interactions, including anti-oxidation capabilities, biodegradability, and low levels of toxicity. Studies show borate ester additives have useful capabilities of rust reduction through the reaction between the BO₃³⁻ from the borate ester and iron oxide to form a tribofilm, which diminishes friction [15]. Multifunctional borate derivatives include boron-based dithiophosphate compounds, which are shown to have notable properties of thermal and hydrolytic stability, as well as load-carrying and anti-wear benefits [15].

Organo-molybdenum compounds, including molybdenum dithiocarbamate (MoDTC) and molybdenum dialkyldithiophosphate (MoDDP), which are also common in automotive engine oils, form layered films that provide substantial friction reduction [17]. These compounds reduce friction by creating microplatelets of low shear strength, lattice-layered molybdenum disulfide (MoS₂), mitigating surface asperities [15]. Despite these attributes, MoS₂ generated by MoDTC faces challenges related to low solubility, oxidation, and temperature instability [15]. Organic friction modifiers (OFMs), such as fatty acids and fatty esters, amides and amines, carboxylates and alcohols, and glycerol mono-oleates, are often used in automotive engines and industrial lubricants, where their polar functional groups adsorb onto metal surfaces to form low-friction boundary films that reduce friction, though their efficacy decreases with extreme temperatures [17].

Carboxylates and alcohol derivatives, ether, ester, ketone, mercaptocarboxylate, and thioesters have been shown to be successful friction modifiers in lubricants. Sorbitan esters, especially, have been practical friction reducers, and many derivatives in this category are considered environmentally compatible and sustainable. Glycerol mono-oleate (GMO) is a notable friction modifier for steel-on-steel mechanical systems, and it operates by creating a friction-reducing straight-chain carboxylic acid through the hydrolysis of GMO [15]. In comparison to derivatives of fatty acids or esters, imide-based friction modifiers have enhanced thermal and hydrolytic stability. Furthermore, organic polymers with adsorptive polar functional groups also serve as friction modifiers, altering the bulk fluid rheological properties.

Polymethacrylates (PMAs), as well as functionalized PMA polymers and copolymers, are capable of adsorbing onto both nonpolar hydrophobic and polar hydrophilic surfaces from aqueous solution, working as viscosity index improvers and dispersants as well as friction modifiers [15]. A few ashless phosphorus compounds, including phosphate esters and phosphite esters, phosphonates, and amine salts, are also chosen for several friction modifiers and anti-wear additives [15]. While non-nanomaterial advanced and developing additives, especially ionic liquids, can offer stronger tribological and rheological results than many conventional additives, the unique capabilities of nanomaterials, as well as the wide variety of substances and particles that can be used or combined, continue to promise a comparatively multifaceted and versatile option for lubricant and grease additives.

5. Mechanisms of Tribological Performance Enhancement through Nanomaterials and Advanced Friction Modifiers

Nanomaterials enhance tribology through a wide variety of chemical and physical phenomena, determined through their shape, dimensionality, and chemical composition [18]. The four primary mechanisms through which they reduce friction (see Fig. 3) are the rolling effect, the polishing effect, surface repair, and protective tribofilm formation [20]. Beyond these four, there are other fundamental

Table 1: Prominent Types of Nanomaterials

Metals	• Copper (Cu) • Silver (Ag) • Nickel (Ni) • Zinc (Zn)
Metal Oxides	• Copper Oxide (CuO) • Zinc Oxide (ZnO) • Titanium Dioxide (TiO₂) • Aluminum Oxide (Al₂O₃)
Metal Sulfides	• Copper Sulfide (CuS) • Tungsten Disulfide (WS₂) • Molybdenum Disulfide (MoS₂)
Carbon Derivatives	• Carbon Nanotubes • Carbon Nano-Onions • Graphene • Carbon Dots

Source: [11]

Table 2: Prominent Types of Advanced Friction Modifiers

Borate-Based Friction Modifiers	• Tris(4-Dodecylphenyl) Borate • Borated Aliphatic Amines • Mixed Borate Esters
Organic Friction Modifiers	• Fatty Acids & Fatty Esters • Amides & Amines • Carboxylates & Alcohols • Glycerol Mono-Oleate (GMO)
Organo-Molybdenum Compounds	• Molybdenum Dithiocarbamate (MoDTC) • Molybdenum Dialkyldithiophosphate (MoDDP)
Ionic Liquids	• Phosphonium-Based Ionic Liquids • Ammonium-Based Ionic Liquids • Pyridinium & Pyrazolium-Based Ionic Liquids

Source: [15, 16]

phenomena by which nanomaterials operate within a lubricant or grease. Overall, the results of these effects combined lead to consequential differences in energy use and lubricant and equipment lifespan; the coefficient of friction (COF) and wear scar diameter (WSD) are two measurements often used to quantify the benefits of base oil enrichment. Table 3 maps the principal mechanism or mechanisms associated with several prominent nanomaterials. While numbers vary depending on additive composition and the original base oil used, studies show nanomaterials such as 1 wt% titanium dioxide in polyalphaolefin (PAO) reduce wear by up to 97%, and nanoparticles such as 0.5-5 wt% tin dioxide in PAO reduce the coefficient of friction by up to 65.4% [3,5] (see Table 4).

5.1 The Rolling Effect

The rolling effect, sometimes referred to as the direct or primary effect, describes the mechanism in which spherical nanoparticles serve as small-scale ball bearings and convert sliding friction to rolling friction [20]. Graphene quantum dots (GQDs), as well as carbon quantum dots (CQDs), have

gained attention for their exceptional rolling effects, but generally any spherical nanoparticles can participate in this phenomenon [3,13]. For example, studies have shown ZrO₂/SiO₂ nanoparticles can reduce the coefficient of friction by performing the rolling effect in the zone of friction [20]. Hexagonal boron nitride (h-BN) in SAE 15W-40 has been shown to reduce COF and mechanical wear via the rolling effect, and h-BN in combination with graphene nanosheets has been further shown to optimally improve lubrication [11,13]. Other nanoparticles, which are particularly effective in the primary effect, in combination with other friction-reduction methods, are copper (Cu), titanium dioxide (TiO₂), nanodiamonds, and fullerene-like WS2 [2,11].

