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Review article

Enhancing tribological performance: A comprehensive review of graphene-based additives in lubricating greases

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ABSTRACT

The integration of carbon-based additives, such as graphene, graphene ox- ide (GO), and reduced graphene oxide (rGO), into lubricating greases has attracted significant interest in the field of tribology. These materials exhibit unique properties such as exceptional mechanical strength, low interlayer shear resistance, and high thermal conductivity, which act to enhance the performance of lubricating greases. This review paper explores grease formation, types, and performance, focusing on the potential advantages and limitations of graphene derivatives as lubricant additives. Graphene has been shown to reduce friction and wear, improve load-carrying capacity, and enhance thermal stability through various research projects. Despite the promising results, challenges such as effective dispersion, scalability of synthesis, and grease structure compatibility remain. This paper provides a comprehensive overview of current research, highlighting the benefits, limitations, and future directions for graphene-based additives in lubricating greases.

1. Introduction

Friction, an inherent consideration on every moving part, is critical to a machine's efficiency over time. Tribology, the science of friction, wear and lubrication, is a multidisciplinary field that aims to optimize performance through lubrication. Movement and surface interactions in machinery lead to energy loss, material degradation and increased maintenance costs which tribology aims to minimize. The impact of friction is significant, with more than 80 % of abnormal wear being caused by failures in lubrication [1].

Stemming from this need, various lubrication systems exist, with most commercial lubricants beginning as base oil. Derived from crude oils, lubri- cating oils were first developed in the 18th and 19th centuries when whale blubber could no longer meet industrial needs [2]. In the 1930s, the first fully synthetic oils, which now make up around 10 % of the lubricant market, were developed alongside the idea of incorporating additives into lubricants [2,3]. Modern-day additives are vital, allowing lubricants to survive a wide variety of conditions that were previously inaccessible [2].

Around this period, the first modern commercial greases were introduced by combining soaps with various lubricating oil compounds to thicken them. While Lithium-based grease makes up the lion's share of the industry, with more than 70 % market share, several other thickening agents exist [4]. Some other common agents include calcium sulfonate, polyurea, clay, aluminum, and calcium, as well as complex versions of some thickeners. With new ad- vancements in oil and grease, a wide variety of additives were tested and implemented to alter the characteristics of the final lubricant. Some com- mon additives include antioxidants, dispersants, anti-wear, demulsifiers, anti- foam, pour point depressants and friction modifiers. Additives act on various chemical principles but are generally grouped by their effect on the lubricant [5].

All things considered, tribology is incredibly important to modern-day technology and impacts the functionality of many machines. Not only that, but tribology has the capacity to cut costs and aid the environment, with new lubricants being able to save an estimated 33 million USD and 145 megatons of CO2 emissions annually [6]. As modern technology advances, demanding higher speeds and greater forces, tribology has been forced to adapt, develop- ing cutting-edge lubricants capable of withstanding these extreme conditions. Due to this demand, the lubricant market is predicted to grow by 52 million USD between

Abbreviations: GO, graphene oxide; RGO, reduced graphene oxide; PAO, polyalphaolefins; EP, extreme pressure; ZDDP, zinc dialkyl dithiophosphate; CVD, chemical vapor deposition; DMF, dimethylformamide.

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2022 and 2031, which means the demand for innovations is vast.

Graphene, derived from graphite, as seen in Fig. 1, is a material consisting of a single layer of carbon atoms arranged in a hexagonal lattice that has emerged as a novel additive aiming to improve frictional properties in lubricants [7]. Initially discovered and synthesized by Geim and Novoselov in 2004, graphene has demonstrated exceptional physical, chemical and me-chanical properties [8]. The unique properties of graphene are attributed to its atomic-level honeycomb structure and its strong covalent bonding across a single plane [9]. These characteristics could allow graphene to form a protective film on contact surfaces, significantly reducing friction and wear [10]. Graphene's high thermal conductivity aids in heat dissipation, an im- portant consideration for high-speed applications and elevated temperature conditions such as those in the mining, energy and aerospace industries.

Graphene's potential as an additive is being studied under various condi- tions, including high temperatures, heavy loads and different pressures. Several key issues have been discovered, including difficulty dispersing graphene in both oil and grease and the issue of graphene agglomerating once in solution [12]. However, it is likely that once it is thoroughly dispersed in grease, the compound's high viscosity could prevent problems common to graphene- enhanced lubricants. To maximize performance, evenly dispersed graphene is key [13]. More research is still required to fully understand the impact of graphene on lubricants.

This paper aims to review and compare the results of previous studies about graphene-enhanced greases and their applications in tribology. Various forms of graphene and their applications as additives will be analyzed. Graphene's performance as an additive and its benefits and challenges will be evaluated. This work aims to simplify the development process and provide a foundation for future research.

2. Grease

2.1. Formation of grease

Grease is formed by thickening a base oil with a thickening agent, usually a soap, to create a semi-solid lubricant [14]. The base oil, which usually constitutes 70–90 % of the grease, can be mineral, synthetic, or biological [14,15]. Mineral oils are derived from refined crude oil and are the most used due to their cost-effectiveness and abundance. Synthetic oils, which include polyalphaolefins (PAOs) and esters, offer superior performance characteris- tics, such as better thermal stability and oxidation resistance, but come at a higher cost [16]. Bio-based oils, derived from vegetable oils, provide an environmentally friendly alternative and are gaining popularity due to their biodegradability and renewable nature [17].

