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REVIEW ARTICLE

Engineering Various Morphologies of 2 Dimensional Nanomaterials for Enhanced Nanolubricant Efficiency: A Review

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Abstract

A revolutionary method for addressing issues with contemporary lubrication systems, such as wear, friction, and thermal instability, is the incorporation of 2- dimensional (2D) nanoparticles as additives in nanolubricants. The 2D nanomaterials are perfect for improving the tribological performance of lubricants because of their special qualities, which include high specific surface area, great thermal conductivity, and remarkable chemical stability. However, these materials' dimensional morphology - which includes forms like sheets, flakes, nanospheres, and nanoflowers - is crucial in defining how they interact with base oils and contact surfaces, which in turn affects how effective they are as nanolubricant additives. This work offers a thorough analysis of the synthesis processes - such as chemical vapor deposition, hydrothermal synthesis, solvothermal procedures, and exfoliation techniques - that are used to create various dimensional morphologies of 2D nanomaterials. Every synthesis technique is evaluated for its impact on the structural and functional characteristics of the final nanomaterials, scalability, cost-effectiveness, and morphological control. The connection between dimensional morphology and tribological performance is also examined, emphasizing the ways in which particular morphologies support base oil dispersion behavior, wear resistance, friction reduction, and thermal stability. Concerning scalability, affordability, and compatibility with different lubricant formulations, the review also highlights the present difficulties in creating and applying 2D nanomaterials in nanolubricants. The development of next-generation nanolubricants with specific qualities for industrial and automotive applications is finally advanced by suggesting future research areas. The significance of morphological optimization and synthesis processes in utilizing the complete potential of 2D nanomaterials for high-performance lubricating systems is highlighted by this work.

Keywords: Anti-wear, Dispersion stability, Friction reduction, Lubrication mechanism, Morphologies, Nano-MoS_2, Nanomaterials, Nanolubricant

Introduction

The development, synthesis, characterization, and use of materials and devices by altering their size and shape at the nanoscale is known as nanotechnology. The term "nanometer" was coined by Richard Adolf Zsigmondy in 1914 [1]. The precise idea of nanotechnology was first presented in 1959 by American scientist and Nobel Prize winner Richard Feynman [2]. Materials are defined as nanomaterials if their size or one of their dimensions is in the range of 1 to 100 nm [3].

The need for ecologically friendly and energy-efficient solutions is increasing, which has accelerated research into sophisticated lubricating systems. High-performance machinery problems like wear, friction, and thermal instability may be resolved with nanolubricants, which use nanoscale additives to improve the performance of traditional lubricants.

Due to its special qualities, such as high specific surface area, superior thermal conductivity, and outstanding tribological performance, 2-dimensional (2D) nanomaterials have attracted a lot of interest among the various additives[4]. These characteristics make 2D nanomaterials perfect for use in a variety of industrial and automotive applications as nanolubricants.

Two-dimensional nanomaterials' shape has a significant impact on how well they work in nanolubricants. These materials' size, shape, and structural arrangement - known as their dimensional morphology - have a significant impact on how they interact with base oils and contact surfaces. The tribological behaviors of various morphologies, including sheets, flakes, nanoflowers, and nanospheres, vary[5] .

For example, sheet-like structures enable smooth layer-to-layer sliding, effectively reducing friction, while spherical morphologies function as rolling elements, helping to minimize wear. Optimizing and understanding these morphologies is essential for designing high-performance nanolubricants suited to specific operating conditions[6]. One of the most difficult yet essential aspects of using 2D nanomaterials is creating them with regulated dimensional morphologies[7]. Several synthesis processes have been developed to generate desired morphologies, including hydrothermal synthesis, solvothermal methods, chemical vapor deposition (CVD), and exfoliation[8] . Every technique has its own benefits and drawbacks with regard to morphological control precision, cost, and scalability. For instance, CVD enables the creation of superior monolayer 2D materials, whereas solvothermal and hydrothermal methods offer more versatility in the creation of flower-like or hierarchical structures[9] . The final nanoparticles' physical and chemical characteristics are greatly influenced by the choice of synthesis method, which also affects how well they work as nanolubricant additives.

An extensive study of the synthesis techniques and dimensional morphologies of 2D nanomaterials utilized as nanolubricant additives is the goal of this paper. By investigating the connection between synthesis methods, morphological traits, and tribological performance, this study aims to demonstrate how 2D nanomaterials have the potential to completely transform the lubrication industry. Next-generation nanolubricants with improved sustainability and efficiency will be developed as a result of the review's identification of present issues and potential research avenues through interlayer exfoliation, effectively reducing friction[10] .

Overview of nanolubricants

Nanolubricants are made by adding nanoparticles or nanomaterials to lubricants as shown in Figure 1. They usually have a particle diameter of 1 - 100 nm[11]. The use of nanolubricants in base oils or coatings has been shown in lab experiments to significantly reduce wear and friction, exhibiting intriguing tribological features. There are two ways to create nanolubricants: 1-step and 2-step methods. The nanolubricants are made immediately by a chemical procedure in the 1-step approach [12]. The 2-step process involves first creating the nanomaterials as a dry powder using physical or chemical procedures, and then dispersing them into base oil using a combination of techniques with or without surfactants or dispersants[13].

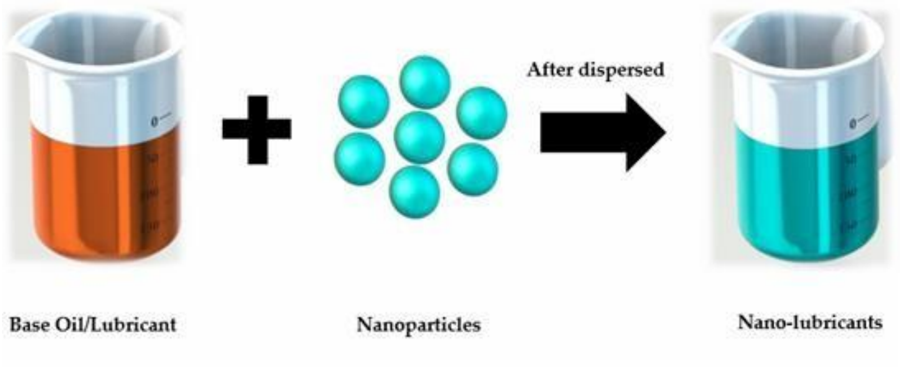

Figure 1 Formation of nano-lubricants [14].

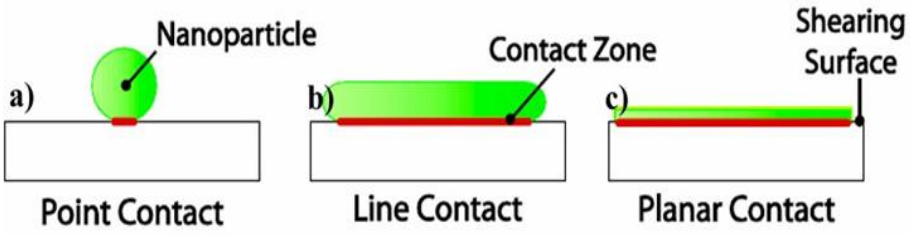

Figure 2 Effect of nanoparticles shape upon loading [14].

Figure 2 shows the Schematic diagram of the effect of nanoparticles shape upon loading a) point contact b) line contact c) planar contact.

Significance for lowering friction and wear

Wear and friction are the two main causes of component failure, increased energy consumption, and decreased efficiency in mechanical systems[15] . By creating a lubricating layer between moving surfaces, conventional lubricants lower friction. However, in harsh operating circumstances such high temperatures, pressures, and shear rates, they are limited[16] . These difficulties are addressed by nanolubricants utilizing the special qualities of nanoparticles, including: (1) Increased Capacity for Load-Bearing: By functioning as tiny ball bearings, nanoparticles can lessen the amount of direct contact between surfaces. (2) Enhanced Thermal Stability: Nanoscale additives improve heat dissipation, which is essential for preserving lubricant performance in hot environments [17], [18], [19]. (3) Self-Healing Properties: Certain nanomaterials have the ability to reduce wear by filling in surface microcracks and grooves .

Limitations of conventional lubricants and the contribution of additives

Insufficient Thermal Stability: Traditional lubricants break down quickly at elevated temperatures, resulting in reduced viscosity and diminished lubrication effectiveness [20]. Suboptimal Friction Reduction: The larger molecular size of conventional additives limits their ability to effectively reduce friction at the nanoscale. Inadequate Wear Resistance: Conventional lubricants often fail to provide robust protection under extreme load and high-speed conditions Environmental Impact: Many conventional lubricants contain non-biodegradable and toxic additives, raising concerns about environmental safety. Susceptibility to Degradation and Oxidation: Over time, conventional lubricants undergo oxidation, leading to sludge formation and a decline in performance. Additives are widely utilized to address the shortcomings of conventional lubricants and improve their overall performance[21], [22] . They fulfill various critical roles, including: (1) Anti-Wear Additives: Form protective layers on surfaces to reduce wear. (2) Viscosity Modifiers: Ensure stable viscosity across different temperature ranges. (3) Oxidation Inhibitors: Protect against degradation caused by oxidation. (4) Detergents and Dispersants: Inhibit sludge buildup and maintain system cleanliness. Despite their effectiveness, traditional additives often fall short under[23].

Unique properties of 2D nanomaterials

Two-dimensional (2D) nanomaterials possess remarkable characteristics that make them highly effective as additives in nanolubricants. These properties include: (1) High Specific Surface Area: Their extensive surface-to-volume ratio enhances interaction with base oils and surfaces, boosting lubrication performance. (2) Excellent Thermal Conductivity: Superior heat dissipation properties help regulate operating temperatures and prevent thermal degradation. (3) Layered Structure: The sliding ability between layers minimizes friction and reduces wear[24], [25], [26], [27].

(4) Chemical Stability: Strong resistance to oxidation and corrosion ensures durability and long-lasting performance.

Examples of 2D nanomaterials: Numerous 2D nanomaterials have shown great promise as nanolubricant additives, including: Titanium Dioxide (TiO_2): Noted for its exceptional durability and thermal stability. Zinc Oxide (ZnO): Provides superior anti-wear and anti-corrosion properties. Tungsten Diselenide (WSe_2): Delivers excellent friction reduction and wear resistance. Tungsten Disulfide (WS_2): Known for its ultra-low friction and high load-carrying capacity. Molybdenum Diselenide ($MoSe_2$): Combines chemical stability with efficient friction reduction. These 2D nanomaterials, with their unique capabilities, significantly enhance the performance of nanolubricants across a wide range of operational conditions[28] .

Importance of dimensional morphology [115]

The morphology of nanoparticles (NPs) plays a vital role in nanolubricants, affecting their load-bearing capacity and interaction with friction surfaces. NPs commonly exist in 5 forms: Spherical, granular, sheet, onion, and tube, with spherical NPs being the most prevalent[29] . After nucleation, crystalline structures adjust to minimize surface energy, favoring a spherical shape when the energy is isotropic, which enhances the rolling mechanism between friction surfaces[30]. Spherical NPs create point contact, nanosheets enable line contact, and nanoplatelets exhibit planar contact with lubricated surfaces[31], [32], [33], [34]. Onion-shaped NPs combine internal lamellar and external spherical structures, with their stability influencing tribological performance - stable onions retain a spherical shape, while exfoliation converts them into sheets[35]. Their lack of dangling bonds minimizes reactivity and agglomeration, improving lubricant efficiency [36]. Sheet-like NPs, such as graphene, transition metal dichalcogenides, ZrP, and hBN, facilitate lubrication. The development, synthesis, characterization, and use of materials and devices by altering their size and shape at the nanoscale is known as nanotechnology[37]. The term “nanometer” was coined by Richard Adolf Zsigmondy in 1914. Sheet-like NPs, such as graphene, transition metal dichalcogenides, ZrP, and hBN, facilitate lubrication.

Types of 2D nanomaterials for nano lubricants

Graphene and its derivatives

Graphene additives

Excellent mechanical qualities of graphene allow it to be utilized as a lubricant additive to protect the surface in frictional contact. The lubricating film’s ability to support loads may also be improved by lowering the local temperature of the friction pairs due to graphene nanosheets’ strong thermal conductivity[38], [39], [40], [41]. Also helpful in enhancing its tribological characteristics is the weak interlayer interaction. Recently, a magnetorheological fluid (MRF) was treated with graphene to enhance its rheological and tribological characteristics.

GO additives (graphene oxide additives)

Since GO dissolves in water without the need for surfactants or dispersants, it is always used in lubricants that are based on water. Numerous factors, including the GO solution’s pH, concentration, and degree of oxidation, among others, influence the tribological characteristics of the GO water-based lubricant additive. For example, GO nanosheets with varying levels of oxidation that were made by adjusting the oxidizing agent concentration and reaction conditions showed a range of lubricating properties[42] . These phenomena are mostly explained by the fact that GO with a high degree of oxidation has more functional groups that contain oxygen and a wider layer spacing. These factors influence the development of protective and adsorption films as well as the materials’ tribological characteristics. By interlaminate shearing, GO nanosheets can enhance engine oil’s lubricating properties[43]. Furthermore, GO is non-toxic and anticorrosive, which makes it a potential material for a wide range of mechanical applications.

However, adding GO to certain non-polar solvents results in a severe agglomeration and restack phenomenon that somewhat impairs its tribological performance and even causes wear [44]. Reducing the oxygen-containing functional groups on GO nanosheets is an attractive approach to address this issue. Thus, research has been done on reducing GO to rGO using various reduction techniques[45].

rGO additives (reduced graphene oxide)

rGO demonstrated good dispersibility in Trimethylopropane trioleate (TMPTO) and Polyalphaolefin (PAO) 40 base oil at different concentrations and maintained stability for 244 h at a 0.25 weight percent concentration [46]. In contrast, GO nanosheets were less dispersible in oil than rGO, as evidenced by the fact that, even though they could disperse in TMPTO and PAO 40 base oil with sonication, subsidence occurred after just 24 h. With 20 and 24 % decreases in wear track widths, respectively, the tribological tests demonstrated that the TMPTO and PAO 40 base oils containing 0.25 weight percent rGO had the best antiwear qualities.

GO was decreased by hydrazine monohydrate in a different study, and the resulting compounds were added to lubricating grease[47], [48], [49], [50]. Grease's improved tribological qualities were noted. With the help of KOH, GO is utilized as a precursor to create ultra-high exfoliation rGO (UH-rGO) by thermal reduction. It is then added to PAO_6 oil and hydraulic oil as a lubricant. The UH-rGO exhibits a unique 2-dimensional layered microstructure with a large specific surface area, minimal agglomeration and restack, and long-term stability in lubricants. It can also significantly improve the tribological characteristics of lubricants in terms of anti-wear and anti-friction because of the sliding- oriented transformation of UH-rGO.