5.2 The Polishing Effect

The polishing effect, also called the indirect or secondary effect, characterizes the process in which nanoparticles smooth surface asperities, reducing mechanical wear [20]. The reduction of surface roughness due to the rapid and effective buffing role of nanoparticles significantly minimizes friction and friction-related energy losses [21]. Many particles may simultaneously participate in polishing surface asperities as well as in the rolling effect; nanomaterial categories with hard materials typically excel at the polishing effect, including aluminum oxide (Al₂O₃), TiO₂, nickel (Ni), and copper oxide (CuO) [2,11]. Studies indicate that concentrations of 0.4 to 8.0 wt% TiO₂ are optimal for friction reduction in water-based environments, while concentrations of around 0.3 wt% Cu reduced wear up to 64% in mineral base oils [20].

5.3 Surface Repair

Surface repair, also known as self-mending, identifies the process in which nanomaterials are deposited in openings and fill surface defects that develop through constant operation, improving smoothness and reducing wear [20]. Results have shown that the extremely small additives reduce the topographical roughness of the worn metal surfaces, and the rapid and effective penetration of nanoparticles minimizes mass-loss-related mechanical failures [22]. In addition to particle size, the melting point of the nanomaterial can influence the mending mechanism by affecting their tendency to undergo softening or plastic deformation under frictional contact, allowing some soft metallic nanoparticles to deform and compact to fill wear cracks and surface defects in addition to their other mechanisms [11]. Surface repair may also occur in conjunction with film formation, where nanomaterials fill wear scars through compaction and tribo-sintering and gradually form a protective surface layer as the boundary grease film becomes disrupted during operation [2]. While surface repair is most commonly achieved with face-centered cubic soft metals, other particles may be especially good at participating in deposition, including zinc oxide (ZnO), molybdenum disulfide (MoS₂), Cu, CNTs, and Al₂O₃ [2,11].

5.4 Tribofilm Formation

Finally, tribofilm formation, or the protective film mechanism, refers to the phenomenon that takes place when nanomaterials deposit on mechanical surfaces and form a material layer to reduce contact between multiple moving surfaces [20]. Nanoparticles are shown to form chemical reaction protective tribofilms on the surfaces of metals, which improves the load-carrying capacity of the machinery and reduces its wear [20]. CNTs and CNOs have also been shown to generate tribofilms that protect against wear from rolling and sliding motions [23,24]. Nanomaterials composed of graphene and graphene derivatives participate heavily in both tribofilm formation and, similarly, in tribochemical reactions and adsorption, another mechanism that forms protective layers [13]. Zinc oxide (ZnO) in mineral or soybean oil, CuO, and MoS₂ are notable nanomaterials that produce tribofilms [11].

5.5 Other Means of Friction Reduction

Other prominent means by which nanomaterials and other advanced friction modifiers enhance lubrication include electrochemistry, high surface energy, thermal stability, unique microstructure, and quantum size effects [6,13,18]. Nanomaterials such as silicon dioxide (SiO₂) and silicon carbide (SiC) have been shown to utilize the size effect and the quantum tunneling effect, in which nanoparticles have a finite probability of crossing an energy barrier they otherwise could not, to resist friction and abrasion [6,16]. CQDs have been shown to improve lubricity and load-carrying capacity through unique surface chemistry determined by quantum confinement, which results in discrete electronic energy levels and subsequently altered optical and electronic properties [16]. Metals, metal oxides, and metal composites, especially, have been shown to increase the conductivity of lubricant or grease systems, thereby reducing energy losses associated with charge accumulation and electrostatic interactions at lubricated interfaces [13]. Carbon derivatives and their composites, particularly CNTs and graphene, can also increase electrical conductivity, which, in combination with increased thermal activity, facilitates the beneficial transfer of electrons and heat produced by friction between metal parts [23]. 2D graphene nanosheets particularly have been shown to display superlubricity and induce low-friction states, as weak van der Waals forces between the layers permit near-frictionless sliding [16]. Synergistic chemical bonding between nanomaterials in a composite may further lead to improved viscosity for the lubricant or grease, as one study found with CuO nanoparticles and CNTs in a 10W-40 base oil [20].

5.6 Additional Advantages of Nanomaterials

Beyond friction reduction, nanomaterials provide several other notable benefits to base oils. The extremely small size of nanoparticles means that they often diffuse more evenly than do conventional micromaterial additives, despite their agglomeration tendencies with time [25]. In addition to the electrochemical conductivity exhibited by metals, metal oxide nanomaterials also demonstrate extreme hardness, which improves wear resistance. Silver nanomaterials are shown to have exceptional thermal conductivity and stable operation at high temperatures. Carbon nanotubes specifically are known for elasticity, allowing them to remain durable and functional under extreme physical stress [23]. Nanomaterials such as cerium oxide, silver oxide, and iron oxide increase the anti-oxidation capacity of the base oil, prolonging the lifespan of lubricants and greases and protecting machinery from wear [26]. Nanomaterials also have higher thermal conductivity compared to base oils, improving heat dissipation and reducing the adverse effects of elevated temperatures [25]. Ultimately, nanomaterials have been shown to benefit lubricants and greases by increasing viscosity, pressure distribution, and load-carrying capacity, as well as by decreasing the COF and the WSD [20]. Table 3 lists the primary mechanism(s) for several nanomaterials that have gained popularity, while Table 4 shows a summary of the friction reduction and wear reduction of several prominent nanomaterials and composites, indicating the significant benefits of the adoption of nanolubricants.