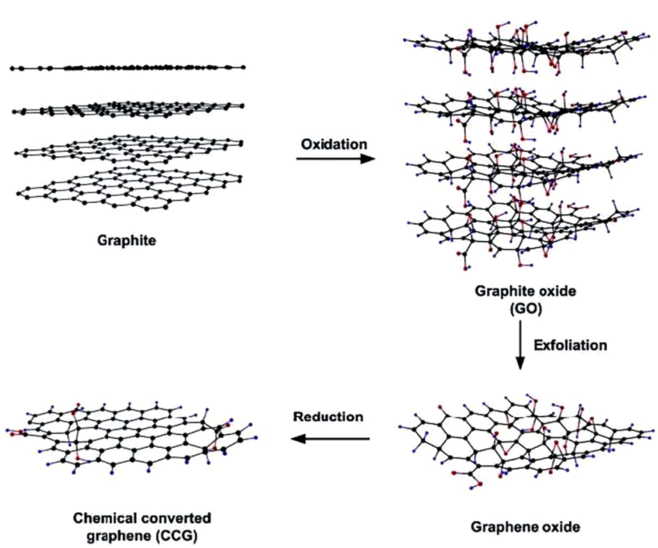

Fig. 1:. Synthesis process for graphene from graphite [11].

The thickening agents used in grease are crucial for its performance char-acteristics. These agents, often metallic soaps like lithium, calcium, and alu- minum, create a fibrous matrix that traps the oil [18]. This matrix structure functions like a sponge, holding the oil in place and releasing it gradually under mechanical stress to provide continuous lubrication [14]. The process of creating grease begins with heating the base oil to a temperature that allows the thickening agent to dissolve. The specific temperature and ingredients used depend on the type of grease being manufactured [16]. For example, in lithium-based grease production, the base oil is heated to approximately 85 °C [16]. Once the desired temperature is reached, the thickening agent is added. The production of various types of grease could include substances such as 12-hydroxystearic acid and lithium hydroxide, which undergo a saponifica- tion reaction to form the soap thickener at a slightly higher temperature [19,16]. This mixture is then heated to a high temperature (around 200 °C for lithium) and mechanically stirred to ensure uniform consistency [17–21]. Once the thickener is fully integrated, the mixture is gradually cooled. During cooling, additional base oil, along with most additives, can be added to adjust the grease's consistency and performance characteristics [22]. The final product is often homogenized using a three-roll mill or similar equipment to ensure a smooth texture and uniform distribution of oil. The composition breakdown of lubricating grease, as shown in Fig. 2, illustrates the typical proportions of base oil, thickener, and additives.

2.2. Types of grease

Various types of grease are formulated to meet specific performance re- quirements and applications. Each type of grease is distinguished by the thickening agent used, which imparts unique properties to the lubricant. Some of these greases include Lithium, Calcium, Polyurea and Lithium Complex.

2.2.1. Lithium

Lithium grease is the most widely used grease, prized for its versatility and balanced performance characteristics. It is produced by thickening mineral or synthetic oils with lithium soap, typically lithium 12-hydroxystearate [16]. This type of grease offers excellent mechanical stability, water resistance, and high-temperature performance, making it suitable for a wide range of applications from automotive to industrial machinery [19]. Lithium grease can operate effectively at temperatures up to 190 °C, making it ideal for many high-stress and high-temperature environments. The low price threshold encourages further optimization, which has resulted in a significant number of additives appearing in lithium greases to improve their performance. This versatility has cemented lithium grease's status as a preferred lubricant in numerous industries. The microstructure of lithium grease is shown in Fig. 3a.

2.2.2. Calcium

Calcium grease is known for its excellent water resistance, making it ideal for applications in wet environments. This grease is formed by thickening mineral oil with calcium soap, typically calcium hydroxide and a fatty acid like stearic acid [24]. It generally has a low melting point, not exceeding 100 °C, which limits its use in high-temperature settings [24]. Additives are often applied in calcium greases to combat its inherent high-temperature weakness and extend its lifespan [25]. One of the primary advantages of calcium grease is its ability to maintain consistency and lubrication properties even when exposed to water. This characteristic makes it particularly effective in environments with regular moisture exposure or submersion [26]. Calcium grease is cost-effective and easy to manufacture, and it is commonly used in marine equipment, automotive chassis lubrication, and agricultural machinery. The water-resistant properties of calcium grease are evident in the microstructure depicted in Fig. 3b.

Fig. 2. Composition breakdown of lubricating grease [23].

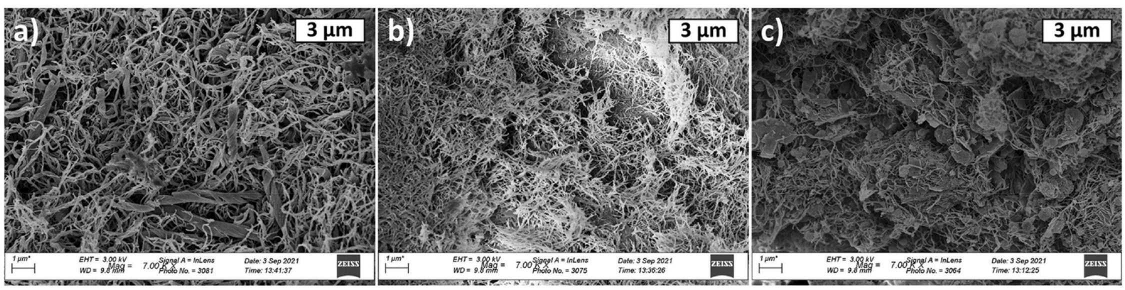

Fig. 3. SEM micrographs corresponding to (a) Lithium grease; (b) Calcium grease; (c) Polyurea grease [28].