Hexagonal boron nitride

Hexagonal boron nitride (h-BN) has gained significant attention due to its unique properties. It consists of 2D boron and nitrogen atom layers, where strong intralayer covalent bonds provide high tensile strength and stiffness, making it suitable for high-contact-pressure applications. Meanwhile, weak van der Waals forces between layers enable easy shearing along the basal plane, contributing to its excellent lubricating performance[51], [52]. Despite these advantages, h-BN has poor dispersion stability in lubricants, limiting its effectiveness[53]. Researchers have explored dispersants and surface modifications to enhance its stability. Polyisobutylene succinimide significantly improved dispersion, and nano-sized h-BN particles exhibited better wear resistance than their micro-sized counterparts. Additionally, surface modification using the silane coupling agent A-151 improved lipophilicity, enhancing dispersion stability and boosting anti-wear and friction-reducing properties in castor oil.

To improve compatibility with lubricants, h-BN nanosheets (h-BNNSs) - single- or few-layered versions of h-BN - have been widely studied. In Figure 3, Exfoliating bulk h-BN powders with NaOH/KOH hydrothermal treatment produced h-BNNSs with superior dispersion.

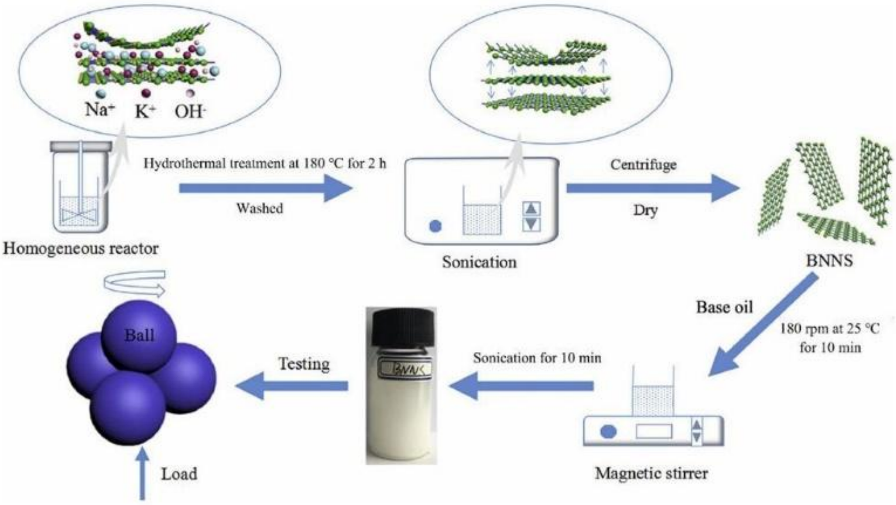

Figure 3 Schematic illustration of preparation process and performance testing of exfoliated BNNSs [54].

Their incorporation into base oil reduced the coefficient of friction (COF) and wear scar density (WSD) by approximately 35.7 and 35.2 %, respectively. Ball-milled h-BNNSs further demonstrated excellent friction reduction and wear resistance[55] . However, interlayer slippage and incompatibility with base oils often lead to agglomeration, negatively affecting tribological performance. Chemical functionalization has emerged as an effective strategy to prevent clustering and ensure stable dispersion in lubricants[56], [57]. **Table 1** summarizes the comparative analysis of 2D nanomaterials for nano-lubricants.

Table 1 Comparative analysis of 2D nanomaterials for nano-lubricants.

Nanomaterial Additive	Main Characteristics	Lubrication Mechanism	Key Benefits	Challenges & Drawbacks	Ref
Graphene Additives	High mechanical strength, excellent thermal conductivity	Forms a protective film, reduces friction and wear	Enhances load-bearing capacity, improves heat dissipation	Prone to agglomeration in certain solvents, dispersion issues	[58]
Graphene Oxide (GO) Additives	Water-dispersible, rich in oxygen-containing functional groups	Creates adsorption and protective layers, enables interlaminate shearing	Non-toxic, anti-corrosive, effective in water-based lubricants	Agglomeration in non-polar solvents, tribological properties depend on oxidation level	[59]
Reduced Graphene Oxide (rGO) Additives	Improved oil dispersibility, enhanced stability in lubricants	Facilitates sliding-oriented transformation, enhances anti-wear and anti-friction performance	Maintains stability in base oils (PAO, TMPTO), significantly reduces wear	Requires a reduction process, limited dispersion in specific oils	[60]
Hexagonal Boron Nitride (h-BN)	Soft material with strong in-plane bonding and weak interlayer forces	Shears along basal planes, providing effective lubrication	High resistance to wear, performs well under high pressure	Poor dispersion in base oils, agglomeration concerns	[61]
Hexagonal Boron Nitride Nanosheets (h-BNNSs)	Exfoliated ultra-thin layers for enhanced dispersion	Reduces coefficient of friction (COF) and wear scar diameter (WSD)	Superior dispersibility in lubricants, excellent anti-wear properties	Needs chemical functionalization for long-term stability, interlayer slippage can affect performance	[62]

Other emerging 2D nanomaterials

Black phosphorous

A peculiar substance that has garnered a lot of scientific interest is black phosphorus (BP). Because of its unique characteristics, which include weak interlayer contacts, an anisotropic lamellar structure, good thermal stability, an adjustable bandgap, and high carrier mobility, BP can be used as a liquid lubricant additive in a variety of applications, including tribology[63] . Few-layer BP is now a viable lubricant additive due to its strong heat stability and low shear strength. Several recent advances in the tribological performances of BP nanosheets have addressed their lubricating mechanisms and micro-friction characteristics when used as additives in lubricants that are based on water or oil.

A silicon nitride tip was used to examine the nanofriction characteristics of BP sheets that had degraded. Due to environmental degradation, the lubrication behaviors of the BP flakes significantly improved and there was less friction in the degraded area of the BP nanosheets [64]. Significantly, a synergistic effect between water and the chemical groups formed on the oxidized surface was seen; this could explain why the deteriorated BP flakes exhibited less friction. Investigations were conducted into the tribological performance of BP in conjunction with composites based on polytetrafluoroethylene [65]. The test findings demonstrated that BP considerably lowered the composites' wear rate. On the contact surface, transfer-film formation was thought to be the lubricating mechanism of BP [66].

In general, the practical application of BP is hindered by its environmental instability. To tackle this issue, various approaches have been suggested, including passivation layer protection, organic compound modification, and metal nanoparticle augmentation. Furthermore, BP has gained popularity among academics due to its strong performance as a lubricant additive in the field of super lubricity in recent years. BP nanosheets that have been altered by NaOH may become super lubricating when serving as additives for lubricants based on water [67].

A research of macroscale super lubricity was conducted by dispersing BP quantum dots (BPQDs), which were manufactured with an average lateral size of 6.5 ± 3 nm and a thickness of 3.4 ± 2.6 nm, in ethylene glycol (EG). The BPQD-EG aqueous suspension was found to establish a macroscale super lubricity state at a high contact pressure of 336 MPa, and its wear rate under lubrication at the Si_3N_4/sapphire frictional interface was 5.96 % that when using EG aqueous solution lubricant. The exceptional anti-wear and lubricating action is thought to have been induced by the oxidative products of BPQDs, the low shear stress between the BPQD interlamination, and the rolling impact of BPQDs.

Layered double hydroxides

Using micro emulsification to modify the hydrothermal reaction time, 3 different kinds of nanosized Ni-Al layered double hydroxides (LDHs) were created[68] . Utilizing atomic-force microscopy and transmission electron microscopy, the materials' 3-dimensional nanoscale architectures and layered structures were revealed. A gas-to-liquid 8 (GTL8) base oil was mixed with the samples as lubricant additives, and the samples' tribological performance under various loads was assessed using a ball-on-disk tribometer [69].

The anti-wear performance was enhanced and the COF was decreased by around 10 % with the addition of nano-LDH at a contact pressure of 2.16 GPa. As illustrated in **Figure 4**, the bigger nanoplatelets (NiAl-24 h) had exceptional tribological characteristics, which were ascribed to their better crystallinity and the creation of a tribo-film with distinct mechanical characteristics under frictional conditions. The study in **Figures 4(a)** and **4(b)** used 2 types of lubricant containing 1 weight percent (wt%) Nickel-Aluminum Layered Double Hydroxides (Ni-Al LDHs).

These LDHs were prepared with different hydrothermal reaction times: 24 h (NiAl-24 h) and 6 h (NiAl-6 h).

The lubricants were tested under a load of 100 N, see Figure 4(c) and 4(d), to simulate real-world conditions. The focus is on analyzing the wear track - the area on the surface that experiences wear due to sliding. The diffraction patterns in **Figures 4(b)** and **4(d)** most likely reveal variations in the crystalline structure, indicating that a weaker or less ordered material is produced by the shorter reaction period

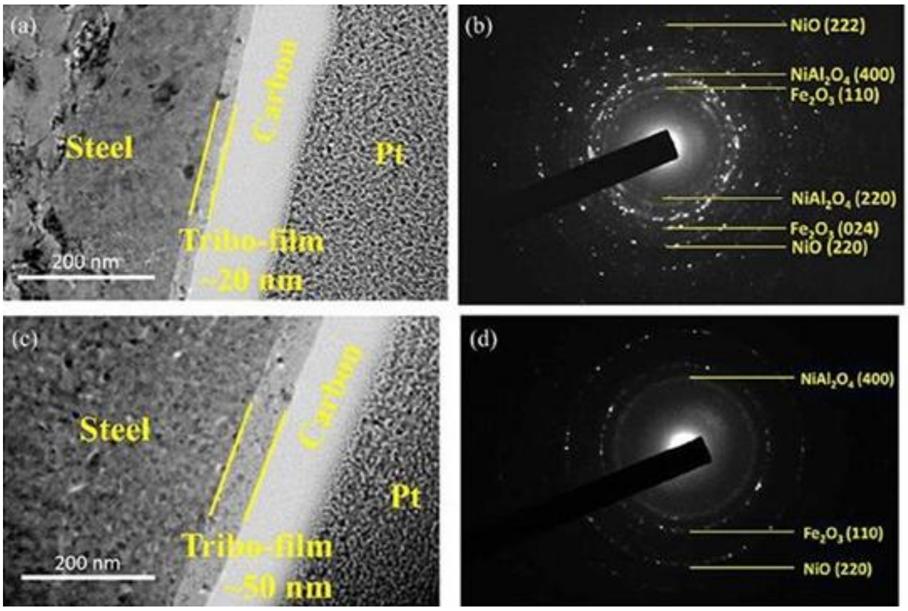

Figure 4 Analysis of tribofilm formed on the wear track lubricated by (a,b) 1 wt% Ni- Al LDHs with a hydrothermal reaction time of 24 h (NiAl-24 h) and (c,d) 1 wt% Ni-Al LDHs with a hydrothermal reaction time of 6 h (NiAl-6 h) at 100 N. (a,c) Cross-sectional TEM images and (b,d) diffraction patterns of tribofilm [54].

As such, nano-LDHs have great tribological properties and a lot of promise for use as lubricant additives in industrial settings[70] . NiAl-LDH nanoplatelets have been created using a microemulsion technique, containing a few ordered layers. As seen in **Figure 5(a)**, the polarized OH- groups of NiAl-LDH and the -NH^{3+} head groups of oleyl amine produced electrostatic interactions that caused the nanoplatelets to stabilize. In addition, the -OH groups of the assistant surfactant 1-butanol decreased the hydrophobicity of the nanoplatelets[71] . The result of directly spreading the nanoplatelets in water was a translucent, stable solution. Given the nano-additives' small size and exceptional dispersion, a lubricating layer was seen to form during friction tests at high contact pressures (originally at 1.5 GPa). A tribological performance is shown in **Figure 5(b)** for various lubricants. The sample with 0.5 weight percent NiAl-LDH nanoplatelets in **Figure 5(c)** performed exceptionally well in terms of lubrication. In particular, it had a lower WSD of 43.2 %, a lower COF of 83.1 %, and lower WSD of 88.5 %, and the 59.5 % reduced depth and wear-track widths in comparison to clean water. Because of their layered structure, weak contacts, and high laminate load-carrying capacity, the exfoliated nanosheets were adsorbed on the sliding solid surfaces during friction, preventing the asperities from clashing directly.

Table 2 summarizes the comparative evaluation of black phosphorus and layered double hydroxides as emerging 2D nanomaterials for nano-Lubricant.

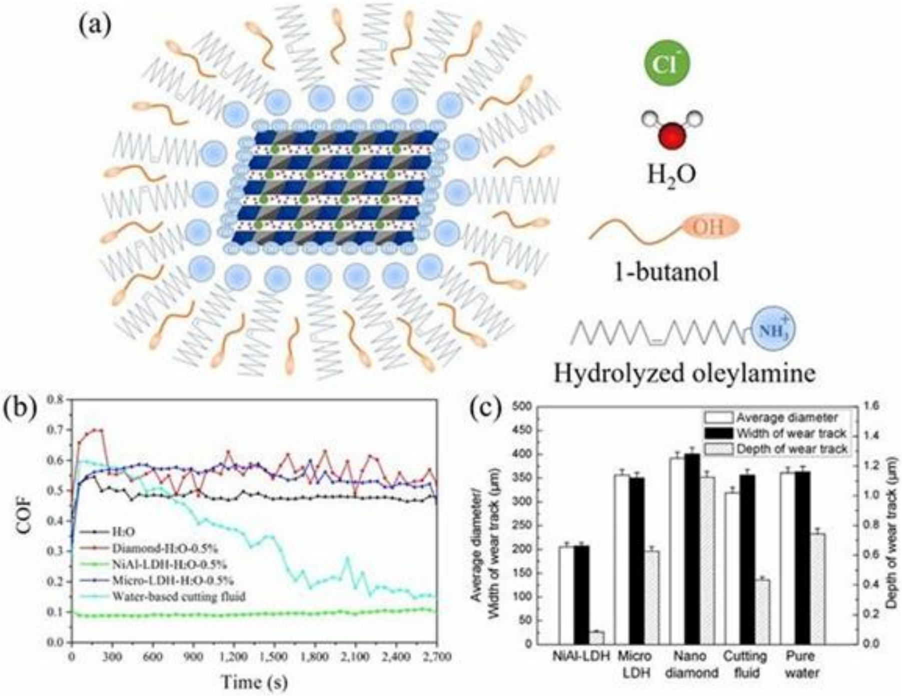

Figure 5 Schematic model of NiAl-LDH/OAm and the results of the tribological tests of 5 lubricant samples, which contain the diamond nanoparticles, NiAl-LDH nanoplatelets, LDH micro platelets, water-based cutting fluid, and pure water. (a) Schematic model of NiAl- LDH/OAm. (b,c) COF and wear condition of 5 lubricant samples, which cover diamond nanoparticles, NiAl-LDH nanoplatelets, LDH micro platelets, water-based cutting fluid, and pure water[54] .

Table 2 Comparative evaluation of black phosphorus and layered double hydroxides as emerging 2D nanomaterials for nano-lubricants.