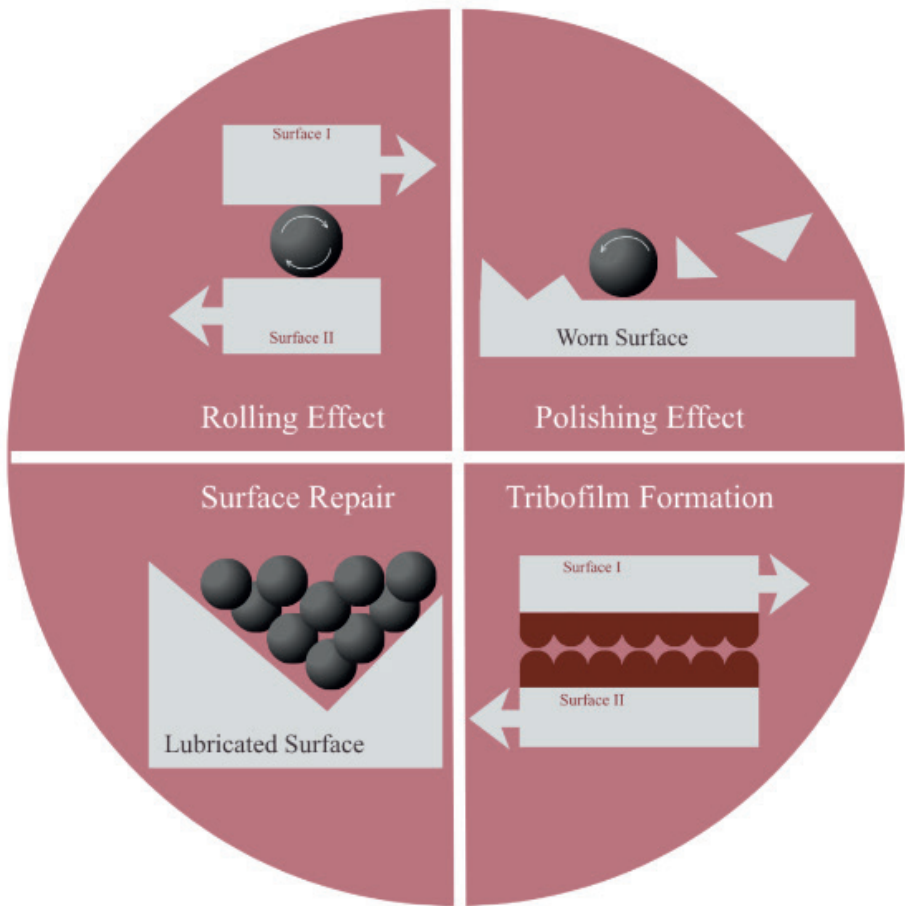


Figure 3: Lubrication Mechanisms of Nanomaterials
Source: [20, 34]

Table 3: Principal Mechanism(s) for Prominent Nanomaterials

Material	Rolling	Polishing	Mending	Tribofilm Formation	Conductivity
WS ₂			●	●	
Cu	●				●
ZnO	●			●	
Al ₂ O ₃	●	●	●	●	
SiO ₂	●		●		
MoS ₂			●	●	
h-BN	●				●
CNTs			●	●	●
TiO ₂	●	●			
CuO	●	●		●	

Source: [11, 13, 25]

Table 4: Comparison of the Effects of Nanomaterial Additives on Friction and Wear

Nanomaterial	Base Oil	COF Reduction	Wear Reduction	Source
TiO ₂	PAO	40%	97%	[3]
ZnO	-	9.9%	31.2%	[5]
CeO ₂	PAO	-	66%	[3]
Al ₂ O ₃	5w30	45%	21%	[5]
SnO ₂	PAO	65.4%	43.7%	[5]
MoS ₂ /GnP	Bio-Oil	60%	50%	[13]
MoS ₂	Diocetyl sebacate	37%	35%	[5]
TiO ₂ /SiO ₂	Palm Oil	-	10.4%	[5]
Al ₂ O ₃ /SiO ₂	PAO 6	20%	-	[5]
Cu/r-GO	PAO	40%	*35%	[13]
GO/CeO	rapeseed oil	36.5%	62.4%	[3]
CuO/r-GO	10w40	46.62%	77.05%	[3]
WS ₂ /GnP	PAO ₄	18%	*20%	[13]
ZrO ₃ /r-GO	Paraffin Oil	28%	*22%	[13]
SiO ₂ /GO	Ethylene Glycol	22%	*25%	[13]

6. Environmental Compatibility and Sustainability Considerations

Nanomaterials and advanced friction modifiers can benefit the environment by increasing the efficiency of mechanical systems, thereby conserving energy and reducing waste [6]. The reduction in wear-induced mechanical failures conserves resources by extending equipment service life and reducing the frequency of component replacement [5]. Furthermore, the incorporation of nanomaterials can enhance lubricant longevity, decreasing the need for lubricant replenishment and disposal [27].

Regarding the environmental compatibility of the additives themselves, carbon derivatives are generally considered more environmentally friendly than many metal-based additives, while some metal nanoparticles raise concerns of triggering toxic metal waste regulations [2]. Silicon carbide specifically has been shown to improve the performance of lubricating grease without changing the chemical composition, maintaining environmental standards [25]. Studies show that oxide nanoparticles may require more energy to produce than other additives and lead to increased carbon emissions, while CNTs may have adverse health effects for human respiratory exposure [28].

Life cycle assessment (LCA) is an international standardized methodology based on the International Organization for Standardization (ISO) 14040 series, and it is often used to study and compare the sustainability of various nanomaterials and other additives over the complete duration of their creation, use, and disposal [8,26]. LCA holistically analyzes the cradle-to-gate, cradle-to-use, cradle-to-grave, and cradle-to-cradle timelines of the nanomaterial, measuring its sustainability, toxicity, and compatibility during each interval (see Fig. 4) [28]. The cradle-to-cradle examination evaluates the recyclability of a nanolubricant, intending to support a circular economy and near-carbon neutrality [27]. LCA studies of nanomaterials inspect the acquisition of raw materials to assess sustainability and availability of resources, the manufacturing process to ascertain the amounts and quality of energy used and the production of pollutants and emissions, the use phase to further understand the emissions and effluents, as well as their impacts on human health and atmospheric toxicity, the end-of-life to compare biodegradability and levels of toxic waste, and recyclability to formulate a circular economy for these materials [15]. Bottlenecks exist, especially in manufacture assessment, as many procedures are commercially confidential, and in recycling, as lubricant or grease additives are often consumed or burned during use and refining, leaving them at low concentrations by the end of their lifespan in the base oil [15,28]. However, most current studies on the sustainability or environmental compatibility of nanomaterial additives are either cradle-to-gate or cradle-to-grave, indicating that complete sustainability analysis covering the entire life, end, and regeneration is a topic for continued research into the benefits and drawbacks of nanomaterials [28].