2.2.3. Polyurea

Polyurea grease is known for its high-temperature stability, long service life, and excellent oxidation resistance. It is made by thickening base oils with polyurea compounds, which provide a stable structure that withstands temperatures up to 180 °C [27]. One significant benefit of polyurea grease is its chemical stability, which makes it suitable for use with various materials, reducing the risk of chemical reactions that could cause degradation [27]. Polyurea grease also offers good water resistance and mechanical stability, maintaining consistency and lubricating properties under mechanical stress and in the presence of moisture. These characteristics make polyurea grease an excellent choice for applications requiring reliable, long-term lubrication. Polyurea grease is commonly used in applications requiring long-term lubri- cation and minimal maintenance, such as electric motors and sealed-for-life bearings. Fig. 3c provides a close-up of polyurea grease, revealing its thermal stability and long-lasting performance.

2.2.4. Lithium complex

Lithium complex grease is a high-performance lubricant that extends the capabilities of traditional lithium grease. It is produced by adding secondary agents, such as borates or sulfonates, to the base lithium soap. This en- hancement provides lithium complex grease with higher dropping points, often exceeding 250 °C, making it suitable for extreme temperature applications [24]. Its enhanced properties also provide better oxidation stability and thermal resistance along with reduced wear and corrosion, further extending the lifespan of the lubricated components [27]. It also offers excellent mechanical stability, water resistance, and load-carrying capabilities, making it ideal for heavy-duty industrial applications such as automotive wheel bearings and heavy machinery.

2.3. Performance

Grease performance is evaluated based on various factors, including price, temperature stability, water resistance, mechanical stability, load-carrying capacity, and oxidation stability. Understanding these performance metrics is crucial for selecting the most effective grease for a given application.

Temperature Stability: Temperature stability measures a grease's ability to maintain its lubricating properties across a given temperature range. Greases must perform consistently without breaking down in both high- and low-temperature environments, depending on their application. Some greases are optimized for the higher range of temperatures often seen in heavy machinery, whereas others can be optimized for low temperatures, such as those seen in arctic or underwater conditions [29,21].

Water Resistance: Grease's ability to resist water is critical for applications in wet or humid environments. This is an important consideration whenever there is a risk of the grease being exposed to or submerged in water. Water resistance establishes how a grease will react to water exposure, with some grease types having much higher resistance to the impact of water on their structure [29,21].

Mechanical Stability: Grease's mechanical stability is crucial for maintaining its consistency and performance under shear and working conditions. This property determines how well a grease can withstand repeated mechanical stress without significant changes in its structure or performance characteristics. Greases with high mechanical stability are less likely to soften or leak out of bearings and other components during operation [30].

Load-Carrying Capacity: The ability of grease to support and maintain protection under heavy loads is essential for its effective performance in high-stress environments. This characteristic is particularly important in applications where the grease is subjected to high pressures and must maintain a protective film between moving surfaces. Greases with high load-carrying capacity ensure that machinery can operate under severe conditions without increased wear or damage [31].

Oxidation Stability: Grease's resistance to oxidation is a key factor in determining its longevity and effectiveness in long-term applications. Oxidation stability measures how well a grease can withstand the chemical reactions with oxygen that occur over time, which can lead to the formation of harmful acids and sludge. Greases with high oxidation stability are less likely to degrade, ensuring consistent performance and extended service life in various operating conditions [32].

Shear Stability: The ability of grease to maintain its consistency and structure under mechanical shear forces is known as shear stability. This property is crucial in applications where the grease is subjected to continuous or intermittent shearing, such as in bearings or gears. Greases with high shear stability resist thinning or breakdown, ensuring consistent lubrication and protection of components even under rigorous operational conditions [29,21].

These performance characteristics, as shown in Table 1, explain why certain greases are preferred for specific applications. For instance, lithium complex grease's ability to withstand high temperatures and heavy loads makes it ideal for industrial machinery [33]. For effective application and maintenance, choosing the right grease based on these performance metrics is essential, ensuring optimal lubrication and longevity of machinery and components. The type and concentration of thickening agents and additives significantly impact grease performance, altering mechanical stability and oxidation resistance, which are critical to many applications [33].

2.4. Additives

Additives are crucial in enhancing grease's performance characteristics by addressing specific functionality requirements and improving overall lu- brication efficiency. Common additives used in grease formulations include antioxidants, anti-wear agents, extreme pressure (EP) additives, corrosion inhibitors and friction modifiers [34,35].

Antioxidants: These are essential for preventing oxidation, which can lead to the formation of acidic by-products and sludge that degrade grease quality and reduce its effective lifespan. Common antioxidants used in grease formulations include phenolic antioxidants and amine antioxidants [36]. These compounds stabilize the grease com- position, helping maintain its performance over extended periods and under high-temperature conditions [26,27,35].