Nanomaterial Additive	Key Properties	Lubrication Mechanism	Advantages	Limitations	Ref
Black Phosphorus (BP)	Weak interlayer forces, anisotropic layered structure, high thermal resistance	Develops a transfer film, achieves superlubricity through oxidation and rolling action of BP quantum dots (BPQDs)	Exceptional tribological performance, effective under high contact pressures	Prone to environmental degradation, requires protective coatings or chemical modification	[72]
Layered Double Hydroxides (LDHs)	Layered nanosheet structure, electrostatic stabilization, excellent dispersibility	Creates a tribo-film that reduces asperity contact and enhances lubrication	Superior wear resistance, effective COF reduction, stable in water-based lubricants	Performance depends on crystallinity and reaction time, requires fine-tuning for industrial applications	[73]

Morphological dimensions and their synthesis

Zero-dimensional (0D)

The 0D nanomaterials, including nanospheres, nanoparticles, nanocrystals, and quantum dots, are characterized by minimal anisotropy[74] . Their size influences quantum confinement, impacting optical and electronic behavior. For instance, GaAs/AlGaAs quantum dots synthesized via droplet epitaxy demonstrated ultra-narrow excitonic emission and extended recombination lifetime [75].

Various synthesis techniques have been explored. Hierarchical WO_3 hollow shells in different shapes were produced by calcining acid-treated $PbWO_4/SrWO_4$ precursors, enhancing photocatalytic activity and BET surface area [76]. Dendritic platinum nanoparticles, synthesized using Pluronic F-127, offer high surface area and open nanostructures, making them suitable for industrial applications[77] .

Although significant progress has been made in gold nanoparticle synthesis, precise assembly control remains a challenge. Ligand-driven self-assembly enables the creation of multidimensional architectures, allowing for tunable micro- and nanostructured materials[78] . Functionalized colloidal gold nanoparticles with photocleavable succinimide ester groups facilitated controlled amine derivative release upon irradiation, aiding intracellular signaling studies. Furthermore, $Fe_3O_4@SiO_2$ hollow mesoporous nanospheres, synthesized using carbon spheres as templates, were loaded with doxorubicin hydrochloride, demonstrating enhanced cytotoxicity compared to drug-free variants [79].

One-dimensional (1D)

The 1D nanomaterials such as nanorods, nanowires, and nanotubes resemble nanoscale cables or threads and are promising for miniaturized devices and nanotechnology[80] . PbS quantum rods (1.7 nm) were synthesized in a single-step process, exhibiting high fluorescence and distinct optical properties[81] . These nanorods hold potential for biological labeling, FRET, and optoelectronics. Additionally, ZnS nanorods combined with liquid crystalline materials formed highly ordered nanohybrid structures.

In Figure 6, the incredibly tiny nanorods produce neatly arranged locally aligned arrays because of their strong intrinsic dipole moment and good miscibility with liquid crystalline components.

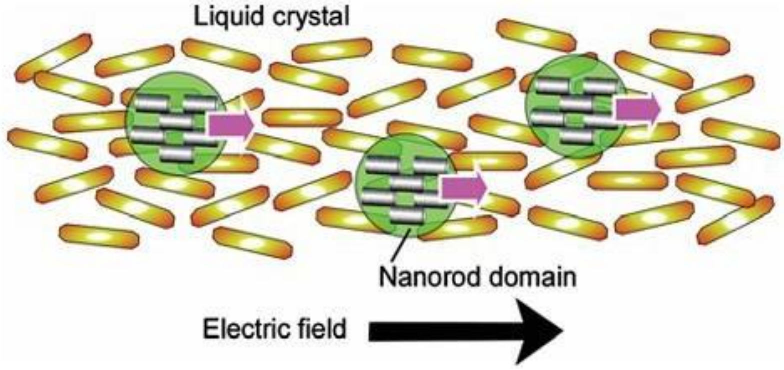

Figure 6 Alignment of liquid crystalline domain upon orientation control of 1D nanorods driven by external electric fields [82].

An external field adjusted the blend's orientational order, enabling customizable electro-optic properties for improved viewing angles. This nanorod-based system enhances efficiency, contrast, and response time, solving key display challenges. Ge nanowire arrays were directly grown on a tilted Si substrate, with annealing boosting current density and reducing turn-on voltage. Research has also been done on 1D nanowire architectures made of organic materials. In Figure (7), Block copolymers of tetraphenylporphinatozinc (II) as a donor and C60 fullerene as an acceptor, were created by the living ring-opening metathesis polymerisation (ROMP), and were used to create a nanowire structure with carefully regulated segregation of electron donor[83] and acceptor moieties. 1D nanowire structure of tetraphenylporphinatozinc are shown in Figure 7.

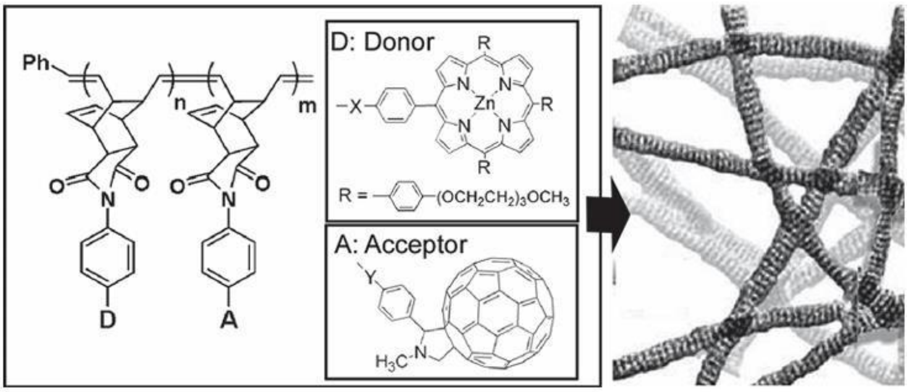

Figure 7 The 1D nanowire structure of tetraphenylporphinatozinc (II) (donor) and C60 fullerene (acceptor): Chemical structures (left) and morphology (right) [82].

The 1D nanowires with a zebra-stripe pattern (~ 5.5 nm periodicity) were formed from amphiphilic ROMP block copolymers, enabling fast photocurrent switching under white light. Nanocarbon structures, including fullerene nano whiskers, nanotubes, and 2D sheets, converted into 1D nanorods upon water exposure[84] . Carbon nanotubes (CNTs) are crucial in nanoelectronics, with metal infiltration influencing their growth and conductivity. Hybrid CNTs, infused with materials like CuI or Ga-doped ZnS, exhibited modified mechanical behavior and controlled release of substances[85]. Multi-terminal CNT circuits demonstrated high conductivity and strength, while ZnS-filled CNTs improved durability. Additionally, superconducting in nanowires and In-ZnS heterojunctions were developed.

Two-dimensional (2D)

The 2D nanomaterials, including nanosheets and graphene, excel in converting physical, chemical, and biological processes into device signals. They also encompass thin-film structures formed via LB, LbL assembly, and SAM modification. Nanostructures involved in interfacial phenomena are also considered in this category. **Figure 8** illustrates inorganic nanosheets synthesized through wet methods [27].

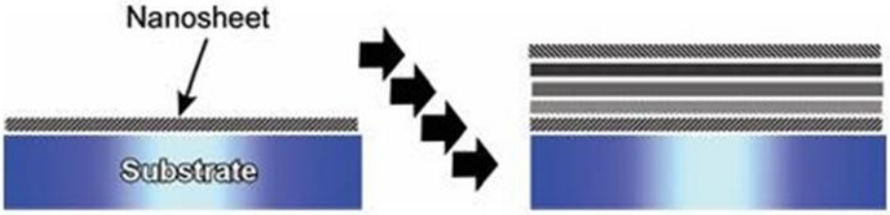

Figure 8 Layered assembly of nanosheets (side view) [82].

Nickel oxides with a hydrated layered structure were synthesized via bromine oxidation and acid treatment, enabling Co-Ni layered hydroxides formation through oxidative intercalation and ethanol-assisted anion exchange, producing carbonate-free nanosheets with strong anion-exchange reactivity[86], [87]. The Langmuir-Blodgett (LB) technique) structured stacked nanosheets into ordered multilayer films, such as $Ti_{0.87}O_2$ nanosheets, useful for seed layers and high-k applications. Graphene's electrical properties face challenges like band gap generation. Bilayer graphene showed resistance enhancement, absent in other layers, while Raman spectroscopy linked phonon dispersion at graphene-substrate junctions to defects or symmetry breaking [88], [89]. Graphene quantum dots exhibited single-electron transport via electron beam lithography. Nanoribbon junctions showed perfect transmission or 0 conductance dips due to anti-resonance, allowing current control via edge structuring.

Three-dimensional (3D)

The internal nanostructure of 3D bulk materials plays a crucial role in determining properties such as mechanical strength and magnetism. Atom probe analysis helps uncover structure-property relationships in materials used for energy storage, data storage, and high-performance applications, including high-strength magnesium alloys, recording media, and high-coercivity magnets.

Advanced fabrication techniques have enabled the development of ferroelectric, magnetic, and superconducting materials, such as iron oxyarsenide (superconducting at 42 K), NaV_2O_4 (mixed-valent oxide), and $NaOsO_3$ (which transitions from metal to insulator at 410 K) . Nanoparticles (NPs) are classified based on size, composition, and function into categories like organic, inorganic, ceramic, composite, and carbon-based materials, including natural, accidental, and artificial NPs.

Classification of nanoparticles on basis of composition

Composites nanoparticles

Two or more distinct constituent unit materials with varying physicochemical properties are combined to create the result, which has unique features not found in the initial separate components. Planning the composite NPs materials ahead of time has the advantage of giving them recommendations, and the attributes primarily depend on the curing, shape, orientation, and matrix selection. High stiffness, low adhesion, and strength are often cited as ways to improve the friction and wear characteristics of polymeric materials.

Appropriate fillers were mixed during the procedure, and a significant amount of graphite was carefully added to lower adhesion. This composition lowers the coefficient of friction (COF) in the operation by enabling the creation of a friction-reducing agent layer on the sliding surfaces. Since friction produces a lot of heat, the use of polymers with high temperature resistance supplements (carbon nanotube matrix) is advised. Composite materials with outstanding thermal and polymeric behavior are produced by combining these matrices.

Figure 9 shows the composite blending with their anticipated functions. NPs have several basic characteristics that make them beneficial in tribology, such as (a) low reactivity with other additives; (b), greater durability; (c) being not soluble in non-polar base oil, (d) being highly non-volatile and able to tolerate cold temperatures, and (e) film creation on various material surfaces is simple.

Figure 9 Polymer composite formulation for optimal lubrication .

Carbon nanoparticles

Fullerenes

The spherical carbon molecules known as fullerenes (C60) are composed of carbon atoms joined by sp2 hybridization . With diameters varying from 8.2 nm for single layers to 4 - 36 nm for multilayered fullerenes, the spherical structure is composed of around 28 - 1,500 carbon atoms. Fullerenes contain nanomaterials made up of globular hollow cages, including allotropic forms of carbon. Commercial interest has been sparked by their electrical conductivity, high strength, structure, electron affinity, and flexibility.

Carbon nanotubes (CNT)

The graphene nano foil used to create carbon nanotubes (CNTs) has a honeycomb structure, meaning that atoms split into hollow coils to form nanotubes. Single-layered CNTs are as small as 0.7 nm, while multi-layered CNTs are as large as 100 nm. The lengths of CNTs typically vary from a few micrometers to several millimeters. The ends may be closed by half fullerene molecules or they may be empty. A graphite sheet rolling on itself is comparable to the structure of these. They are called single-walled (SWNTs), double-walled (DWNTs), or multi-walled carbon nanotubes (MWNTs) due to the fact that the rolled sheets may have 1, 2, or more walls. They are frequently synthesized via deposition of carbon precursors, especially the atomic ones. With the use of an electric arc or laser, carbons are vaporized from graphite and placed on metal particles[90] . Recently, the chemical vapor deposition (CVD) approach has been used to create them.

Nanofiber of carbon

The same process that produces graphene nanofoil and carbon nanotubes is used to create carbon nanofiber. The distinction is that it replaced conventional cylindrical tubes with one that is wrapped into a cone. **Table 3** summarizes the classification and comparative analysis of composite and carbon-Based nanoparticles.

Table 3 Classification and comparative analysis of composite and carbon-based nanoparticles.

Nanoparticle Category	Types	Structure & Composition	Synthesis Techniques	Distinct Properties	Applications	Ref
Composite Nanoparticles	Polymer-based, Metal-based, Ceramic-based	Combination of multiple materials with distinct physicochemical characteristics	Chemical synthesis, Self-assembly, Blending	High stiffness, Low adhesion, Improved friction & wear resistance	Lubricants, Protective coatings, Structural reinforcements	[91]
Carbon-Based Nanoparticles	Fullerenes	Hollow, spherical carbon molecules (C60) with sp^2 hybridization	Arc discharge, Laser ablation, Chemical Vapor Deposition (CVD)	High strength, Electrical conductivity, Structural flexibility, Electron affinity	Nanoelectronics, Drug delivery, Catalysis	[92]
	Carbon Nanotubes (CNTs)	Cylindrical graphene sheets rolled into tubes; categorized as single-walled (SWNTs), double-walled (DWNTs), or multi-walled (MWNTs)	Arc discharge, Laser ablation, CVD	Exceptional mechanical strength, High electrical & thermal conductivity, Large aspect ratio	Energy storage, Nanoelectronics, Composite reinforcement	[93]
	Carbon Nanofibers	Cone-wrapped structures formed similarly to CNTs but with a conical arrangement	CVD, Electrospinning	Lightweight, High surface area, Excellent conductivity	Biomedical applications, Sensors, Energy storage	[94]

Nanomaterials have attracted significant attention as advanced lubricants due to their outstanding tribological and mechanical properties. Their unique characteristics provide notable advantages over conventional lubricants by improving performance and minimizing friction and wear.

Table 4 summarizes the comparative analysis of 2D nanomaterials and traditional lubricants, highlighting their benefits and enhanced lubrication efficiency.

Parameter	2D Nanomaterials	Traditional Lubricants	Ref
Lubrication Mechanism	Forms ultra-thin protective films, minimizing surface contact and reducing interlayer friction.	Relies on oil or grease-based films to separate moving surfaces and reduce wear.	[95]
Friction Reduction	Provides extremely low friction due to weak van der Waals forces between layers.	Offers moderate friction reduction, often requiring performance-enhancing additives.	[96]
Wear Resistance	Exhibits excellent wear resistance due to strong intralayer bonding.	Can degrade over time, leading to increased surface wear.	[97]
Thermal Stability	Maintains performance under extreme temperatures without significant degradation (e.g., graphene, MoS_2)	Prone to thermal breakdown or evaporation at high temperatures.	[98]

Parameter	2D Nanomaterials	Traditional Lubricants	Ref
Oxidation Resistance	Naturally resistant to oxidation, ensuring prolonged effectiveness.	Susceptible to oxidation, necessitating the use of stabilizers.	[99]
Load-Bearing Capacity	High mechanical strength allows efficient load distribution and enhanced surface protection.	May require additives to sustain performance under heavy loads.	[100]
Environmental Impact	Generally eco-friendly, with potential applications in dry lubrication systems.	Some formulations contain harmful additives that contribute to environmental pollution.	[101]
Dispersion in Base Fluids	Requires functionalization to ensure stable dispersion in oils and greases.	Easily integrates with base oils for uniform lubrication.	[102]
Cost and Scalability	Higher initial costs due to synthesis and processing challenges, but offers long-term efficiency gains.	More affordable upfront but requires frequent reapplication and maintenance.	[103]

Synthesis of metal oxide nanoparticles (MONPs)

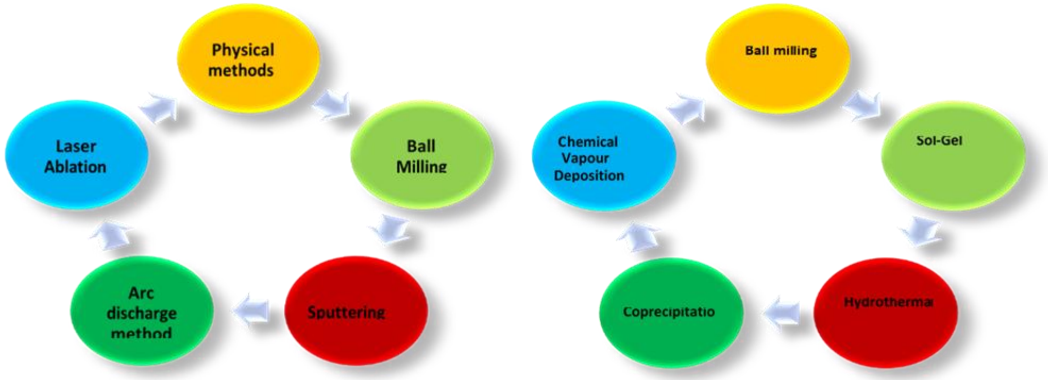

Figure 10 Overview of physical and chemical methods for MONPs.