Nanomaterials continue to require additional LCA research, as incompleteness and inconsistencies complicate comparison and analysis between studies due to the wide variety of methodological approaches and data collection techniques. Nizam et al. reported that current obstacles with LCA models include omission of extra functionalities of the nanomaterial product under observation,

insufficient transparency during the production and manufacture of nanomaterials, and a shortage of characterization methods for some new and developing nanomaterial products [28]. Finally, sustainability is a holistic quality, and there are diverse contributing factors, and the process of determining if an additive is sustainable is far from linear. Non-toxicity, biodegradability, environmental friendliness, energy efficiency, and other contributors do not always align, and researchers must compare the handprint, or lifetime usefulness in lowering energy expenditures, with the footprint, or environmental effects, of a nanolubricant or enhanced additive [27].

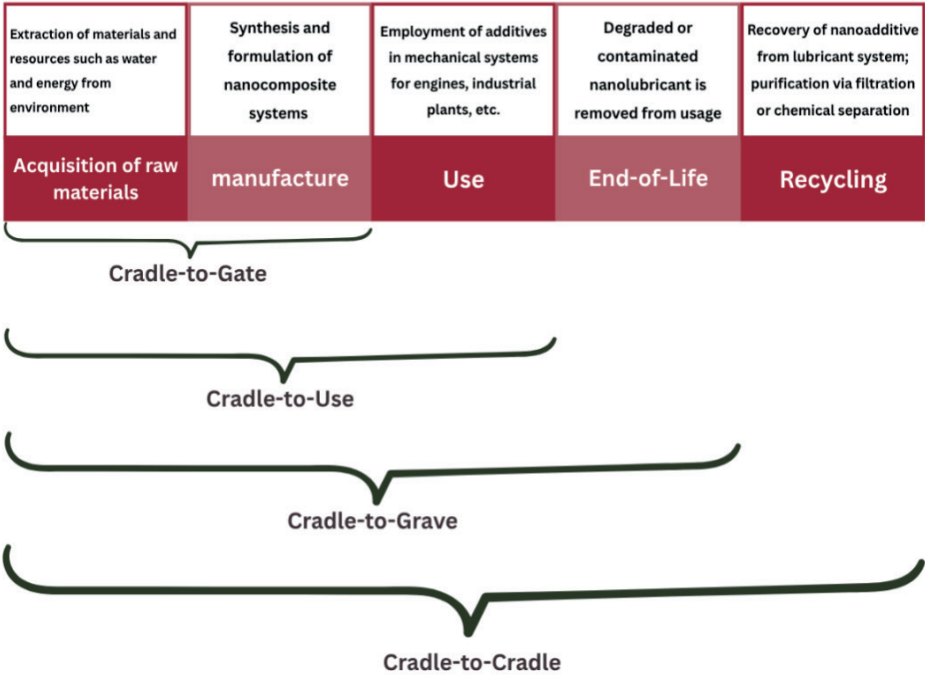


Figure 4: Life Cycle Assessment (LCA)
Source [28]

7. Current Challenges Associated with Nanomaterials and Advanced Additives

The use of nanomaterials as lubricant or grease additives is a developing field, and researchers continue to strategize how best to overcome current concerns, including chemical compatibility, stability in base oils, environmental responsibility, and large-scale production costs [12]. Many challenges are specific to the type of nanomaterial in use, as differences in chemical composition affect their toxicity, scalability, cost, and environmental impact (see Table 5). While many conventional and advanced particle additives face dispersion challenges, dispersion instability is a primary concern for metal oxides due to their high density. Metal chalcogenides, such as MoS₂, WS₂, CuS, and tungsten diselenide (WSe₂), perform most effectively in a vacuum or dry running conditions, as they tend to degrade quickly in wet or oxidizing environments and to oxidize at raised temperatures [18]. Soft metal nanoparticles, such as those made of Cu, Zn, Sn, or Mg, although typically durable and oxidation-resistant, will react with sulfur or chlorine if it is present in the operating environment, leading to rapid corrosive wear [18]. Carbon derivatives such as nanodiamonds, CNTs, graphene and its derivatives, and fullerenes, while heat-resistant and radiation-hard, generally offer lower load-carrying capacity in comparison to metal derivatives and exhibit quickly degrading lubricity in a vacuum or inert atmosphere [18]. Organic or polymeric nanomaterials, conversely, do not exhibit substantial changes in COF values in vacuum, oxidizing, moist, or dry atmospheres, but their low melting point and low thermal