Extreme Pressure Additives: These additives are formulated to enhance the load-carrying capacity of grease, enabling it to withstand heavy loads without breaking down [37,38]. Sulfur-phosphorus compounds and chlorinated paraffins are commonly used extreme-pressure additives [39]. These additives chemically react with metal surfaces to form a protective layer that can endure high pressures and prevent seizure and galling under extreme conditions [40].

Corrosion inhibitors: These act to protect metal surfaces from rust and corrosion, which can be particularly detrimental in environments exposed to moisture or harsh chemicals [38]. Barium sulfonates and calcium sulfonates are typical corrosion inhibitors used in grease formulations [40]. These inhibitors form a barrier that prevents water and corrosive agents from reaching the metal surface, thus prolonging the life of both the grease and the machinery it lubricates [38,40].

Friction modifiers: Friction modifiers are additives that reduce friction between moving parts, thereby improving machinery efficiency and reducing energy consumption [41]. Molybdenum disulphide (MoS_2) and graphite are common friction modifiers [42]. These modifiers can be organic or inorganic compounds that modify the surface properties to achieve lower friction coefficients. Carbon-based additives such as graphene, graphite, and carbon nanotubes are of this class and offer a new method for reducing friction [41,42].

Anti-Wear Agents: Anti-wear agents are designed to reduce the wear and tear on metal surfaces. Zinc dialkyl dithiophosphate (ZDDP) is a widely used anti-wear additive [34,35]. These agents form protective films on contact surfaces, minimizing direct metal-to-metal contact and thus decreasing wear. This is particularly important in high-load applications where components are subjected to significant stress and potential damage [24,27].

While traditional additives like MoS_2 for friction modification and ZDDP for anti-wear are well-established, nanomaterials like graphene are showing potential to be a major step forward in lubrication technology. Emerging research suggests that graphene could significantly enhance both friction re- duction and wear protection, offering promising advancements in additive performance.

3. Graphene based additives in grease

Graphene-based additives such as graphene, graphene oxide (GO), and reduced graphene oxide (rGO) are novel friction-reducing additives that have gained lots of traction over the last 10 years. Their single-atom thick structure allows them to form a protective tribo film on surfaces, thus reducing friction. Though all three graphene derivatives act similarly for lubrication, their solubility, chemical, and electrical properties vary significantly [43,44]. To create GO, graphene can be chemically oxidized. This creates a new compound which has improved solubility in several key solvents, such as water. However, these additional oxygen-containing groups reduce electrical conductivity and mechanical strength. Aiming for a more balanced performance, rGO was developed and produced by reducing GO. rGO, while not as conductive as pure graphene, has significantly improved conductivity and mechanical strength compared to GO and retains some of the enhanced solubility of GO [43]. As is evident from Table 2, each form of graphene has advantages and disadvantages, and the most effective form is highly dependent on the application at hand.

One significant similarity between the various graphene derivatives is their lubrication method. Graphene and its derivatives can create thin tribo-films on surfaces and use the weak inter-lamellae forces between their planes to improve lubrication. A key aspect of graphene is the vast differences in attraction strength across different planes [45]. When forces occur in-plane with the graphene structure, it is one of the strongest materials ever measured, but when two planes are slid against one another, the relatively weak van der Waals interactions allow easy movement [10,45]. In practice, as two faces attempt to make

Table 2
Comparison of graphene, GO, and rGO properties.

Property	Graphene	GO	rGO
Solubility	Low	High	Medium
Electrical Conductivity	High	Low	Medium
Mechanical Properties	Highest strength and flexibility	Lower strength but still quite strong	Better than GO, worse than graphene

Table 1
Comparison of different types of grease and their properties.

Type of Grease	Temperature Range (°C) [29, 21]	Water Resistance [29, 21]	Mechanical Stability [29, 21]	Load-Carrying Capacity [21,31]	Applications [29,21,31,32,33]
Lithium	-25 to 190	Good	Excellent	Good	Automotive, industrial machinery
Lithium	-25 to 190	Good	Excellent	Good	Automotive, industrial machinery
Calcium	-20 to 100	Excellent	Good	Moderate	Marine, automotive chassis, agriculture
Polyurea	-20 to 180	Good	Excellent	Good	Electric motors, sealed-for-life bearings
Lithium Complex	-30 to 250	Excellent	Excellent	Excellent	Automotive wheel bearings, heavy machinery

mechanical contact, thin graphene layers can form on their surfaces and conceal minor imperfections in the contact, creating smooth and lubricated motion [46]. This lubrication process appears to function at various loading forces and temperature conditions. Increased pressure and temperature resulted in reduced graphene flake size, which still provided sig-nificant lubrication benefits [46]. The molecular structures of graphene and its derivatives, GO and rGO, are illustrated in Fig. 4, highlighting their structural differences and the potential impact on lubrication properties.

Larsson et al. completed a comprehensive analysis of lithium complex and polypropylene greases enhanced with 0.1 wt % of graphene, GO and rGO [47]. Their investigation revealed that at these concentrations, the graphene additive has little to no effect on the lubrication, but they hypothesized that to experience effective graphene lubrication, sufficient particle density must be achieved in order to form a surface film. Considering their results and the results of others like Zhang et al. and Djas et al., which both showed significantly reduced friction and wear by the addition of graphene in greater concentrations, it is likely that increased graphene in a grease does lead to better tribofilm formation which can assist in the protecting and lubrication of various contacting faces [48,49].