Figure 10 mentions all the physical and chemical methods for synthesis of MONPs: Ball Milling, Sputtering, Arc Discharge, Laser Ablation and Ball milling, sol-gel, hydrothermal, coprecipitation, chemical vapour deposition.

Ball milling

High-energy collisions between balls and a powder are used in the mechanical process of ball milling to create nanoparticles[104] . Because of its ease of use, affordability, and scalability, it is extensively utilized. This process works best for producing nanoscale materials with a large surface area and evenly distributed constituents. The principle: The effect and attrition principles underpin the procedure. The material being ground (the powder) fractures and breaks up into smaller pieces as a result of the energy transferred by the milling balls' collisions. **Figure 11** shows the schematic representation of ball milling method (physical method).

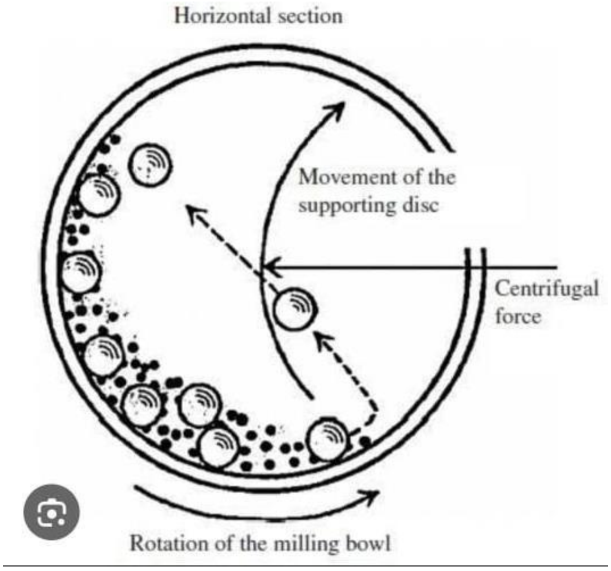

Figure 11 Schematic of ball milling [https://images.app.goo.gl/QAK5GryiXYjMBuGU7].

Procedure

Preparation: A ball mill is a container or vial composed of sturdy materials such as steel, ceramic, or tungsten carbide that holds the material to be processed and the milling balls. Sometimes, a tiny bit of a liquid medium - like water or ethanol - is introduced to lower friction and stop agglomeration. The milling process: In a ball milling machine, the container is closed and rotated rapidly (either by centrifugal or planetary action) [105]. The material is repeatedly struck by the free-moving, highly energetic balls, which reduces the size of the particles. Timespan: The ultimate particle size is determined by how long the milling process takes. Finer nanoparticles are produced via longer milling durations. Collection: Once the procedure is finished, the result is gathered and may be cleaned, dried, and sieved to produce nanoparticles.

Sputtering

Subjecting solid surfaces to high-energy particles like gas or plasma, a method known as sputtering is utilized to create nanomaterials. One efficient technique for creating thin films of nanomaterials is sputtering. During the sputtering deposition process, tiny atom clusters are physically ejected based on the incident gaseous-ion energy after being bombarded by energetic gaseous ions. There are several methods for carrying out the sputtering process, including magnetron, radio-frequency diode, and DC diode sputtering. Sputtering is typically done in an evacuated chamber that has been filled with the sputtering gas [106]. The cathode target receives a high voltage, and the gas and free electrons collide to form gas ions.

Atoms are ejected off the target's surface as a result of the positively charged ions' rapid acceleration in the electric field when they approach the cathode target. WSe_2-layered nanofilms are created via magnetron sputtering on SiO_2 and carbon paper substrates. Because it is less expensive than electron-beam lithography and produces nanomaterials with fewer imperfections, the sputtering process is intriguing.

Arc discharge method

Nanoparticles, particularly those based on carbon, such as metal nanoparticles, fullerenes, and carbon nanotubes (CNTs), are frequently created using the arc discharge process. The process vaporizes the material and produces nanoparticles by forming a high-energy arc between 2 electrodes. How It Operates: 2 electrodes - typically composed of metal or graphite - are positioned inside a chamber. The environment is controlled by filling the chamber with either a liquid (like water) or an inert gas (like argon or helium). ArcStructure: In order to create a high-temperature plasma arc (up to 3,000 - 4,000 °C), a high electric current is transmitted between the electrodes [107] . A heated vapor of atoms is created when the electrode material is vaporized. Creation of Nanoparticles: After rapidly cooling, the vaporized material condenses as nanoparticles. The walls of the chamber, the electrodes, or the surrounding media may all get covered in these nanoparticles. Acquiring: Depending on the configuration, either the chamber or the liquid medium is used to collect the nanoparticles. In **Figure 12**, arc discharge method schematic diagram is shown for synthesis of nanoparticle.

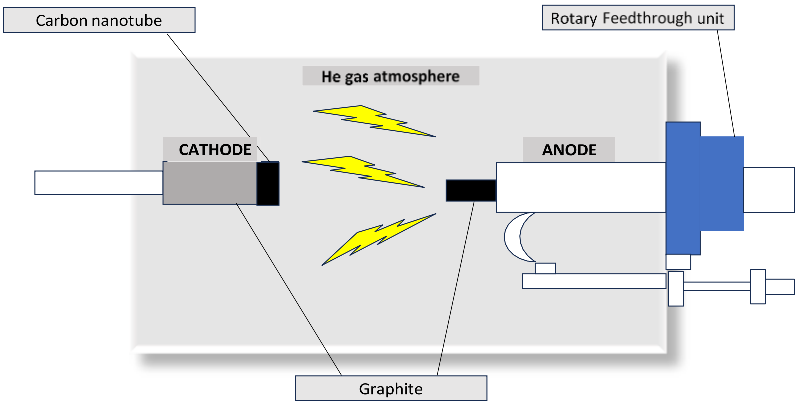

Figure 12 Schematic of the arc discharge setup for nanoparticle synthesis[108].

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Laser ablation method

The laser ablation process provides a flexible and accurate way to create nanoparticles. Atoms or clusters that condense into nanoparticles are ejected when a solid target material is exposed to high-energy laser radiation in a controlled setting[109] .

How it operates

In a chamber, a solid target material - such as metal or semiconductor - is positioned. Inert gases (such as argon or helium) or liquids (such as water or ethanol) are usually used to fill the chamber. Laser Irradiation: The material of interest is exposed to a high-energy laser beam. A plasma plume is created when the target's surface is heated by the extreme energy and vaporizes. The Formation of Nanoparticles: The substance condenses into nanoparticles as it cools after vaporization. The size and shape of the nanoparticles depend on the medium (gas or liquid). Collection: Either a substrate is coated with the nanoparticles or they are extracted from the media.

Sol-gel (chemical methods)

One of the well-known synthetic methods for creating premium MONPs and mixed oxide composites is the sol-gel process[110] . Excellent control over the materials' surface characteristics and texture is possible with this technique. The sol-gel process can be broadly characterized by 5 essential steps: hydrolysis, polycondensation, ageing, drying, and heat decomposition.

Step 1: The precursors, such as metal alkoxides, undergo hydrolysis in water or alcohol. In order to create metal oxide, which is required for the synthesis of MONPs, oxygen is provided by organic solvents like alcohol or water. Aqueous sol-gel is a technique that uses water as a reaction medium; nonaqueous sol-gel is a procedure that uses an organic solvent as a reaction media. An acid or a base, in addition to water and alcohol, aids in the hydrolysis of the precursors. The general chemical reaction involved in the process of hydrolysis is given below. In hydrolysis, $M\text{-}OR + H_2O \rightarrow MOH + ROH$, where M is metal and R is an alkyl group (C_nH_{2n+1}). The gel formation process is significantly influenced by the water content; a higher water content promotes the production of a higher ratio of bridging to nonbridging oxygens, which results in a more polymerized and branched structure during condensation.

Step 2: In the liquid state, polymeric networks expand to colloidal dimensions through the condensation of nearby molecules, which removes water and alcohol and forms metal oxide bonds. With M = metal and X = H or an alkyl group (C_nH_{2n+1}), M-OH +

XO-M → M-O-M + XOH (condensation).

Step 3: The ageing process causes the gel's structure and characteristics to continuously alter. Polycondensation and gel network reprecipitation persist in the localized solution during the ageing process, which eventually reduces porosity and thickens the space between colloidal particles [111].

Step 4: Since water and organic materials separate to form gel, which upsets its structure, the drying process is challenging. The structure of the gel network is affected differently by the 3 distinct drying methods: Freeze-drying, supercritical drying, and atmospheric/ thermal drying. A high temperature causes the porous gel to densify, and the pores can be extracted to create xerogel, which has a high gel shrinkage rate and a comparatively small surface area and pore volume. However, supercritical drying produces aerogels with large surface areas and pore volumes while maintaining almost the same gel network.

In the third kind of drying, the solvents are frozen to create cryogel, which has a comparatively smaller gel network shrinkage than xerogel[112] . When drying, the relative humidity (RH) has a direct impact on the stability and functionality of nanomaterials, making it another crucial parameter. Nanofilms dried at a lower relative humidity are especially more stable than those that have dried at an increased relative humidity.

The next step is heating treatment, or calcination, which removes water molecules and residues from the target sample. The calcination temperature is a crucial factor in regulating the material's density and pore size.The **Figure 13** shows the Schematic of the sol-gel process for synthesizing metal oxide nanoparticles (MONPs).

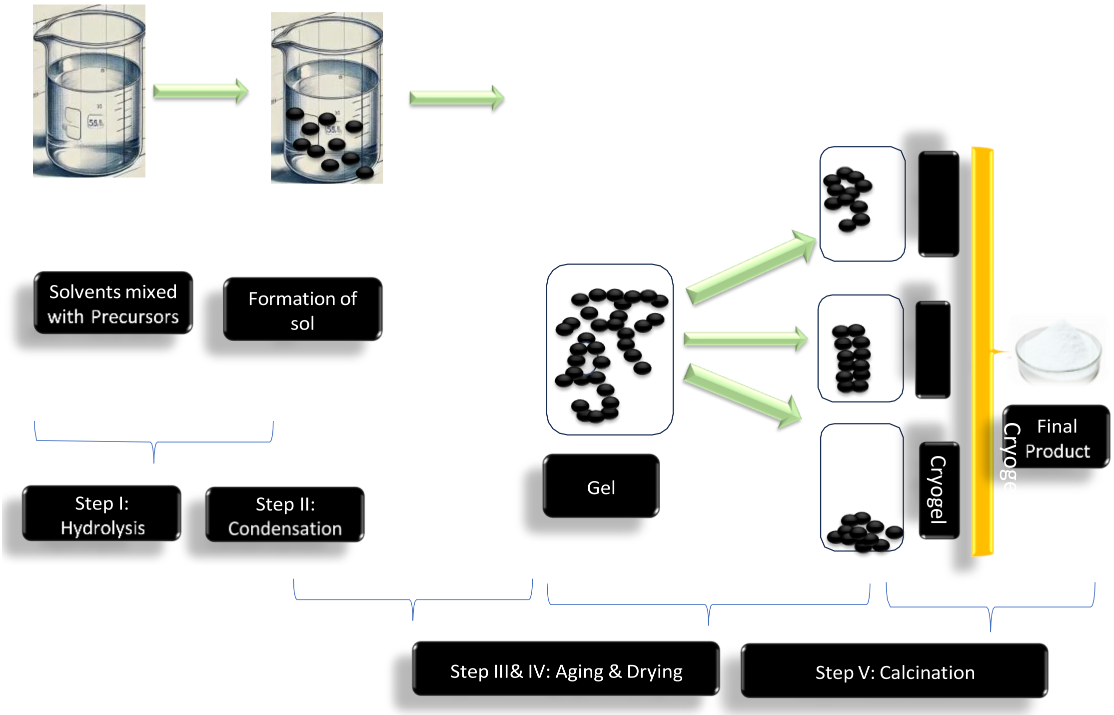

Figure 13 Schematic of the sol-gel process for synthesizing metal oxide nanoparticles (MONPs).

Hydrothermal method

Using substances that are insoluble at room temperature and pressure, the hydrothermal approach creates nanoparticle crystals through a heterogeneous reaction at high temperatures and high pressures. An instrument called an autoclave, a steel pressure vessel that receives water and nutrients, is used to carry out the crystal growth. The typical temperature for hydrothermal synthesis is lower than 300 °C[113] . A favorable reaction field for nanoparticle formation is provided by the critical condition because of the substantial supersaturation and increased reaction rate based on the nucleation theory. This technique has been utilized to create metal oxide nanoparticles, and metal nanoparticles in supercritical water.

Hydrothermal synthesis advantages: Heating and ensuring the solution is at its critical point will make the majority of materials soluble in the right solvent. The potential to replace solid-state synthesis, a notable increase in the reactant's chemical activity, and the ability to prepare compounds that would not be achievable through solid- state reactions using hydrothermal/solvothermal synthesis. It is simple to create products in intermediate, metastable, and specialized phases. It is also possible to synthesize new chemicals in metastable states and other specific condensed states. The end product's size, shape distribution, and crystallinity can be easily and precisely controlled by varying the parameters, including the solvent type, surfactant type, reaction temperature, reaction duration, and precursor type. Materials that are prone to pyrolysis and have high vapor pressures and low melting points will be produced.

Coprecipitation method

Nucleation, growth, coarsening, and/or agglomeration processes all occur simultaneously in coprecipitation reactions [114]. The following traits of coprecipitation reactions are present: Secondary processes like Ostwald ripening and aggregation significantly alter the size, morphology, and characteristics of the products. The products are typically insoluble species that are formed under high supersaturation conditions. Nucleation is a crucial step that results in the formation of numerous small particles. A chemical reaction is typically the cause of the supersaturation conditions required to cause precipitation. Coprecipitation synthesis methods are categorized based on the type of materials formed and the specific synthesis conditions. Here's an overview.