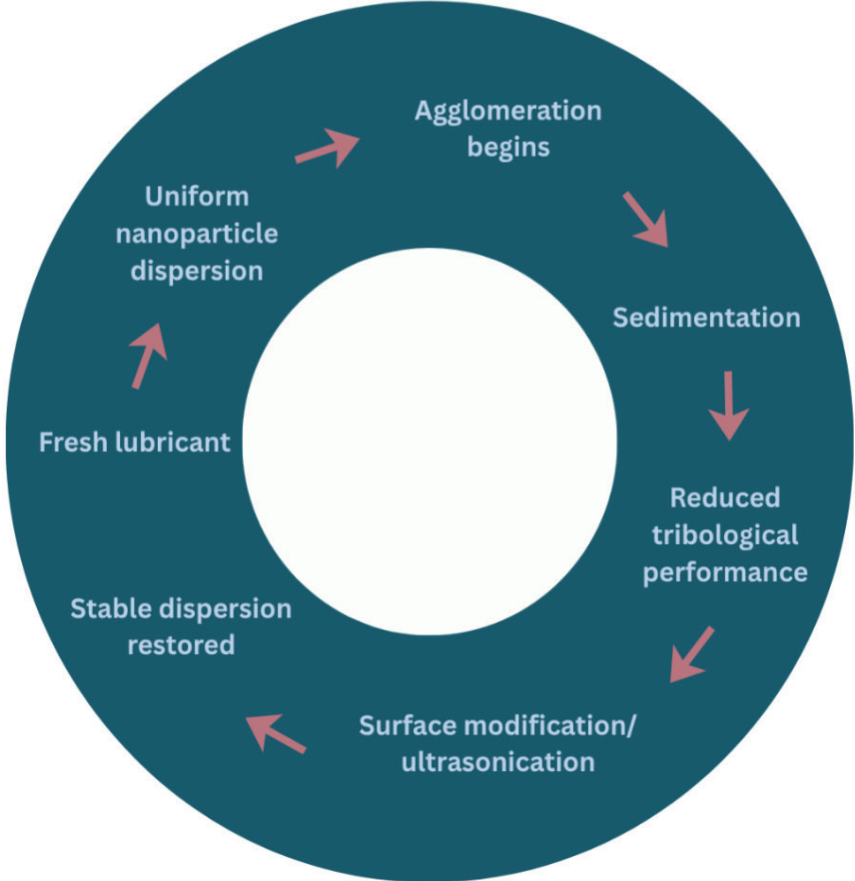


Figure 5: Dispersion Stability Process of Nanoparticles in Base Oil
Source: [2, 18]

Table 5 Summary of Notable Disadvantages of Various Nanolubricant Categories

Nanomaterial Catagory	Primary Disadvantage
Metal Oxides	Dispersion instability
Metal Chalcogenides	Rapid degradation in moist or oxidized environments, readily oxidize at high temperatures
Soft Metals	Rapid corrosive wear if sulfur or chlorine is present
Carbon Derivatives	Lower load-carrying capacity
Organic & Polymeric Materials	Low melting point, low thermal conductivity

Source:[18]

conductivity render them less useful than other nanomaterials in the field [18]. A notable obstacle associated with pure metal additives is that metal nanomaterials, particularly copper, do not display optimal compatibility with base oils due to their high surface activity; surface modification techniques such as chemical functionalization, surface grafting, or physical coating may be utilized to mitigate these complications [20]. Producing pure metal nanomaterials or metal composites that have low toxicity and no negative environmental effects relating to the disposal of their waste is another challenge for industries [2]. Conversely, carbon-based nanomaterials such as graphene and CNTs, while relatively non-toxic and environmentally friendly, carry higher production energy costs than their metal-based counterparts [3].

A challenge that extends beyond metal compounds or carbon derivatives to most nanomaterials is maintaining a stable, uniform distribution of nanoparticles within a grease over time, as the concentration of nanomaterials may become non-uniform due to agglomeration or sedimentation [2]. The stages of this process, from uniform dispersion through agglomeration and sedimentation to restoration by surface modification or ultrasonication, are summarized in Fig. 5. Finally, producing nanomaterials and other advanced additives in large enough quantities to make the financial benefits outweigh the cost is another difficulty that confronts industries as they progress with the adoption of newer and developing additives [18].

8. Future Research Directions and Technological Outlook

8.1 Dispersion, Stability, and Interfacial Engineering

One of the most significant hindrances facing the addition of nanomaterials to lubricants and greases is their tendency to form aggregation and sedimentation, preventing long-term stability in the base oil to which they are added [18]. Destabilizing forces between nanoparticle surfaces, as well as interactions between nanoadditives and base oils, can hinder dispersion, prompting researchers to develop several different methods to mitigate these effects [18].

Two of the more notable approaches for improving nanoparticle stability in base oils are surfactant-assisted dispersion and surface modifications, the latter of which may have additional purposes and benefits beyond dispersion enhancement (see Fig. 6) [18]. While surfactant-assisted dispersion is often more cost effective than surface modifications, and has many well-researched commercially available material options such as SPAN 80, CTAB, and Tween 20, it bears the added risk of negatively altering qualities of the nanomaterials, such as thermal stability and some surface characteristics [18]. Surface treatments often involve chemical functionalizations using organic or inorganic molecules such as ascorbic acid or amines, and though they seldom cause loss of desirable nanomaterial properties, still require additional research to boost scale-up processes and lower costs [13,18]. Physical dispersion techniques, including ultrasonication, often struggle to maintain prolonged dispersion stability, though these and other mechanical methods carry lower risks of compromising structural integrity [3,33]. Alternative strategies include predispersion, where nanomaterials are uniformly mixed into a small portion of base oil before being added to the final lubricant or grease product [2]. Ultimately, research should prioritize discovering optimal methods to promote sustained uniformity and nanoadditive stability for both extended service periods and intense operating conditions.

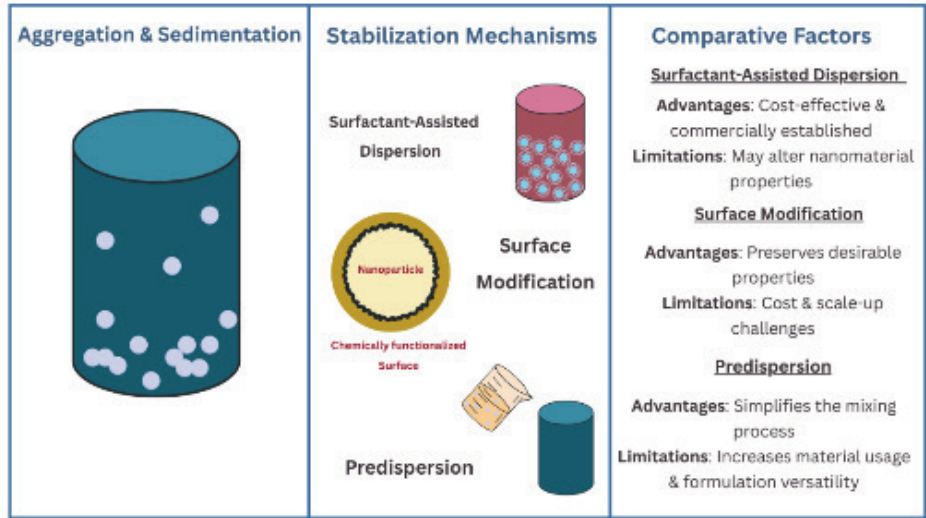


Figure 6: Nanoparticle Dispersion and Stabilization Strategies in Lubricants

Source:[13,18]