3.1. Graphene

3.1.1. Fabrication of pure graphene-enhanced grease

With its intriguing lubricative properties, graphene seems an ideal partner for grease, which would act to slow agglomeration through its viscosity. Graphene exhibits some remarkable chemical properties that contribute to its effectiveness as an additive. It is chemically inert, stable and hydrophobic, making it resistant to corrosion and oxidation [50]. Delocalized electrons across its surface give graphene high electrical conductivity and the ability to be tailored through functionalization [51]. Functional groups such as hydroxyl, carboxyl, and epoxy groups can be introduced to graphene's surface, enhancing its dispersibility in various compounds and providing active sites for interaction with other materials [52].

In order to synthesize graphene, several methods are used, with varying quality, scalability, and cost. These include mechanical exfoliation, chemical vapour deposition (CVD) and chemical reduction of graphite oxide. Mechanical exfoliation involves peeling off layers of graphene from graphite using me- chanical forces. This method is used to produce high-quality graphene, but it is unsuitable for large-scale production [53]. CVD deposits carbon atoms on a substrate to form a hexagonal film at high temperatures [54]. This procedure manufactures high-quality graphene suitable for industrial applications but comes at a high cost [54]. Finally, a scalable and cost-effective graphene can be produced by oxidizing graphite, which is then reduced to graphene [55]].

An important consideration with graphene is the dispersion of the nano-material. As shown by Chouhan et al., the effective dispersion of graphene particles into a lubricating structure significantly impacts its tribological properties [56]. To this end, various methods of dispersing graphene have been explored. Due to its scale, ultrasonication is often used to break apart the agglomerated particles [57]. Unfortunately, due to the high viscosity of grease, ultrasonication is ineffective at dispersing particles once suspended, so actions must be taken to incorporate the graphene into the grease. Fig. 5 demonstrates how graphene oxide samples respond to mechanical mixing and ultrasonication (A), and the stability of samples after 45 days in a steady state condition (B).

Researchers have explored several methods to improve the dispersion of graphene in grease. One common approach is to pre-mix the graphene with a base oil before incorporating it into the grease. This technique involves dispersing graphene in a lower-viscosity medium where ultrasonication can be more effective. The graphene-oil mixture is then blended into the grease, ensuring a more uniform distribution of graphene particles [16]. After creating a homogenous mixture of base oil and graphene, it is easier to incorporate into the thicker grease. With the aim of maintaining the dispersion of the graphene particles.

Mechanical stirring is another method used to improve dispersion. By mechanically agitating the grease, it is possible to break up some of the macro-scale agglomerates and achieve a more even distribution of graphene particles. This method can be particularly effective when combined with heating, which lowers the viscosity of the grease, making it easier to stir and distribute the graphene evenly [58]. Mechanical stirring is often used in industrial processes where large batches of grease must be prepared. The effectiveness of mechanical stirring can be enhanced by using specialized equipment designed to handle high-viscosity materials and ensure thorough mixing [16]. The micro-structure of graphene particles dispersed into the grease via mechanical stirring is shown in Fig. 6, providing a visual representation of the even distribution achieved.

A third approach to improving the dispersion of graphene in grease in-volves using a chemical agent to temporarily reduce the viscosity of the grease, facilitating improved mixing. For instance, toluene can be used as a thinning agent, effectively reducing the viscosity of the grease and allowing graphene to be mixed in using ultrasonication and vortex mixing [59]. Once the toluene-graphene dispersion and grease are thoroughly combined using a shear mixer, the enhanced grease can be gently heated to temperatures slightly above room temperature to evaporate the toluene, restoring the grease to its original viscosity without compromising its structural integrity [59,60].

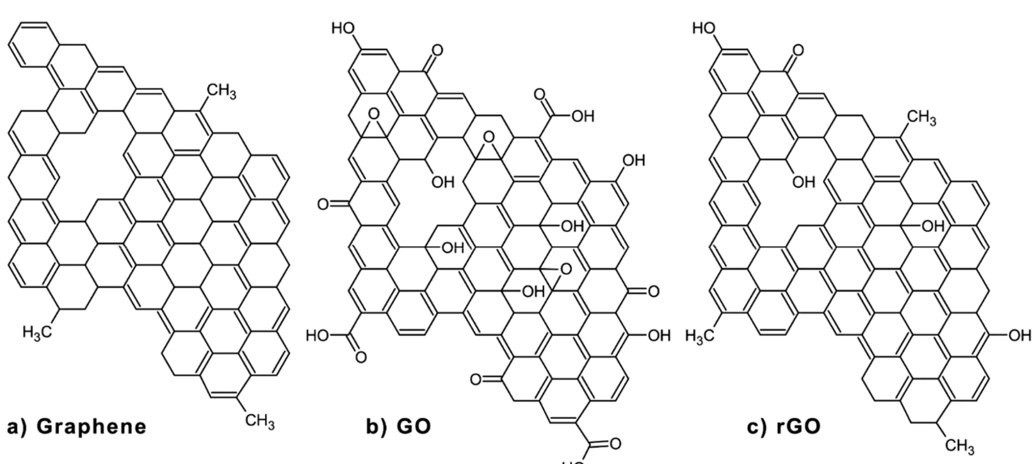

Fig. 4. Molecular structures of graphene, graphene oxide (GO) and reduced graphene oxide (rGO) [47].