Metal formation

From Aqueous Solutions: Metals are precipitated by manipulating factors like pH, temperature, or adding reducing agents. Reduction in Nonaqueous Solutions: Metal ions are reduced within organic solvents, often producing nanostructured metals. Electrochemical Reduction: Metals are deposited or nanoparticles formed through electrochemical processes. Decomposition of Metal-Organic Precursors: Thermal decomposition of metal- organic compounds yields metallic products.

Oxide formation

From Aqueous Solutions: Hydrolysis and condensation of metal ions result in oxide materials such as TiO_2 or ZnO [115]. From Nonaqueous Solutions: Reactions in organic solvents enable control over morphology and composition during oxide synthesis.

Metal chalcogenide formation

Via Molecular Precursors: Metal salts react with sulfur, selenium, or tellurium sources to produce chalcogenides like CdS or ZnSe [116].

Microwave and sonication-assisted coprecipitation

Microwave-Assisted: Rapid, uniform heating with microwaves accelerates reaction kinetics and ensures consistent particle size. Sonication-Assisted: Ultrasonic waves promote uniform mixing, nucleation, and dispersion, yielding homogeneous products. These methods are instrumental in creating materials for applications in catalysis, electronics, and energy storage. **Table 5** summarizes the comparison of Metal Oxide Nanoparticle (MONP) Synthesis Techniques.

Table 5 Comparison of metal oxide nanoparticle (MONP) synthesis techniques.

Technique	Working Principle	Process Overview	Key Benefits	Challenges	Common Applications	Ref
Ball Milling	Mechanical impact and attrition break particles into nanoscale sizes	High-energy collisions between milling balls reduce material size	Cost-effective, scalable, simple process, produces high-surface-area materials	Limited control over particle shape and size distribution	Powder metallurgy, material processing	[117]

Technique	Working Principle	Process Overview	Key Benefits	Challenges	Common Applications	Ref
Sputtering	Ejection of atoms from a solid target via high-energy ion bombardment	Atoms are deposited as thin films on a substrate in a vacuum chamber	Produces high-purity, defect-free nanomaterials, suitable for thin-film coatings	Requires expensive vacuum systems, slow deposition rate	Electronic components, optical coatings	[118]
Arc Discharge	High-temperature plasma arc vaporizes electrode material	A strong electric arc between electrodes generates vapor, which condenses into nanoparticles	Simple and effective for carbon-based nanoparticles	Requires high power input, limited material control	Carbon nanotubes (CNTs), fullerenes, metal nanoparticles	[119]
Laser Ablation	High-energy laser beam vaporizes solid target material	Intense laser pulses create plasma, leading to nanoparticle formation	Precise control over size and shape, versatile for various materials	High equipment cost, requires careful optimization	Nanostructured coatings, advanced nanomaterials	[120]
Sol-Gel Method	Chemical transformation of metal precursors through hydrolysis and condensation	Formation of a gel network, followed by drying and calcination	Precise control over porosity, composition, and surface properties	Time-intensive process, sensitive to environmental conditions	Ceramics, biomedical coatings, catalysis	[121]
Hydrothermal Method	Crystal growth in a high-temperature, high-pressure aqueous environment	Reactants dissolve in water within a sealed autoclave, forming nanoparticles	Enables controlled crystallization, suitable for complex oxides	Requires specialized high-pressure equipment	Energy storage materials, catalysts, advanced ceramics	[122]
Coprecipitation	Simultaneous precipitation and nucleation of nanoparticles from solution	Metal ions react to form insoluble nanoparticles under controlled conditions	Simple, cost-effective, scalable for large production	Difficult to achieve uniform particle size and morphology	Catalysts, magnetic materials, environmental remediation	[123]

Scalability and economic viability of 2D nanomaterials for lubrication applications

Challenges in large-scale production

Scaling up the synthesis of 2D nanomaterials while preserving their structural integrity and functional properties poses several challenges: (1) Purity and Consistency: High-quality nanomaterials are often produced using techniques like chemical vapor deposition (CVD) or mechanical exfoliation, which are difficult to scale due to high energy consumption and batch-to-batch variations. (2) Production Yield and Efficiency: While methods such as liquid-phase exfoliation are more scalable, they often suffer from low yield and inconsistent particle size, impacting lubricant performance. (3) Reproducibility and Process Control: Large-scale manufacturing demands precise control over morphology, defect density, and surface chemistry to ensure uniform tribological performance.

Cost considerations

The economic feasibility of using 2D nanomaterials in lubrication is influenced by several factors: Raw Material Expenses: The high cost of precursor materials, especially for graphene and MXenes, makes large-scale applications challenging. In contrast, materials like MoS_2 and h-BN offer a more affordable alternative due to their abundant natural sources[124] . (2) Processing Costs: Energy-intensive synthesis techniques, such as CVD and plasma-assisted methods, increase production expenses. In contrast, solution-based exfoliation and mechanical milling provide more cost-effective alternatives. (3) Lubricant Integration Costs: Maintaining stable dispersion in lubricants without excessive use of surfactants or additives is crucial. Although surface functionalization enhances performance, it also adds to processing costs.

Strategies for enhancing scalability and cost-effectiveness

Optimizing Scalable Synthesis Techniques: High-yield, low-cost methods like shear exfoliation, electrochemical synthesis, and roll-to-roll production can improve feasibility. Utilization of Low-Cost Precursors: Identifying cost-effective sources, including natural deposits or industrial by-products, can reduce raw material costs[125]. Enhancing Lubricant Formulation Efficiency: Achieving stable dispersion with minimal additives can lower production costs while maintaining optimal lubrication properties. Industry Collaboration and Standardization: Partnerships with lubricant manufacturers and the development of standardized formulations can accelerate industrial adoption.

The 2D nanomaterials have gained significant attention across various fields due to their exceptional properties, including high surface area, superior mechanical strength, excellent electrical conductivity, and remarkable chemical stability.

Energy storage and conversion

Batteries & Supercapacitors: Graphene, MXenes, and transition metal dichalcogenides (TMDs) improve the efficiency of lithium-ion, sodium-ion, and solid-state batteries by enhancing charge storage and ion transport[126]. Hydrogen Production: Molybdenum disulfide (MoS_2) and phosphorene act as efficient electrocatalysts in water splitting, facilitating hydrogen generation. Fuel Cells: Graphene-based catalysts serve as cost-effective alternatives to platinum, improving fuel cell performance.

Electronics and optoelectronics

Next-Generation Transistors: 2D materials such as MoS_2 and black phosphorus are being explored for field-effect transistors (FETs) due to their tunable electronic properties. Advanced Photodetectors & LEDs: TMDs and hybrid perovskite-2D materials enhance the efficiency and flexibility of optoelectronic devices. Wearable and Flexible Electronics: Graphene and MXenes enable the development of bendable circuits for smart wearables and health-monitoring devices.

Biomedical applications

Targeted Drug Delivery: Graphene oxide (GO) and MoS_2 are used as carriers for controlled drug delivery, leveraging their large surface area and biocompatibility. High-Sensitivity Biosensors: 2D nanomaterials significantly improve the detection of biomarkers, pathogens, and toxins. Tissue Engineering: Graphene-based scaffolds support cell growth, making them suitable for regenerative medicine.

Environmental applications

Water Purification: Graphene oxide membranes and MoS_2 nanosheets effectively remove heavy metals, pollutants, and salts from water. Air Filtration: MXene-based materials efficiently capture hazardous gases and airborne particles. CO_2 Reduction: MoS_2 and black phosphorus function as catalysts to convert carbon dioxide into useful hydrocarbons.

Sensors and actuators

Ultra-Sensitive Gas Sensors: 2D materials enable the detection of gases like NO_2, CO, and NH_3 at extremely low concentrations. Pressure & Strain Sensors: Graphene and MXene-based sensors are used in robotics, prosthetics, and health monitoring[127] . Smart Windows: TMDs allow the development of electrochromic devices that dynamically regulate light transmission.

Quantum computing and photonics

Quantum Light Emitters: Defect engineering in hexagonal boron nitride (hBN) enables single-photon emission for quantum applications. Optical Communication Enhancements: 2D materials improve data transmission and signal processing in telecommunications.

Influence of morphology on nano lubricant properties

Tribological performance

The scientific study of interacting surfaces or 2 moving bodies in relative motion is known as tribology. It has to do with wear and tear, lubrication, corrosion, wear and tear on metal surfaces, engine life, and energy losses. Wear and friction losses should be kept to a minimum because of the extremely large energy losses resulting from this process. Choosing appropriate lubricant is the most crucial step in meeting the lubrication needs of the individual application, particularly in tribological features. Tribological performance is associated with wear, friction, and lubrication**.**

The development of a tribofilm, or protective layer, on the contact surfaces is the focus of lubricity. Friction and energy losses are decreased when there is less direct surface contact due to high lubricity . Higher lubricity does not always translate into improved wear protection, though, as lubricants' surface-active ingredients, such as base stocks or additives, are absorbed to form a protective layer on rubbing surfaces.

Three forms of mechanical wear, including adhesion, abrasion, and fatigue, can occur when surface asperities come into contact with one another . When 2 relatively moving surfaces asperity weld and then instantly pull apart due to high loads, high temperatures, or insufficient lubrication, adhesive wear results. When surfaces of varying hardness rub against one another, abrasive wear results.

When a material is subjected to repeated loads, fatigue wear causes localized, gradual structural degradation. The mechanical characteristics of a tribological system, lubrication, and the physicochemical characteristics of the lubricant are the 3 fundamental tribology factors that must be understood before talking about the tribological performance of the nanolubricants.

Energy losses

Friction results in extraordinarily significant energy losses. Friction causes the engine to lose energy, which heats up the engine and wears out the moving part surfaces. Figure 1 illustrates the estimated 75 - 82 % overall energy losses in the vehicle, 68 - 72 % engine losses, 12 - 30 % energy from the fuel used to propel the vehicle, and 3 % energy losses from friction.

Thirty % of the energy was lost as a result of wear and friction . Tribology, additives, and tire and bearing design, are some of the technologies that can minimize energy losses from friction. Additionally, the lubricant that provides the finest lubrication is absolutely necessary to overcome the energy losses. Furthermore, the lubricant that imparts the best additives is necessary to overcome the energy losses. Additionally, the lubricant that provides the finest lubrication is absolutely necessary to overcome the energy losses.

Dispersion stability

NPs have a high surface energy due to their high surface area to volume ratio. Particles with a high surface area agglomerate due to strong molecular interactions. NP aggregation causes sedimentation and a reduction in the capacity for tribological improvement. Therefore, NPs dispersion stability is highly desired for dependable lubricating performance. When the NPs don't aggregate significantly, it's said to be stable.

There are numerous ways to improve dispersion stability. High-shear mixing, homogenizing, ball milling, magnetic force agitation, and ultrasonic agitation are currently suggested techniques . Numerous studies have discussed the techniques they employed for dispersion, such as the use of magnetic stirrers, ultrasonic probe agitation, and homogenization by triple-roller mill, planetary ball mill, ultrasonic shaker, and ultrasonic bath agitation mix technique, high shear homogenizer and agitation. Despite the fact that some researchers only cited ultrasonication for dispersion or neglected to include any method at all, the literature indicates that most researchers employ ultrasonic agitation for NPs dispersion mix technique, along with high shear homogenizer and agitation. The literature states that the currently recommended techniques include ball milling, homogenizing, high-shear mixing, and ultrasonic agitation.

According to reports, graphene disperses in base oil with comparable dispersion stability, removing the element that influences lubricating qualities[128] . Dispersion duration is another crucial factor in minimizing or managing agglomeration. Using magnetic force agitation, it has been determined that the size of NPs aggregates reduces as mixing duration increases. The researchers' dispersion duration ranged from 5 min to 8 h, while most dispersion durations are 30 min or 1 h.

In order to improve dispersion stability, surface functionalization has emerged. Among these are steric and electrostatic stabilization. While steric stabilization is accomplished by coating the NPs surface with a polymer or surfactant, electrostatic stabilization occurs when the ionic surfactants have been absorbed on the NPs surface. In comparison to naked NPs, the surface-functionalized NPs ought to be more lubricating. By stopping material transfer, the former helps shearing surfaces avoid direct contact and cold welding. Furthermore, the hybrid structure of functionalized nanoparticles, which consists of a soft external shell and a hard interior core, permits a high load carrying capacity without lowering lubrication. Therefore, compared to naked NPs, surface-functionalized NPs offer more benefits.

The method of surface functionalization and associated research will be covered. To improve dispersion stability, one technique is surface modification. Oleic acid, a typical modification agent, is frequently employed in numerous investigations to improve dispersion stability . Other agents of alteration have also been investigated. By employing a blend of resin, methylbenzene, and amine chemical to modify its surface, NanoCu has demonstrated good oil-dispersion capacity and agglomeration prevention[129] .

One advantage of methyl-methyl acrylate surface modification of NanoCu is the reduction of wear and friction. Tetrabutylammonium chains that modify the surface of NanoPd lead to an increase in electrical conductivity and loading part life. It should be noted that dual modified CuO by sodium oleate (SOA) and alkylphenol polyoxymethylene ether disperse in water, improving lubricity and providing exceptional dispersion stability. Another well-known work demonstrated that the surface-capped triangle Cu nanoplates made with cetyltrimethylammonium bromide (CTAB) were effective in reducing wear loss (82 %) and friction (12 %) through the development of a tribofilm at the components' interface. Additionally, a surfactant is used in the second approach to improve dispersion stability. As a dispersion, surfactants can also be introduced directly to nanolubricants, making this process simpler and less expensive than surface modification. The limitation of surfactant use in terms of improving thermal conductivity is still a drawback. Polyisobutylene succinimide (PIBSI), sorbitol monooleate (SPAN 80), sodium-dodecyl and oleic acid are examples of surfactants that are used. The dispersion stability of nanoBN and nanoMoS_2 was investigated using 5 different types of surfactants.

They demonstrated that employing a surfactant is advantageous for both suspending the NPs and reducing wear and friction on its own. To investigate the influence of (EP) extreme pressure additives characteristics and dispersion stability in API Group III 150 N base oil, with or without hBN particles, 4 different types of dispersants have been chosen. Every dispersant contributes to the stability of the dispersion and affects the tribological characteristics of the oil. A 10 % improvement in EP performance and greater dispersion stability was demonstrated by 5 % dispersant, while 1 % dispersant had no effect on the oil's EP characteristics. The addition of the hBN particles significantly improved the EP performance by up to 30 % [130].

Achieving stable dispersion is essential for maximizing the performance of 2D nanomaterials in lubricants. However, due to their high surface energy and strong van der Waals interactions, these nanoparticles tend to agglomerate and settle over time. This instability compromises their effectiveness, leading to inconsistent lubrication performance. To overcome these challenges, various strategies such as dispersants, surface modifications, and functionalization techniques have been explored.

Challenges in dispersion stability

Agglomeration Due to High Surface Energy: The large surface area-to-volume ratio of 2D nanomaterials makes them prone to clustering, reducing their ability to form a uniform lubricating film. Sedimentation Over Time: Denser nanoparticles may settle in lubricant formulations, particularly in low-viscosity base oils, leading to uneven distribution[131] . Poor Compatibility with Base Oils: Differences in polarity between nanoparticles and lubricant base oils often hinder stable dispersion.