8.2 Materials Development and Application Specific Design

In terms of the development and production processes of nanomaterial additives, there are several areas that represent promising avenues for research. Additional techniques and mechanisms for

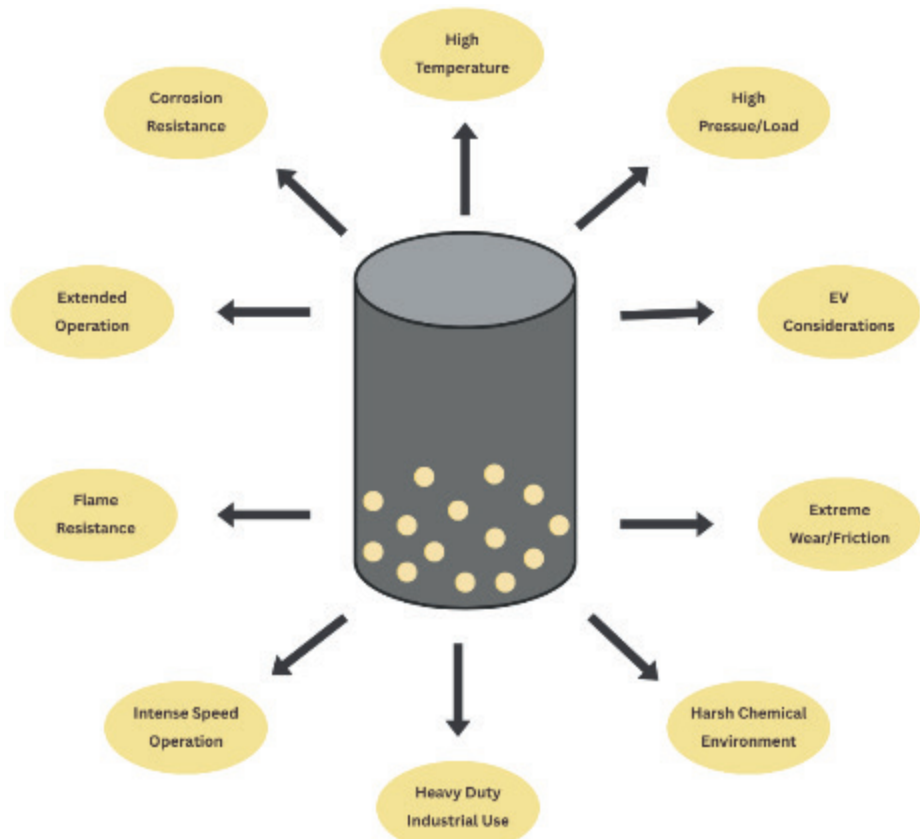


Figure 7: Application Specific Nanoadditive Design

Source: [2, 3, 18]

assessing the extent of surface wear should be developed, as current analysis methods are typically performed after use, and fail to thoroughly evaluate real-time friction and wear behavior at material surfaces [3].

As technology progresses, the creation and fabrication of nanoadditives will increasingly become dependent on the specific application for which their lubricant or grease was intended (see Fig. 7), with lubricant systems being tailored to special conditions such as extremely high temperature or pressure [2,18]. Rapidly expanding technologies such as electric vehicles require tailored nanolubricants to accommodate their special thermal environments and high-pressure operating conditions, which differ from traditional automotive engines [3]. Furthermore, determining distinct nanoadditives that are most suitable for and have the highest chemical and physical compatibility with the given base oil will receive increasing attention from researchers [25]. For instance, MoS2 exhibits peak performance in SAE 50 oil or sunflower oil, while TiO₂ produces maximum compatibility in base oils such as SAE 10W-30 oil, distinctions which are essential for producing ideal lubricant or base multifunctionality and avoiding negative nanoadditive-base oil interactions [25].

Developing nanomaterials that exhibit optimal sustainability and biocompatibility is another important focus area for continuing research investigations. More information is needed concerning the long-term environmental impacts of nanolubricant systems, as well as of the various surfactants and dispersing agents which are used in their production, including any potential adverse effects on human health and safety [33]. Life-cycle assessments (LCAs) require additional research to reveal the most sustainable methods of obtaining raw materials, synthesizing and processing nanosystems, and disposal or recycling of nanolubricant products which have reached the ends of their service lives [28]. This includes analysis concerning the ecological repercussions surrounding the industrial scaling of promising materials and composites [28].

Overall, commercialization can best be accelerated via research in both process streamlining of existing methods to reduce the resource consumption and production costs and the design of new, increasingly scalable processes and techniques for nanolubricant manufacture [3].

8.3 AI Assisted Modeling and Optimization

To improve clarity on the best manner by which to harness the benefits of nanomaterials and other advanced lubricant additives, current and future research may focus on evaluating the optimal concentrations and combinations of constituent substances, as well [13]. Nanomaterial additives may make up anywhere from 0.1% to 30% of a lubricant composition, and the percentage may rise even higher in special cases; determining the ratio of additives that maximizes reductions in friction and wear without causing agglomeration is a key aspect of current and continuing research [5]. Furthermore, modeling may be conducted to ascertain the service life and performance stability of these additives, including dispersion patterns and evolution, as well as the extent to which their functionality degrades over time, as nanomaterial structure and morphology are often altered during chemical functionalization [13,29].