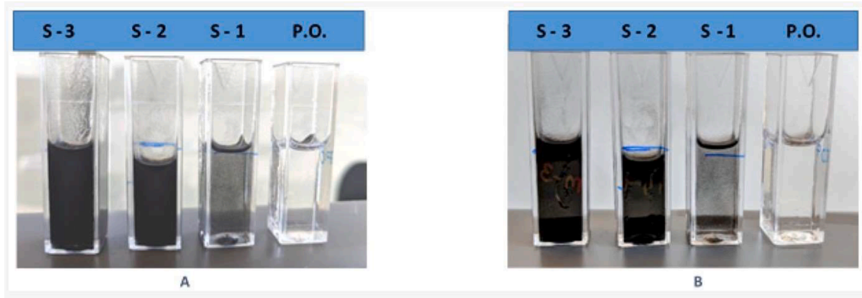

Fig. 5. Four samples of reduced graphene oxide. (A) Samples after mechanical mixing and ultra-sonication, (B) Samples kept in steady state condition for 45 days. [92].

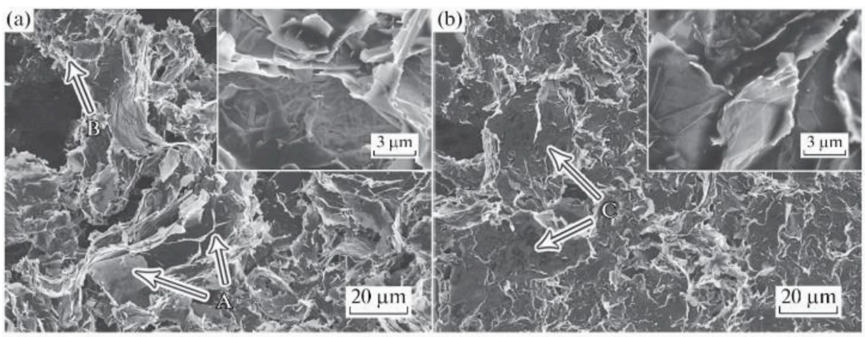

Fig. 6. SEM Micrographs of graphene structure [58].

3.1.2. Performance of pure graphene-enhanced grease

Though graphene can be synthesized through various means, the resulting compound generally only varies in particle size and rate of impurity [45]. It is important to note that these differences in particle size play a key role in forming the lubricating tribofilm. Kumar et al. investigated an array of graphite particles of various sizes [61]. The researchers found that as the particle size decreased, so did the coefficient of friction and the wear scars produced by the enhanced grease. They concluded that this property is caused by graphene layers being sheared off to create the tribofilm, where thinner initial graphite creates a more uniform layer of graphene, which in turn improves lubrication [61]. Fig. 7 illustrates how the size of graphene particles influences their distribution within the grease and highlights the discrete graphite particles that stick to the soap fibers. This research indicates that smaller graphene flakes show more promise as lubricant additives and that particle size plays an important role in the lubricity of the produced graphene-enhanced grease.

Wang et al. utilized few-layer graphene particles with a mean particle size of less than 10 m and noted improved wear and frictional properties compared to a control sample [62]. They found that the graphene grease performed optimally at 1 wt% and theorized that the particles were too easily able to aggregate at 2 wt%, causing a performance reduction [62]. Their work utilized the production of friction byproducts to analyze the performance of the enhanced grease, and the researchers found that though the grease performed well at moderate temperatures, it was outperformed at both high and low temperatures by other nano additives [62]. Fig. 8 illustrates a schematic drawing of the

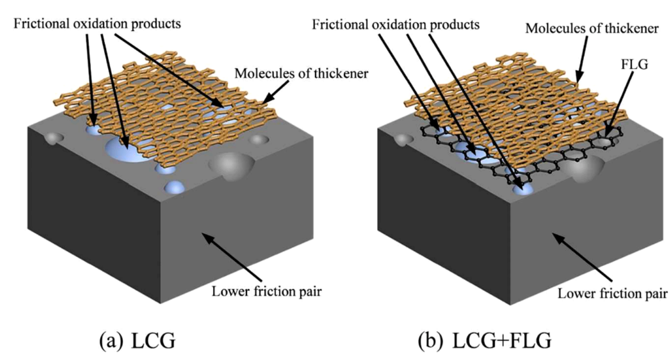

Fig. 8. Schematic drawing of frictional mechanism model [62].

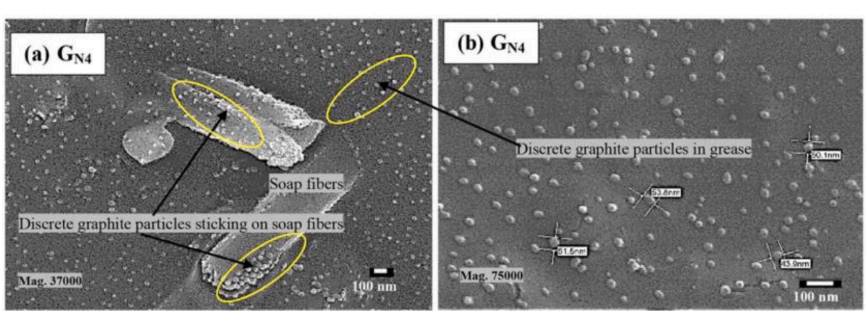

Fig. 7. Graphene particles and size [61].

frictional mechanism model, comparing the lower friction pair with and without few-layer graphene to highlight the impact of the thickener molecules and frictional oxidation products on the system's performance.