Strategies for improving dispersion stability and performance

Incorporation of dispersants and surfactants

Polymeric Dispersants: Additives such as polyisobutylene succinimide (PIBSI), sorbitan monooleate (SPAN 80), and sodium dodecyl sulfate (SDS) enhance nanoparticle solubility in nonpolar base oils. Surface-Active Agents: Surfactants minimize interparticle attraction, preventing agglomeration and ensuring uniform distribution. Optimized Dispersant Concentrations: Research indicates that a 5 % dispersant concentration significantly enhances dispersion stability and tribological performance, whereas lower concentrations have minimal impact[132] .

Surface modification and functionalization

Steric Stabilization: Polymer coatings such as oleic acid or polyvinylpyrrolidone (PVP) create a physical barrier that prevents nanoparticle aggregation. Electrostatic Stabilization: The adsorption of ionic surfactants onto nanoparticle surfaces introduces repulsive forces, reducing clustering. Hybrid Nanoparticles: Functionalized nanomaterials with a soft outer layer and a rigid core (e.g., alkylphenol-modified CuO) enhance dispersion while maintaining high load-bearing capacity.

Advanced dispersion techniques

Ultrasonication: High-frequency sound waves break up aggregates and enhance nanoparticle distribution[133] . High-Shear Mixing: This method applies intense mechanical forces to achieve uniform dispersion. Ball Milling and Magnetic Stirring: These techniques refine particle size and promote even distribution.

Ensuring long-term stability

Time-Dependent Stability Considerations: Nanoparticles must remain well-dispersed over extended periods to sustain their lubrication benefits. Monitoring and Evaluation: Techniques such as dynamic light scattering (DLS) and sedimentation analysis can assess the long-term stability of dispersed nanoparticles . Optimized Lubricant Formulations: The combination of multiple stabilization approaches enhances long-term dispersion without altering lubricant properties. **Table 6** summarizes the influence of morphology on nanolubricant properties and performance.

Table 6 Influence of morphology on nanolubricant properties and performance.

Category	Tribological Performance	Energy Losses	Dispersion Stability	Ref
Definition	Examines wear, friction, and lubrication between moving surfaces.	Energy dissipation caused by friction and wear in mechanical systems.	The ability of nanoparticles (NPs) to stay evenly distributed in lubricants without clumping.	[134]
Key Influencing Factors	- Types of wear: adhesion, abrasion, and fatigue. - Lubricity and tribofilm formation. - Additives in lubricants.	- Friction-induced energy loss. - Heat buildup in engines. - Wear of mechanical parts.	- Surface energy and particle interactions. - Tendency of NPs to clump together.	[135]
Impact	- High friction decreases efficiency. - Surface wear shortens equipment lifespan	- About 30% of vehicle energy is lost due to wear and friction. - Heat and surface damage accelerate engine deterioration.	- Poor dispersion reduces lubrication efficiency. - Particle sedimentation lowers stability.	[136]
Ways to Improve	- Selecting suitable lubricants. - Adding anti-wear agents.	- Using high-performance lubricants and additives. - Advancing bearing and tire designs to reduce losses.	- Employing high-shear mixing, ball milling, and ultrasonic dispersion. - Using surfactants or surface treatments	[137]
Research Methods	- Studying tribofilm formation.	- Measuring friction losses in mechanical systems.	- Comparing different dispersion techniques.	[138]

Category	Tribological Performance	Energy Losses	Dispersion Stability	Ref
	- Testing different oils and additives.	- Analyzing vehicle energy consumption.	- Evaluating long-term dispersion stability	
Role of Nanoparticles	- Reduce friction and wear by creating a protective layer	- Enhance lubrication, lowering energy losses	- Functionalization prevents aggregation and improves stability	[139]
Surface Modification	- Helps in forming a protective layer for better lubrication.	- Not directly relevant	- Improves dispersion through steric and electrostatic stabilization (e.g., oleic acid, surfactants).	[140]
Examplesh	- Graphene and Cu nanoparticles enhance lubricity and wear resistance	- hBN particles boost extreme pressure performance by 30 %.	- CuO modified with sodium oleate enhances stability and lubrication.	[141]

The empirical data on the tribological advantages of various 2D nanomaterial morphologies, experimental findings from multiple studies have been gathered. **Table 7** summarizes the reduction in friction coefficient, improvement in wear rate, and dispersion stability.

Table 7 Reduction in friction coefficient, improvement in wear rate, and dispersion stability for different 2D nanomaterials utilized as lubricant additives.

2D Nanomaterial	Friction Coefficient Reduction (%)	Wear Rate Improvement (%)	Dispersion Stability	Key Findings
Graphene	30 - 50 %	40 - 60 %	High	Forms a protective tribofilm, reducing direct surface contact.
MoS_2	20 - 45 %	35 - 55 %	Moderate	Provides excellent load-bearing capacity and reduces wear.
h-BN	25 - 40 %	30 - 50 %	High	Enhances lubricity and thermal stability, preventing oxidation.
WS_2	35 - 55 %	45 - 65 %	Moderate to High	Exhibits superior anti-wear performance under extreme conditions.
MXenes	40 - 60 %	50 - 70 %	Moderate	Delivers excellent lubrication through surface adsorption.

Industrial significance and practical applications of nanolubricants

Nanolubricants offer notable advantages across various industries, including automotive, aerospace, manufacturing, and energy production. However, their commercial viability depends on factors such as large-scale production, cost-effectiveness, regulatory compliance, and long-term performance validation.

Industrial applications and case studies

Automotive and transportation sector

Engine Oils and Transmission Fluids: The incorporation of nanolubricants in commercial engine oils has led to reduced friction, enhanced fuel efficiency, and extended engine lifespan. Studies have demonstrated that graphene and MoS_2-based additives can lower friction and wear by 10 - 30 % compared to conventional lubricants[142] .

Aerospace and defense applications

Lubrication for Extreme Conditions: Aircraft engines, space vehicles, and military equipment require lubricants that function under extreme pressure and temperature variations. Boron nitride (BN) and tungsten disulfide (WS_2) nanoparticles have demonstrated superior thermal stability and wear resistance, making them ideal for aerospace applications.

Industrial machinery and manufacturing

Metalworking Lubricants and Cutting Fluids: Nanolubricants are used in machining operations such as milling, turning, and grinding, where they help reduce tool wear and improve surface finish. Studies show that nano-additized cutting fluids can extend tool life by up to 40 % and improve machining accuracy. Case Study: A manufacturing plant integrating graphene-based nanolubricants into its CNC machining operations reported a 25 % increase in tool lifespan and 15 % reduction in energy consumption due to decreased friction.

Renewable energy and power generation

Wind Turbine Gear Oils: Nanolubricants have been tested in wind turbine gearboxes to minimize friction and wear. Research indicates that using CuO and ZnO nanoparticle-infused lubricants can reduce maintenance costs by 20 % and extend service intervals.

Challenges to commercial adoption

Despite their potential, several barriers hinder the large-scale implementation of nanolubricants in industrial applications:

Large-scale production and cost considerations

While nanolubricants show exceptional performance in laboratory conditions, mass production remains costly due to expensive raw materials and complex synthesis processes. The requirement for specialized equipment to ensure uniform dispersion of nanoparticles further increases production costs.

Stability and long-term performance

Maintaining consistent dispersion stability over extended periods is crucial, as nanoparticle agglomeration can compromise the effectiveness of nanolubricants. Comprehensive field testing and long-term performance validation are necessary to confirm their reliability in industrial operations.

Compatibility with existing lubrication systems

Some nanolubricants may be incompatible with traditional lubricants or existing machinery, requiring modifications to lubrication systems. Concerns about filter clogging and sedimentation in high-precision equipment need to be addressed.

Regulatory and environmental considerations

The environmental impact and health risks associated with nanoparticles remain under regulatory scrutiny.

Compliance with global safety and environmental regulations is essential for large-scale commercialization.

Future directions and industry integration strategies

To facilitate widespread industrial adoption, the following strategies should be considered: Cost-Effective Manufacturing: Advancements in green synthesis methods and scalable production techniques can help lower costs. Hybrid Lubricant Formulations: Combining nanolubricants with conventional lubricants can offer a balance between performance and affordability. Collaborative Research and Industry Partnerships: Engaging with key players in the automotive, aerospace, and manufacturing sectors for extensive field trials[143] . Regulatory Compliance and Safety Assessments: Conducting comprehensive environmental impact studies to ensure adherence to global lubrication standards.

Conclusions

Summary of findings

The study of synthesizing different dimensional morphologies of 2D nanomaterials has revealed their immense potential as additives for nano lubricants. Through various synthesis techniques - such as chemical vapor deposition, hydrothermal methods, solvothermal processes, and exfoliation - researchers can achieve precise control over nanomaterial morphology, including structures like sheets, flakes, nanospheres, and nanoflowers. Each of these morphologies plays a distinct role in enhancing the tribological performance of nano lubricants. The review has shown that optimized morphologies can reduce friction, provide superior wear resistance, and improve thermal and chemical stability, demonstrating the transformative impact of morphology on lubricant performance

Importance of morphology in optimizing nano lubricant performance

The morphology of 2D nanomaterials is a crucial factor influencing their effectiveness as additives. Morphologies such as nanosheets and nanoflakes exhibit exceptional sliding properties, reducing friction between moving surfaces. Spherical and flower-like morphologies act as rolling elements or stress distributors, providing enhanced wear resistance and load- bearing capacity. Furthermore, layered morphologies facilitate heat dissipation, ensuring thermal stability under extreme operating conditions. By tailoring the morphology during synthesis, nanomaterials can be optimized for specific tribological needs, paving the way for the development of nano lubricants with exceptional performance characteristics[144] .

Call for interdisciplinary research to address challenges

Despite the promising advances, significant challenges remain in the synthesis and application of 2D nanomaterials as nanolubricant additives. Issues such as scalability of synthesis methods, cost-effectiveness, and ensuring compatibility with various base oils need to be addressed [145]. Moreover, achieving consistent dispersion of nanomaterials in lubricant formulations is another critical hurdle. Tackling these challenges demands interdisciplinary collaboration among material scientists, chemists, tribologists, and engineers. Joint efforts can lead to the development of innovative synthesis techniques, cost-efficient manufacturing processes, and environmentally sustainable solutions, enabling the widespread adoption of these advanced nano lubricants. By fostering such collaborative research, the full potential of 2D nanomaterials can be realized, driving advances in lubrication technology and contributing to energy efficiency and sustainability across industries [146] .

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References

[1] M Abo-Zahhad and Z Said. *Stability of nanorefrigerants and nanolubricants. In*: Z Said and AK Tiwari (Eds.). Nano-refrigerants and nano-lubricants: Fundamentals and applications. Elsevier, Amsterdam, The Netherlands, 2024, p. 73-99.

[2] T Mog. Advances of synthesis of hexagonal boron nitride for industrial applications: A review. *Materials International* 2024; **6(3)**, 23.

[3] N Al-Harbi and NK Abd-Elrahman. Physical methods for preparation of nanomaterials, their characterization and applications: A review. *Journal of Umm Al-Qura University for Applied Sciences* 2024. https://doi.org/10.1007/s43994-024-00165-7

[4] SI Ali, D Dutta, A Das, S Mandal and AC Mandal. Understanding the structure-property correlation of tin oxide nanoparticles synthesized through the sol-gel technique. *Journal of Luminescence* 2023; **253**, 119465.

[5] V An, Y Irtegov and C De Izarra. Study of tribological properties of nanolamellar WS_2 and MoS_2 as additives to lubricants. *Journal of Nanomaterials* 2014; **2014(1)**, 865839.

[6] A Arora, KUV Kiran, B Ramakrishnan, BR Sunil, R Dumpala. Effect of heat treatment on mechanical and tribological characteristics of Electroless Ni-P deposits. *Journal of Physics: Conference Series* 2019; **1355(1)**, 012032.

[7] H Assad, IA Lone, A Sihmar, A Kumar and A Kumar. An overview of contemporary developments and the application of graphene-based materials in anticorrosive coatings. *Environmental Science and Pollution Research* 2023. https://doi.org/10.1007/s11356-023-30658-7

[8] NF Azman and S Samion. Dispersion stability and lubrication mechanism of nanolubricants: A review. *International Journal of Precision Engineering and Manufacturing - Green Technology* 2019; **6(2)**, 393-414.

[9] SVAR Sastry and CVR Murthy. Harnessing biomass energy for the production of biodiesel. *IACSIT International Journal of Engineering and Technology* 2012*;* **4(3)**, 279-281.

[10] N Baig. Two-dimensional nanomaterials: A critical review of recent progress, properties, applications, and future directions. *Composites Part A: Applied Science and Manufacturing* 2023; **165**, 107362.

[11] SA Bakhramov, UK Makhmanov and BA Aslonov. Fullerene nanowhiskers and control their geometric dimensions. *Condensed Matter Physics* 2023.https://doi.org/10.20944/preprints202307.0121.v1

[12] M Ben Arbia, H Helal and E Comini. Recent advances in low-dimensional metal oxides via sol-gel method for gas detection. *Nanomaterials* 2024; **14(4)**, 359.

[13] RB Berk, T Beierling, L Metzger and HA Gasteiger. Investigation of the particle formation mechanism during coprecipitation of Ni-rich hydroxide precursor for Li-ion cathode active material. *Journal of the Electrochemical Society* 2023; **170(11)**, 110513.

[14] T Bertaglia, CM Costa, S Lanceros-Méndez and FN Crespilho. Eco-friendly, sustainable, and safe energy storage: a nature-inspired materials paradigm shift. In *Materials Advances*. *Royal Society of Chemistry* 2024; **5(19)**, 7534-7547.

[15] G Boidi, B Ronai, D Heift, F Benini, M Varga, MC Righi and A Rosenkranz. Tribology of 2D black phosphorus - Current state-of-the-art and future potential. *Advances in Colloid and Interface Science* 2024; **328**, 103180.

[16] SVAR Sastry and P Sreenu. New energy sources and its sustainability. *In*: Proceedings of the IEEE International Conference on Engineering Education: Innovative Practices and Future Trends, Kottayam, 2012.

[17] D Bokov, A Turki Jalil, S Chupradit, W Suksatan, M Javed Ansari, IH Shewael, GH Valiev and E Kianfar. Nanomaterial by sol-gel method: Synthesis and application. *Advances in Materials Science and Engineering* 2021; **2021(1)**, 5102014.

[18] N Borane, R Boddula, N Odedara, J Singh, M Andhe and R Patel. Comprehensive review on synthetic methods and functionalization of graphene oxide: Emerging applications. *Nano-Structures & Nano-Objects* 2024; **39**, 101282.

[19] EL Castellanos-Leal, A Osuna-Zatarain and A Garcia-Garcia. Frictional properties of 2-dimensional nanomaterials as an additive in liquid lubricants: Current challenges and potential research topics. *Lubricants* 2023; **11(3)**, 137.

[20] SVAR Sastry and CVR Murthy. Biodiesel reactor modeling using fuzzy logic. *International Journal of Emerging Technology and Advanced Engineering* 2013; **3(5)**, 436-39.