Artificial intelligence (AI) may offer valuable support by enabling rapid predictive modeling of these behaviors, as AI tools can be trained to comprehend and anticipate the behavior of nanomaterials and their composites in various lubricants or greases [29]. Scientists may generate databases to be utilized by artificial neural networks (ANNs) or other artificial intelligence models such as Adaptive Boosting, Random Forest (RF), Ensemble Learning, Decision Tree (DT), or Support Vector Machine (SVM) [30]. Models could be designed to estimate the degradation of the lubricant quality, rate of agglomeration, and viscosity of different nano-aided lubricants and greases as a function of the type of lubricant or grease base oil, the type and amount of nanomaterial added, shear rate, temperature, and solid volume fraction [30]. AI would be particularly useful in the development of smart nanolubricants, or mixtures capable of sensing and responding to variations in pressure, temperature, and/or load to optimize performance in real time [31]. Wang et al. used an ANN to form an optimal nanogrease that utilized a composition of chemically functionalized graphene (FGR) and chemically functionalized carbon nanotubes (FCNT) to synergistically limit friction and wear. In comparison with the base grease, the ANN-designed FGR/FCNT grease was reported to show a 25.66% decrease in WSD and a 29.34% decrease in average friction coefficient (AFC). The WSD,

AFC, carbon content, thermal stability, and interface morphology of the ANN-designed FGR/FCNT grease were all superior to those of the FGR/FCNT grease with amounts determined manually by the human researchers [29]. Beyond smart lubricants and AI usage, compatibility with the environment, especially for metals, and the minimization of the environmental footprint are also strong focuses for continuing and future research [5].

Fig. 8 outlines a roadmap for the research directions outlined above, from novel additive development through hybrid nanocomposites and machine learning optimization toward smart lubricants and a circular economy.

9. Economic Feasibility and Commercial Deployment

9.1 Performance Evaluation and Characterization Techniques

Before the commercial implementation of nanomaterials and other advanced lubricant additives, comprehensive tribological, physicochemical, and surface characterization tests are needed to validate their performance under industrial operating conditions. Fig. 9 summarizes the sequence of this evaluation workflow, from base oil and nanoparticle selection through dispersion, stability testing, tribological testing, and surface characterization to final optimization. Table 6 shows several commonly used testing instruments, as well as the performance parameter they assess and the measurement by which they qualify this parameter. Tribological evaluation is often performed using standardized configurations such as four-ball, ball-on-disk, ball-on-flat, pin-on-disk, and piston skirt-liner tribometers, which measure friction reduction, wear resistance, and load-carrying capacity [2,6,23]. Of these, the four-ball tribometer is the most widely utilized due to its ability to study a broad variety of factors, including COF, WSD, last non-seizing load (LNSL), weld load, load-wear index, lubricity, and extreme-pressure (EP) characteristics [23].

Li et al. employed ball-on-flat testing with a reciprocating AISI 52100 steel ball against an aluminum alloy substrate to provide representative contact conditions for electric vehicle gearbox applications by simulating Hertzian contact stresses and interfacial sliding behavior [24]. Long-term bearing durability, bearing vibration, corrosion resistance, and customized tests for specific applications are further used to assess nanolubricant reliability under practical service conditions [23]. Wear mechanisms are tested using optical microscopy as well as through WSD, and scanning electron microscopy (SEM) further reveals the surface morphology and topographical changes of the operating machinery. Additional surface analytical techniques, including energy-dispersive X-ray spectroscopy (EDS), X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM), identify tribofilm chemistry, nanoscale surface features, and nanoadditive dispersion, while X-ray diffraction (XRD) and Raman spectroscopy provide information on crystalline phases and chemical transformations induced during sliding [22,23]. Finally, thermal and oxidative stability are evaluated using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), resulting in a comprehensive assessment of additive performance and durability for lubricants and greases [32].

Table 6: Research and Industrial Testing for Nanolubricants

Parameter	Measurement/Test	Instruments/Standard	Source
Wear prevention & resistance	WSD, wear rate	Four-ball wear test, pin-on-disk, ball-on-disk	[2], [6]
Load-carrying capacity, EP performance	Max non-seizure load, weld load	Four-ball EP test	[23]
Friction reduction	COF	Four-ball tribometer, pin-on-disk, ball-on-disk	[2], [6], [29]
Surface characterization	SEM	Scanning electron microscope	[23]
Thermal stability	DSC, TGA	Thermal analyzer	[32]
Durability	Long-term ball bearing	Original setup	[23]
Surface wear	WSD	Optical microscope	[23]
Grease consistency	Penetration	ASTM D217	[2]
Crystal structure	XRD	X-ray diffractometer	[21]

9.2 Economic Value and Lifecycle Cost Viability

To assess the economic and industrial value of advanced and alternative lubricant additives, the cost of their production, synthesis, and adoption must be compared with the benefits they exclusively provide. The increased performance of lubricants and greases with nanoparticle additives results in lower energy losses, longer equipment lifespan, and better lubricant stability against extreme conditions, leading to an overall reduction in expenditures on replacement equipment and lubrication, as well as lowering the amount of dissipated energy [25]. Impediments related to wear and lubrication failure are estimated to be responsible for up to 80% of the failures of

machine parts, as well as being the primary cause of aging in mechanical equipment [6,12]. Due to the significant role played by abrasion and drag in a wide variety of industrial processes, the benefits of reducing frictional losses are considerable, with researchers estimating that economic losses related to wear and friction lie between 2% and 7% of the annual gross domestic product in developed countries [12]. The adverse effects of friction and wear have other financial consequences beyond shortened machinery lifespan, such as necessitating more recurrent maintenance within a briefer timeframe, or requiring additional cooling to compensate for overheating generated by excess friction [18].

Despite the lowered operational costs and energy consumption, the use of nanomaterials and advanced friction modifiers can still be significantly expensive compared with conventional lubricant additives [25]. Nanomaterials pose high costs for production, surface modification, and anti-agglomeration methods, particularly because the technology is still emerging and has not yet achieved universal adoption or large-scale manufacturing efficiencies; additional economic challenges hindering implementation include processes to ensure high solubility and quality requirements (see Table 7) [18]. One source estimated these costs to make nanolubricants 10% more expensive on average than conventional lubricants, including both production and life-cycle price increases [18]. However, since the concentrations of nanomaterials within lubricants or greases are relatively quite small, in nearly all cases below 30%, this added cost is only a minor challenge [2,5]. Furthermore, companies may save money on regulatory fines due to potential increased ecological benefits associated with nanolubricant additives; beyond regulatory benefits, the value of saved energy also boosts nanolubricants' favorability [2]. Overall, it is important to weigh the performance value of a specific material against its environmental and economic tradeoffs, as a substance that performs well but is expensive or environmentally demanding may not be commercially viable [31]. Although challenges concerning cost and production remain, current research continues to tackle these complications, and as additional long-term field testing is published, the commercial feasibility of large-scale production and use will become more apparent [25]. As AI develops and enables the creation of increasingly intelligent lubricants, advanced and developing lubricants will become more predictable, useful, and more desirable for industrial applications [33]. Life-cycle assessment (LCA) and technoeconomic analysis (TEA) are both necessary to holistically characterize the value of nanolubricants and nanogreases [13].