Investigating a similar nanomaterial, Prasad et al. created a graphene- enhanced grease by diluting their lithium-complex base grease with chloro- form, which could rapidly evaporate out after the graphene was incorporated [63]. Using a four-ball tribometer, they found that 1 wt% graphene (the highest weight percent included in their trial) provided a 19.5 % reduction in the friction coefficient and a 23.73 % reduction in wear scar diameter. The researchers also analyzed the rheological behaviours of the enhanced grease and found that graphene can improve the flow of greases at high sheer rates. This group also noted that further study is needed into the impact of graphene on surface texture and grease film thickness to better understand the impact of graphene on lubrication [63].

An important similarity in many studies is the use of lithium or lithium complex greases. This is likely due to the simplicity and commonality of many lithium greases, along with their overwhelming market share. Unsurprisingly, with over 70 % of the grease market, all three of the above studies used lithium-based greases [8 (go back and find), [61–63].

Delving into the interactions of lithium complex grease and graphene, Wang et al. studied not only the friction impact of few-layer graphene but also its impact on the microstructure of lithium complex grease [64]. They synthesized their pure grease in the lab to avoid the contamination of other additives [64]. The researchers determined that graphene can enhance the viscosity and elasticity of lithium complex grease by thickening the grease structure, which also improves frictional properties [64]. As shown in Fig. 9, the SEM micrographs reveal the microstructural differences in lithium complex grease with and without 2 wt% few-layer graphene, highlighting how graphene alters the internal structure of the grease and improves its lubricative properties. This underscores the importance of not only studying graphene as an additive but also investigating its broader impact on the oil matrix structure.

Similarly, Niu et al. considered how graphene impacts a titanium complex grease and noted a reduction in coefficient of friction by 21.25 % using 0.06 wt% graphene [65]. This is a significantly lower wt% compared to that used in many of the lithium-based papers, potentially due to the differences in thickener structure. Niu et al. stated that above 0.06 wt%, the graphene began to agglomerate and had reduced efficacy [65]. The researchers also suggested that at higher concentrations, graphene agglomeration not only occurs but also disrupts the thickener structure of the grease, reducing its effectiveness.

Testing the impact of graphene agglomeration on its effectiveness as an additive, Kaiyue et al. created various grease samples, some using pure graphene and some using a modified "[P66614][DEHP] -G" graphene [16]. This modified graphene was produced with a method proposed by Chaoliang et al. [66]. The [P66614][DEHP]-G graphene was optimized for long-term dispersion in organic compounds like oil and was shown to reduce wear by as much as 58 % when dispersed in oil [66]. Kaiyue et al. used this modified graphene and compared it to unmodified graphene to assess the importance of adequate graphene dispersion into the grease structure. The researchers found that the modified graphene had the best tribological properties, providing an 18.84 % reduction in friction. Their testing showed that though graphene improved the properties of lithium complex grease, the modified grease outperformed it in both wear scar area and coefficient of friction. They also noted that the modified grease had increased chemical stability, better shelf stability and improved tribofilm production. This paper demonstrated that graphene modified for dispersion can improve tribological properties in both oil and grease, even relative to unmodified graphene [16,66].

In a similar study, Liang et al. investigated the effectiveness of graphene modified with oleic acid, which aims to improve dispersion [67]. Both the pure graphene and modified graphene samples outperformed the control sample in terms of friction coefficient and wear scar diameter, with the modified graphene having better results than the pure graphene. A notable difference in this study compared to others is their use of multi-layer graphene and their optimal samples of 0.15 and 0.2 wt % for graphene and modified graphene, respectively [67]. The researchers also outlined the importance of dispersion stability when it comes to corrosion resistance in their paper [67]. Furthermore, Fig. 10 highlights that the suspension stability, wear scar diameter, and friction coefficient varied significantly depending on the additive concentration, with modified graphene consistently outperforming pure graphene. Overall, Liang et al. demonstrated the importance of dispersion for optimal graphene performance and completed a series of corrosion tests that showed that both pure graphene and modified graphene can improve chemical performance in grease [67].

An important distinction between pure graphene and the various modified forms is their thermal properties. As a highly conductive material, graphene can distribute and dissipate thermal loads effectively [68]. Investigating these properties, Fu et al. looked at both the tribological and thermal properties of greases enhanced by graphene [68]. They found that graphene effectively reduces the coefficient of friction, the wear scar diameter, and the thermal conductivity of the produced grease [68]. Compared to the control sample, the 4 wt% enhanced grease showed a 55.5 % increase in thermal conductivity, which would allow this grease to dissipate heat more efficiently. The ability to dissipate temperature effectively is an important consideration in many lubrication applications and is a property that graphene can benefit [68].

Wang et al. investigated the efficacy of graphene under various contact forms to gain more inside into its mechanism of action [69]. They found that the additive effectively reduced both friction and wear under all tested contact forms. They also discovered that graphene was acting as a catalyst for the formation of Fe_2O_3 and Li_2O tribofilms which may help chemically protect surfaces from friction [69].