[21] JV Embden, S Gross, KR Kittilstved and D Gaspera, E. Colloidal approaches to zinc oxide nanocrystals. *Chem. Rev.* 2022; **123**, 271-326.

[22] M Chhattal, A Rosenkranz, S Zaki, K Ren, A Ghaffar, Z Gong and PG Grützmacher. Unveiling the tribological potential of MXenes-current understanding and future perspectives. *Advances in Colloid and Interface Science* 2023; **321**, 103021.

[23] KM Chin, S Sung Ting, HL Ong and M Omar. Surface functionalized nanocellulose as a veritable inclusionary material in contemporary bioinspired applications: A review. *Journal of Applied Polymer Science* 2018; **135(13)**, 46065.

[24] F Choudhary, P Mudgal, A Parvez, P Sharma and

H Farooqi. A review on synthesis, properties and prospective applications of carbon nanomaterials. *Nano-Structures & Nano-Objects* 2024; **38**, 101186.

[25] O Dagdag and H Kim. Recent advances for poly(cyclotriphosphazene) functionalized graphene oxide composites: Synthesis, properties and applications. *Journal of Industrial and Engineering Chemistry* 2024; **136**, 89-122.

[26] TK Das, S Basak and S Ganguly. 2D nanomaterial for microplastic Removal: A critical review. *Chemical Engineering Journal* 2024; **492**, 152451.

[27] Deepika. Nanotechnology implications for high performance lubricants. *SN Applied Sciences* 2020; **2(6)**, 1128.

[28] F Delkhosh, A Qotbi, AH Behroozi and V Vatanpour. Magnetron sputtering in membrane fabrication and modification: Applications in gas and water treatment. *Journal of Industrial and Engineering Chemistry* 2025; **143**, 85-108.

[29] A Dhanola and KK Gajrani. Novel insights into graphene-based sustainable liquid lubricant additives: A comprehensive review. *Journal of Molecular Liquids* 2023; **386**, 122523.

[30] L Duan, J Li and H Duan. Nanomaterials for lubricating oil application: A review. *Friction* 2023; **11(5)**, 647-684.

[31] MA Eldoma, N Zouli, GA Elawadi, MA Mahmoud, IY Qudsieh, OY Bakather, M Hassan, MS Alomar, AFF Abouatiaa, SEF Hegazi, YA Elsheikh, KA Mahmoud and IG Alhindawy. Utilizing a one-step hydrothermal method for fabrication and evaluation of radiation shielding characteristics in Pb(ZrO_3)-doped zirconia: Synthesis and characterization. *Journal of Materials Science* 2024; **59(8)**, 3253-3269.

[32] SVAR Sastry and CVR Murthy. Synthesis of biodiesel by insitu transesterification of karanja oil. *Bangladesh Journal of Scientific and Industrial Research* 2014; **49(4)**, 211-218.

[33] SVAR Sastry and KV Rao. Studies on conversion of FA's and FFA's to alkyl esters using WCO's of different origin. *Materials Science Forum* 2019; **97**, 1-72.

[34] M Erdi Korkmaz and M Kumar Gupta. Nano lubricants in machining and tribology applications: A state of the art review on challenges and future trend. *Journal of Molecular Liquids* 2024; **407**, 125261.

[35] SVAR Sastry, I Vishnupriya and A Sahoo. Acid catalysis of waste cooking oils for biodiesel production. *Iranian (Iranica) Journal of Energy & Environment* 2019; **10(2)**, 91-95.

[36] Y Fan, L Xu, S Liu, J Li, J Xia, X Qin, Y Li, T Gao and X Tang. The state-of-the-art and perspectives of laser ablation for tumor treatment. *Cyborg and Bionic Systems* 2024; **5**, 0062.

[37] L Fernandez-Diaz, J Castillo, E Sasieta-Barrutia, M Arnaiz, M Cabello, X Judez, A Terry, L Otaegui, MC Morant-Miñana and A Villaverde. Mixing methods for solid state electrodes: Techniques, fundamentals, recent advances, and perspectives. *Chemical Engineering Journal* 2023; **464**, 142469.

[38] Q Gao, S Liu, K Hou, Z Li and J Wang. Graphene-based nanomaterials as lubricant additives: A review. In *Lubricants* 2022; **10(10)**, 273.

[39] M Garcia Tobar, RW Contreras Urgiles, B Jimenez Cordero and J Guillen Matute. Nanotechnology in lubricants: A systematic review of the use of nanoparticles to reduce the friction coefficient. *Lubricants* 2014; **12(5)**, 166.

[40] GK Ghosh, A Kotia, N Kumar and SK Ghosh. Optimization and modeling of rheological characteristics for graphene-gear oil based nanolubricant using response surface methodology. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 2021; **630**, 127605.

[41] T Ghosh, P Banerji and NC Das. *Synthesis methods for the preparation of fullerenes*. *In*: K Joseph, R Wilson, G George and S Appukuttan (Eds.). Zero-dimensional carbon nanomaterials. Woodhead Publishing, Cambridgeshire, United Kingdom, 2024, p. 135-151.

[42] X Gong, Y Lin, X Li, A Wu, H Zhang, J Yan and C Du. Decomposition of volatile organic compounds using gliding arc discharge plasma. *Journal of the Air and Waste Management Association*2020; **70(2)**, 138-157.

[43] V Harish, MM Ansari, D Tewari, AB Yadav, N Sharma, S Bawarig, ML García-Betancourt, A Karatutlu, M Bechelany and A Barhoum. Cutting-

edge advances in tailoring size, shape, and functionality of nanoparticles and nanostructures: A review. *Journal of the Taiwan Institute of Chemical Engineers* 2023; **149**, 105010.

[44] L Hernandez-Tabares, FJ Chao-Mujica, JG Darias-Gonzalez, LM Ledo Pereda, M Antuch, E Carrillo-Barroso, JE Chong-Quero and LF Desdin-Garcia. Review of the design and operation criteria of a dc submerged arc discharge carbon nanostructure synthesis installation. *Journal of Nanomaterials* 2024; **2024(1)**, 9949667.

[45] KR Hossain, MA Shyeed, M Al Amin, MS Hossain, MS Rahman, MH Rahman and C Nasreen. Nanomaterials function in additive manufacturing. *Journal of Kufa-Physics* 2023; **15(02)**, 23-39.

[46] J Hou, C Hong, W Ling, J Hu, W Feng, Y Xing, Y Wang, C Zhao and L Feng. Research progress in improving sludge dewaterability: sludge characteristics, chemical conditioning and influencing factors. *Journal of Environmental Management* 2024; **351**, 119863.

[47] Q Huang, X Shi, Y Xue, K Zhang and C Wu. Recent progress on surface texturing and solid lubricants in tribology: Designs, properties, and mechanisms. *Materials Today Communications* 2023; **35**, 105854.

[48] SVAR Sastry. The impact of fossil fuels on Global Warming and alternative feasible solutions. *TEST Engineering and Management* 2020; **83**, 14354-14361.

[49] YJJ Jason, HG How, YH Teoh and HG Chuah. A study on the tribological performance of nanolubricants. *Processes* 2020; **8(11)**, 1372.

[50] SVAR Sastry and KV Rao. Characterizing the conversion of transesterification reaction by modeling of glycerol-rich phase. *International Journal of Environment and Waste Management* 2020; **26(3)**, 309-323.

[51] N Jayaprakash, K Elumalai, S Manickam, G Bakthavatchalam and P Tamilselvan. Carbon nanomaterials: Revolutionizing biomedical applications with promising potential. *Nano Materials Science* 2024. https://doi.org/10.1016/J.NANOMS.2024.11.004.

[52] Z Jiang, Y Sun, B Liu, L Yu, Y Tong, M Yan, Z Yang, Y Hao, L Shangguan, S Zhang and W Li. Research progresses of nanomaterials as lubricant additives. *Friction* 2024; **12(7)**, 1347-1391.

[53] K Kant, RC Singh and S Maji. Opportunities to improve the lubrication, fuel efficiency, and emission reduction using nanotechnologies: A review. *Journal of Thermal Analysis and Calorimetry*. 2025. https://doi.org/10.1007/s10973-025-14018-w.

[54] JF Kayode, SA Afolalu, ME Emetere, SI Monye and SL Lawal. Application and impact of tribology in energy-an overview. *E3S Web of Conferences* 2023; **391**, 01081.

[55] A Khan, SN Sapakal and A Kadam. Comparative analysis of graphene oxide (GO) reduction methods: Impact on crystallographic, morphological, and optical properties. *Graphene and 2D Materials* 2024; **9(1-2)**, 101-109.

[56] SR Khapate, TAJ Siddiqui and RS Mane. *Solvothermal technique for the synthesis of metal oxide nanostructures. In*: R Mane, V Jadhav and A Al-Enizi (Eds.). Solution methods for metal oxide nanostructures. Elsevier, Amsterdam, The Netherlands, 2023, p. 95-108.

[57] CM Lai, HG How, YJJ Jason, YH Teoh, H Yaqoob, S Zhang, MR Hatshan and F Sher. Tribological characterisation of graphene hybrid nanolubricants in biofuel engines. *Fuel* 2024; **357**, 129654.

[58] C Lamiel, I Hussain, H Rabiee, OR Ogunsakin and K Zhang. Metal-organic framework-derived transition metal chalcogenides (S, Se, and Te): Challenges, recent progress, and future directions in electrochemical energy storage and conversion systems. *Coordination Chemistry Reviews* 2023; **480**, 215030.

[59] SVAR Sastry. Effect of catalyst and methanol on synthesis of methyl esters from used cooking oil. *Journal of Catalyst & Catalysis* 2021; **8(1)**, 1-10.

[60] D Li, Q Chen, J Chun, K Fichthorn, J De Yoreo and H Zheng. Nanoparticle assembly and oriented attachment: Correlating controlling factors to the resulting structures. *Chemical Reviews* 2023; **123(6)**, 3127-3159.

[61] H Li, W Yang, N Wu, L Sun, P Shen, X Wang and

Y Li. Highly-dispersed carboxymethyl cellulose and polyvinylpyrrolidone functionalized boron nitride for enhanced thermal conductivity and hydrophilicity. *Applied Surface Science* 2023; **617**, 156485.

[62] J Li, D Chen, H Zhang, Z Jiang, K Sun, J Fan and Y Tang. The tribological properties of nano-lubricants and their application on bearings: Recent research progress. *International Journal of Advanced Manufacturing Technology* 2024; **134(7-8)**, 3051-3082.

[63] JML del Río, ER López, F García and J Fernández. Tribological synergies among chemical-modified graphene oxide nanomaterials and a phosphonium ionic liquid as additives of a biolubricant. *Journal of Molecular Liquids* 2021; **336**, 116885.

[64] J Liu, D Hui and D Lau. Two-dimensional nanomaterial-based polymer composites: Fundamentals and applications. In *Nanotechnology Reviews* 2022; **11(1)**, 770-792.

[65] J Luo, M Liu and L Ma. Origin of friction and the new frictionless technology - Superlubricity: Advancements and future outlook. *Nano Energy* 2021; **86**, 106092.

[66] X Luo, S Wu, D Wang, Y Yun, Q An and C Li. Sustainable development of cutting fluids: The comprehensive review of vegetable oil. *Journal of Cleaner Production* 2024; **473**, 143544.

[67] BR Manu, A Gupta and AH Jayatissa. Tribological properties of 2D materials and composites- A review of recent advances. *Materials* 2021; **14(7)**, 1630.

[68] F Marino, JML del Río, ER López and J Fernández. Chemically modified nanomaterials as lubricant additive: Time stability, friction, and wear. *Journal of Molecular Liquids* 2023; **382**, 121913.

[69] SVAR Sastry. Predicting rate equation for the synthesis of Octadec-9-enoic acid methyl esters by the Methanolysis of Pongamia Pinnata Triglycerides Using Sono Reactor. *Journal of Polymer & Composites* 2021; **9(3)**, 45-55.

[70] AR Marlinda, GSH Thien, M Shahid, TY Ling, A Hashem, KY Chan and MR Johan. Graphene as a lubricant additive for reducing friction and wear in its liquid-based form. *Lubricants* 2023; **11(1)**, 29.

[71] T Kulkarni, B Toksha and A Autee. Optimizing nanoparticle attributes for enhanced anti-wear performance in nano-lubricants. *Journal of Engineering and Applied Science* 2024; **71 (1)**, 30-38.

[72] AMM Ibrahim, LI Wei, AI Mourad, AE Mohamed, AM ABD EL-NABY, MS Al SOUFI, MF EZZAT and A ElSHEIKH. Cooling and lubrication techniques in grinding: A state-of-the-art review, applications, and sustainability assessment. *Chinese Journal of Aeronautics* 2023; **36(7)**, 76-113.

[73] VV Mohan, KP Revathy, CB Adithyan and RB Rakhi. Recent developments of tungsten disulfide-based nanomaterials for supercapacitor applications. *Journal of Energy Storage* 2024; **88**, 111505.

[74] S Nayak and K Parida. Plethora of preparatory features on single layered double hydroxide towards energy conversion process. *Materials Research Bulletin* 2023; **162**, 112185.

[75] L Ndlwana, N Raleie, KM Dimpe, HF Ogutu, EO Oseghe, MM Motsa, TAM Msagati and BB Mamba. Sustainable hydrothermal and solvothermal synthesis of advanced carbon materials in multidimensional applications: A review. *Materials* 2021; **14(17)**, 5094.

[76] K Nikita, D Patel and SY Nam. *Functionalized boron nitride-based polymer nanocomposites. In*: G Patel, K Deshmukh and CM Hussain (Eds.). Advances in functionalized polymer nanocomposites. Woodhead Publishing, Cambridgeshire, United Kingdom, 2024, p. 501-543.

[77] CN da Rocha Amaral, LBS Marques, LR Duda and TF Veiga. *Nanolubricants applied in the automotive industry. AEA - Brazilian Society of Automotive Engineering* 2023.

[78] A Nugroho, M Kozin, R Mamat, Z Bo, MF Ghazali, MP Kamil, P Puranto, DA Fitriani, SAAzahra, KP Suwondo, PS Ashfiya and S Daud. Enhancing tribological performance of electric vehicle lubricants: Nanoparticle-enriched palm oil biolubricants for wear resistance. *Heliyon* 2024; **10(22)**, e39742.

[79] SVAR Sastry. Prediction of optimum process parameters for Karanja Biodiesel production using support vector machine, genetic algorithm and

particle swarm optimization. *Iranian Journal of Chemistry and Chemical Engineering* 2022; **41(5)**, 1821-33.

[80] AO Oladipo, TTI Nkambule, BB Mamba and TAM Msagati. Therapeutic nanodendrites: Current applications and prospects. *Nanoscale Advances* 2020; **2(11)**, 5152-5165.

[81] D Oluremi. *Industrial waste as a source for graphene nanosheets*. Federal University of Technology, Ondo, Nigeria, 2025.

[82] S Palchoudhury, K Ramasamy, J Han, P Chen and A Gupta. Transition metal chalcogenides for next-generation energy storage. *Nanoscale Advances* 2023; **5(10)**, 2724-2742.