Table 7: Examples of Challenges Facing Nanomaterial Additive Implementation
Source:[18]

Regulatory	Field Validation	Environmental Regulations	Standartized Testing Protocols
Commercial	Service Life	Limited Initial Market Demand	Quality
Materials Performance	Dispersibility	Long-Term Stability	Chemical Compatibility
Production Costs	Manufacturing Scale	Small Reactor Size	Surface Modifications

9.3 Production Readiness and Commercial Availability

Nanomaterial additives exhibit considerable variation in both cost and commercial maturity, with manufacturing scale and post-synthesis modifications representing the principal factors influencing economic viability [18]. Table 8 lists several notable additives with their relative cost and stage in development, factors that are influenced by the availability of the additive as well as any additional supplies such as dispersing agents and the standardization of material specifications [13].

Carbon derivatives, especially high-purity, layered graphene sheets, nanodiamonds, and fullerenes, are generally more expensive due to limitations in scalable production, purification, and quality control processes [33]. CQDs, CNOs, graphene nanoparticles, and rGO, while often more costly than metal and metal oxide particles, are moderate compared with the higher-purity carbon-based materials, and generally the production costs associated with carbon derivatives may change substantially with commercial scale [3,33]. Overall, most carbon derivatives are available for commercial use, while some carbon hybrids are still in the research and development phase, and many are still undergoing optimization testing [3,34].

Most metal and metal oxide nanoparticles are readily available at relatively lower costs of production, though precious metals such as gold (Au) and silver (Ag) create high-expense nanoparticles [2]. Copper (Cu) and molybdenum disulfide (MoS2) have received extensive research and have been accessible for an extended time compared with other nanoparticles [34,35]. Hexagonal boron nitride (h-BN), MXenes (2D metal carbides, nitrides, and carbonitrides), and new nanomaterials facing development for electric vehicles and anti-agglomeration purposes are still undergoing research and development and may be less available for industrial use [34]. These, as well as inorganic fullerene-like tungsten disulfide (IF-WS2), are relatively more expensive due to their research status and lower levels of production [2,23,34].

Finally, this cost and commercial readiness analysis reflects the behavior of these nanomaterials in traditional lubricants; when incorporated into biolubricants, the same materials often behave differently, requiring additional testing and modifications that may increase costs and lower availability [25]. Further manufacturing considerations that impact cost and availability include reproducibility, quality control, and storage and handling requirements.

- 1 Select base oil
- 2 Select nanoparticle
- 3 Surface functionalization
- 4 Dispersion into lubricant
- 5 Stability testing
- 6 Tribological testing
- 7 Surface characterization
- 8 Performance comparison
- 9 Optimization

Figure 9: Experimental Evaluation Workflow for Nanolubricants

Table 8: Comparison of the Cost and Commercial Readiness of Notable Additives

Nanomaterial	Commercial Availability	Relative Cost	Source
CQDs, CNOs	Rapid development, partial availability	Moderate	[3, 35]
Spherical WS ₂	Available	Low	[34]
Spherical Cu	Most available	Low	[25, 34]
Graphene dots, rGO	Available	Moderate	[33]
Graphene sheets	Available	High	[33]
TiO ₂ , Al ₂ O ₃ , ZnO, CuO	Available	Low	[25, 2]
MXenes	Research & development	High	[34]
MoS ₂	Most Available	Low	[25, 35]
h-BN	Research & development	High	[34]
IF-WS ₂	Rapid development, partial availability	High	[2]
Au, Ag	Available	High	[2]
Fullerenes	Available	High	[33]
Nanodiamonds	Available	High	[33]

10. Final Conclusions

Nanomaterials and other advanced additives such as ionic liquids represent a prominent advancement in the production of lubricants and greases by providing increased tribological performance improvements. The nanoscale dimensions of particles, including metals, metal oxides, and metal sulfides, as well as those of graphene sheets and carbon nanotubes, and the unique chemical and physical capabilities of both nanolubricant additives and other advanced friction modifiers enable multiple friction-reduction mechanisms. These processes, including rolling, polishing, surface repair, and tribofilm formation, in addition to other benefits offered by nanomaterials such as increased surface energy, the quantum size effect, increased conductivity, thermal stability, and elasticity, work individually and synergistically to improve lubricant and grease quality and lifespan. Titanium dioxide, graphene oxide, and aluminum oxide especially have been shown to significantly decrease the COF and WSD while improving load-carrying capacity and enhancing thermal and oxidative stability.

While laboratory studies report impressive reductions in COF and wear, widespread industrial implementation remains constrained by challenges related to additive dispersion, long-term stability in base oils, environmental considerations, manufacturing costs, and practical scalability. Thorough life cycle assessments and standardized testing procedures, including tribological and physicochemical analysis, component bench tests, and field trials, will be essential for accurately evaluating the sustained value of these materials.

Further research should prioritize the optimization of nanomaterial composition, concentration, and hybrid formulation while leveraging computational modeling and artificial intelligence, particularly artificial neural networks, random forest models, or support vector regression, to accelerate additive design and predict long-term nanolubricant performance and behavior. Continued analysis of environmentally benign materials, recyclable lubricant systems, and smart nanolubricants capable of adapting to complex operational conditions will further elevate the practicality of new additive technologies. As production methods mature and costs decline, nanomaterials and other advanced additives have the potential to substantially shape effective industrial operations through improved machinery, reduced energy consumption, and lowered maintenance costs.

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