[83] W Pei, X Pei, Z Xie and J Wang. Research progress of marine anti-corrosion and wear-resistant coating. *Tribology International* 2024; **198**, 109864.

[84] FM Pinto, MCMD de Conti, WS Pereira, JC Sczancoski, M Medina, PG Corradini, JF de Brito, AE Nogueira, MS Góes, OP Ferreira, LH Mascaro, F Wypych and FA La Porta. Recent advances in layered MX2-based materials (M = Mo, W and X = S, Se, Te) for emerging optoelectronic and photo(electro)catalytic applications. *Catalysts* 2024; **14(6)**, 388.

[85] B Podgornik. Adhesive wear failures. *Journal of Failure Analysis and Prevention* 2024; **22(1)**, 113-138.

[86] Y Rabbani, N Hajinajaf and M Shariaty-Niassar. The effect of microparticles/nanoparticles surface modification on the magnetorheological fluid properties: A review. *Journal of Intelligent Material Systems and Structures* 2023; **34(15)**, 1715-1738.

[87] Dhall, S.; Mehta, B.R.; Tyagi, A.K.; Sood, K. A review on environmental gas sensors: Materials and technologies. *Sens. Int.* 2021; ***2***, 100116.

[88] S Ragunath, N Radhika, S Aravind Krishna and N Jeyaprakash. Synthesis of high entropy alloy for surface modification by friction stir process: Recent advances and future directions. *Metals and Materials International* 2024; **30(5)**, 1170-1199.

[89] IS Raja, M Vedhanayagam, DR Preeth, C Kim, JH Lee and DW Han. Development of 2-dimensional nanomaterials based electrochemical biosensors on enhancing the analysis of food toxicants. In *International Journal of Molecular Sciences* 2021; **22(6)**, 3277.

[90] P Rajaram, AR Jeice and K Jayakumar. Review of green synthesized TiO_2 nanoparticles for diverse applications. *Surfaces and Interfaces* 2023; **39**, 102912.

[91] T Ramachandran, H Butt, L Zheng and M Rezeq. A review of 2D metal boride-derived nanostructures: From synthesis to energy storage and conversion applications. *Journal of Energy Storage* 2024; **99**, 113425.

[92] SM Ramteke, M Walczak, M De Stefano, A Ruggiero, A Rosenkranz and M Marian. 2D materials for Tribo-corrosion and -oxidation protection: A review. *Advances in Colloid and Interface Science* 2024; **331**, 103243.

[93] SVAR Sastry. Performance and emission analysis of Karanja Biodiesel using variable compression ratio engine. *International Journal of Environment and Waste Management* 2024; **34(1)**, 119-130.

[94] X Rao, C Sheng, Z Guo, L Dai and C Yuan. A novel finding on tribological, emission, and vibration performances of diesel engines linking to graphene-attapulgite lubricants additives under hot engine tests. *Renewable and Sustainable Energy Reviews* 2023; **182**, 113366.

[95] DL Wilson, J Ahlawat and M Narayan. The role of fullerenes in neurodegenerative disorders. *Journal of Nanotheranostics* 2024; **5(1)**, 1-12.

[96] W Raza, A Shaheen, NA Khan, KH Kim and X Cai. Advanced strategies for the synthesis and modulation of 2D layered heterostructures for energy conversion and storage applications. *Progress in Materials Science* 2024; **146**, 101325.

[97] AA Safronov, VE Kuznetsov, OB Vasilieva, YD DudnikV and N Shiryaev. AC plasma torches. Arc initiation systems. design features and applications. *Instruments and Experimental Techniques* 2019; **62(2)**, 193-200.

[98] VS Saji. 2D hexagonal boron nitride (h-BN) nanosheets in protective coatings: A literature review. *Heliyon* 2023; **9(9)**, e19362.

[99] HM Saleh and AI Hassan. Synthesis and characterization of nanomaterials for application in cost-effective electrochemical devices. *Sustainability* 2023; **15(14)**, 10891.

[100] S Sasaki. Advances in tribology driven by surface

science. *E-Journal of Surface Science and Nanotechnology* 2023; **21(2)**, 98-104.

[101] LM Shaker, AA Al-Amiery and WK Al-Azzawi. Nanomaterials: Paving the way for the hydrogen energy frontier. *Discover Nano* 2024; **19(1)**, 3.

[102] S Shimizu and K Takahashi. Magnetron sputtering thruster operated with a compact gas feeding system using double pulsed valves. *Acta Astronautica* 2024; **221**, 79-84.

[103] A Siddique, M Yaqoob, W Aslam, F Zaffar, S Atiq and MU Shahid. A systematic review on promising development of cost-effective, biodegradable, and environment friendly vegetable based nanofluids as a future resource for green transformer insulation oil. *Journal of Molecular Liquids* 2024; **403**, 124836.

[104] KN Sidh, D Jangra and H Hirani. An experimental investigation of the tribological performance and dispersibility of 2D nanoparticles as oil additives. *Lubricants* 2023; **11(4)**, 179.

[105] ET Sifuentes, OV Kharissova, D Maldonado-Cortés, L Peña-Parás, R Michalczewski and BI Kharisov. A comparison of tribological properties of nanolubricants containing carbon nanotori and additional additives. *Materials Chemistry and Physics* 2021; **272**, 124973.

[106] AT Silvestri, A El Hassanin, G de Alteriis and A Astarita. Energy consumption and tool condition in friction stir processing of aluminum alloys. *International Journal of Precision Engineering and Manufacturing - Green Technology* 2025. https://doi.org/10.1007/s40684-024-00633-9

[107] AP Singh, RK Dwivedi and A Suhane. Influence of nano particles on the performance parameters of lube oil: A review. *Materials Research Express* 2021; **8(10)**, 102001.

[108] T Kulkarni, B Toksha and A Autee, Optimizing nanoparticle attributes for enhanced anti-wear performance in nano-lubricants. *Journal of Engineering and Applied Science* 2024; **71(1)**, 30.

[109] S Singh, M Zeeshan, AAP Khan, M Nazim and AM Asiri. *Prospects and future perspective of nanomaterials for energy storage applications. In*: A Khan, M Nazim and A Asiri (Eds.). Advances in electronic materials for clean energy conversion and storage applications. Woodhead Publishing, Cambridgeshire, United Kingdom, 2023, p. 569-578.

[110] SC Smith and DF Rodrigues. Carbon-based nanomaterials for removal of chemical and biological contaminants from water: A review of mechanisms and applications. *Carbon* 2015; **91**, 122-143.

[111] J Sun and S Du. Application of graphene derivatives and their nanocomposites in tribology and lubrication: A review. *RSC Advances* 2019; **9(69)**, 40642-40661.

[112] J Swapnalin, B Koneru, R Boddula, D Rangappa and P Banerjee. *2D nanomaterials as lubricant additives. In*: AK Nadda, TA Nguyen, S Sharma, M Bilal and RK Gupta (Eds.). Nanotechnology for advanced biofuels: Fundamentals and applications. Elsevier Science, Amsterdam, The Netherlands, 2023, p. 97-112.

[113] A Taghizadeh Tabrizi and N Enzinger. 2D materials enhancing tribological performance in bulk and composite coatings: A review. *Graphene and 2D Materials* 2024. https://doi.org/10.1007/s41127-024-00081-x

[114] NS Chauhan and SS Gill. The impact of nanoparticles on agriculture and soil. Academic Press, London, Elsevier, 2023.

[115] R Thyagarajan and DS Sholl. A database of porous rigid amorphous materials. *Chemistry of Materials* 2023; **32(18)**, 8020-8033.

[116] MM Uddin, MH Kabir, MA Ali, MM Hossain, MU Khandaker, S Mandal, A Arifutzzaman and D Jana. Graphene-like emerging 2D materials: Recent progress, challenges and future outlook. *RSC Advances* 2023; **13(47)**, 33336-33375.

[117] P Uniyal, P Gaur, J Yadav, T Khan and OS Ahmed. A review on the effect of metal oxide nanoparticles on tribological properties of biolubricants. *ACS Omega*. 2023; **9(11)**, 12436-12456.

[118] D Veeman, MV Shree, P Sureshkumar, T Jagadeesha, L Natrayan, M Ravichandran and P Paramasivam. Sustainable development of carbon nanocomposites: synthesis and classification for environmental remediation. *Journal of Nanomaterials* 2021; **2021(1)**, 5840645.

[119] BVN Reddy, BVS Reddy, NS Kumar and KCB Naidu. Materials for conversion of CO_2. *Biointerface Research in Applied Chemistry* 2022;

12(1), 486-497.

[120] L Samylingam, N Aslfattahi, CK Kok, K Kadirgama, N Sazali, KW Liew, M Schmirler, D Ramasamy, WW Harun, M Samykano, AS Veerendra, Semin and S Sivaraos. Enhancing lubrication efficiency and wear resistance in mechanical systems through the application of nanofluids: A comprehensive review. *Journal of Advanced Research in Micro and Nano Engineering* 2024; **16(1)**, 1-18.

[121] B Wang, F Qiu, GC Barber, Q Zou, J Wang, S Guo, Y Yuan and Q Jiang. Role of nano-sized materials as lubricant additives in friction and wear reduction: A review. *Wear* 2022; **490-491**, 204206.

[122] L Wang, Y Bai, Z Ma, C Ge, H Guan and XD Zhang. Tribological performances of hexagonal boron nitride nanosheets via surface modification with silane coupling agent. *SN Applied Sciences* 2021; **3(3)**, 368.

[123] Q Wang, T Hou, W Wang, G Zhang, Y Gao and K Wang. Tribological properties of black phosphorus nanosheets as oil-based lubricant additives for titanium alloy-steel contacts: Lubricaiton of black phosphene. *Royal Society Open Science* 2020; **7(9)**, 368.

[124] S Wang, D Chen, Q Hong, Y Gui, Y Cao, G Ren and Z Liang. Surface functionalization of metal and metal oxide nanoparticles for dispersion and tribological applications - a review. *Journal of Molecular Liquids* 2023; **389**, 122821.

[125] LK Wei, SZ Abd Rahim, MM Al Bakri Abdullah, ATM Yin, MF Ghazali, MF Omar, O Nemeş, AV Sandu, P Vizureanu and AE Abdellah. Producing metal powder from machining chips using ball milling process: A review. *Materials* 2023; **16(13)**, 4635.

[126] D Xia, Y Wang, H Liu, J Yan, H Lin and S Han. Research progress of antioxidant additives for lubricating oils. *Lubricants* 2024; **12(4)**, 115.

[127] R Xia, D Lou, H Younes, J Haiston, H Chen and H Hong. Synergistic effect of hexagonal boron nitride and carbon nanofibers on tribological behavior of nanolubricant. *Tribology International* 2023; **177**, 107957.

[128] Y Xu, Y Li, Q Hou, Y Hao and Z Ding. Ball milling innovations advance mg-based hydrogen storage materials towards practical applications. *Materials* 2024; **17(11)**, 2510.

[129] Y Xuan, L Zhao, D Li, S Pang and Y An. Recent advances in the applications of graphene materials for the oil and gas industry. *RSC Advances* 2023; **13(33)**, 23169-23180.

[130] A Yadav, H Kumar, R Sharma and R Kumari. Synthesis, processing, and applications of 2D (nano)materials: A sustainable approach. *Surfaces and Interfaces* 2023; **39**, 102925.

[131] C Yang, G Wang, Q Bai, D Li and S Guo. Efficient lubrication of alkylated reduced graphene oxide based on tribochemistry. *Surfaces and Interfaces* 2024; **44**, 103624.

[132] K Yang, Y Xiong, G Wu, H Lin, J Tang, C Wu, H Chen and Y Wang. Multi-dimensional nano-additives for their superlubricity: Tribological behaviors and lubrication mechanisms. *Advanced Materials Interfaces*. 2024. https://doi.org/10.1002/admi.202400796.

[133] L Yang, C Wei, F Jiang, D Liang, K Yan, Z Cheng, Z Li and F Ren. Significant reduction in friction and wear of an ultrafine-grained single-phase FeCoNi alloy through the formation of nanolaminated structure. *Acta Materialia* 2024; **263**, 119526.

[134] X Yin, L Mu, Z Jia, H Pang, C Chai, H Liu, C Liang, B Zhang and D Liu. Nanostructure of superlubricating tribofilm based on friction-induced a-C:H films under various working conditions: A review of solid lubrication. *Lubricants* 2024; **12(2)**, 40.

[135] HA Zaharin, MJ Ghazali, N Thachnatharen, F Ezzah, R Walvekar and M Khalid. Progress in 2D materials based Nanolubricants: A review. *FlatChem* 2023; **38**, 100485.

[136] HA Zaharin, MJ Ghazali, N Thachnatharen, F Ezzah, R Walvekar and M Khalid. Progress in 2D materials based Nanolubricants: A review. *FlatChem* 2023; **38**, 100485.

[137] L Zhang, Z Zhang, X Gao, SJ Matlan and NA Taha. The preparations of fluorographene nanosheets and research in tribological properties in high vacuum. *Materials* 2023; **16(11)**, 3929.

[138] P Zhang, J Zhao, C Lu, L Huang, J Lin, Z Lin, D Bu and S Huang. Size dependent photogeneration

charge carrier density of hollow ZnIn2S4 microspheres for enhanced photocatalytic activity. *Chemical Engineering Journal* 2024; **489**, 151331.

[139] T Zhang, C Wang, G Liu, C Yao, X Zhang, C Zhang and Q Chi. High thermal conductivity and low dielectric loss of 3-dimensional boron nitride nanosheets/epoxy composites. *Composites Communications* 2024; **50**, 102007.

[140] Y Zhang, L Li, X Cui, Q An, P Xu, W Wang, D Jia, M Liu, YS Dambatta and C Li. Lubricant activity enhanced technologies for sustainable machining: Mechanisms and processability. *Chinese Journal of Aeronautics* 2024. https://doi.org/10.1016/j.cja.2024.08.034

[141] C Zhao, J Kang, Y Li, Y Wang, X Tang and Z Jiang. Carbon-based stimuli-responsive nanomaterials: Classification and application. *Cyborg and Bionic Systems* 2023; **4**, 0022.

[142] J Zhao, Y Huang, Y He and Y Shi. Nanolubricant additives: A review. *Friction* 2021; **9(5)**, 891-917.

[143] M Zhou. A brief review of nanotechnology. *Journal of Physics: Conference Series* 2023; **2608(1)**, 891-917.

[144] S Zhou, W Li, W Zhao, C Liu, Z Fang and X Gao. Tribological behaviors of polyimide composite films enhanced with fluorographene. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* 2019; **580**, 123707.

[145] H Zhu and J Li. Advancements in corrosion protection for aerospace aluminum alloys through surface treatment. *International Journal of Electrochemical Science* 2024; **19(2)**, 100487.

[146] S Zilabi, M Shareei, A Bozorgian, A Ahmadpour and E Ebrahimi. Advanced journal of chemistry-section b natural products and medical chemistry a review on nanoparticle application as an additive in lubricants nano plastic additive, tribological properties friction coefficient anti-wear. *Advanced Journal of Chemistry, Section B* 2022; **2022(3)**, 209-221.