Through extensive study, it is obvious that pure graphene can improve the frictional performance of various greases, yet it is still unclear how much graphene must be added to achieve optimal

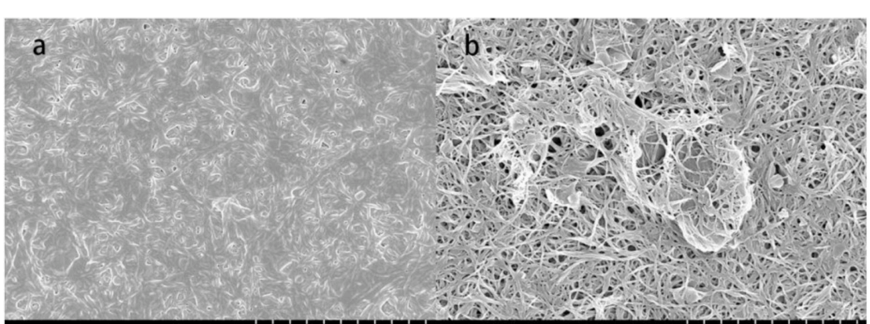

Fig. 9. SEM micrograph of LCG specimens. (a) LCG; (b) LCG with 2 wt% FLG [64].

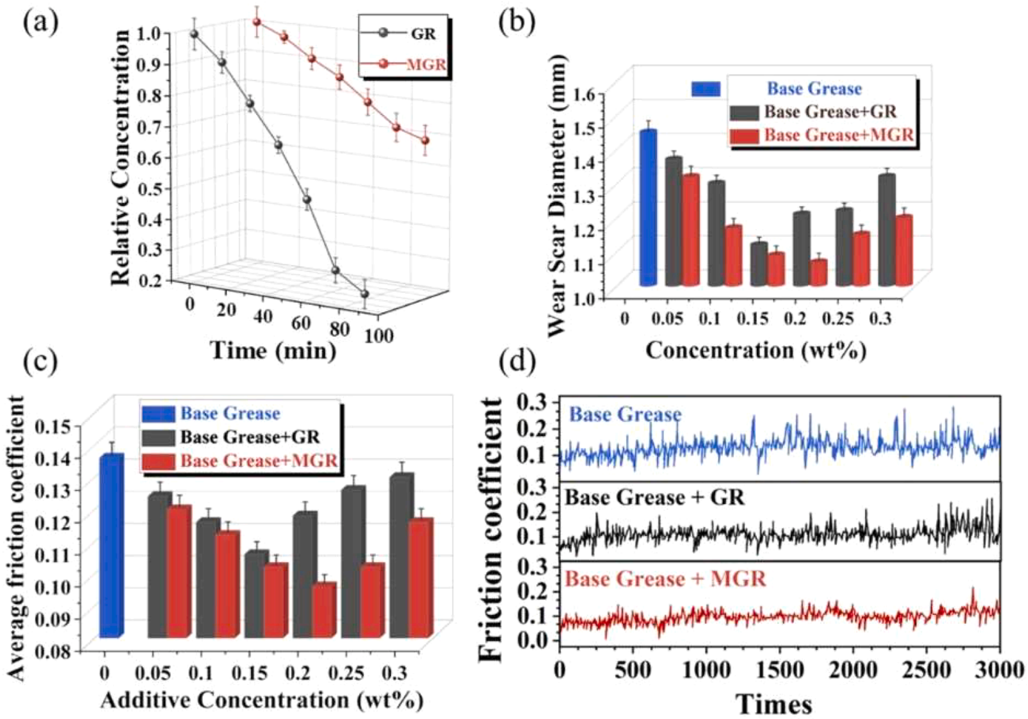

Fig. 10. (a) Suspension stability of the lubricating oils with GR and MGR by UV–vis (b) Relationship between wear scar diameter and concentration of additive. (c) Relationship between average friction coefficient and concentration of additive. (d) Variation curve of friction coefficient lubricated by different greases in four-ball friction test (after Y-axis offset) [67].

performance. It is possible the amount may vary based on the type of graphene, incorporation method, and type of grease thickener. More extensive analysis is needed to better understand how these differences shape the functionality of graphene-enhanced greases if they are to continue to develop.

3.1.3. Differences in the performance of pure graphene

Comprehensive experiments by the scientific community have demon- strated graphene's potential as an additive for various lubricants. Though most researchers have found that graphene can improve lubricative properties, there is still significant variance in the improvement recorded and optimal concentrations found. One of the most important distinctions in the performance of the graphene was its flake size/shape. Another key difference is the base grease, where more research is still needed to properly understand the interaction between graphene and the thickener structure. Lastly, the mixing method plays a

Table 3
Comparison of studies involving graphene as an additive in lubricants.

Paper	Graphene Flake Size	Base Grease Thickener	Mixing Method	Optimal Sample wt%	Coefficient of Friction Reduction	Wear Scar Diameter Reduction
Kumar [61]	50 nm	Lithium	Graphene oil converted into grease	4 % (only sample)	57 %	41 %
Wang [62]	Few-layer 10 μm flakes	Lithium complex	Physical dispersion	1 %	No change	24.49 %
Prasad [63]	Nano- material (assay >99.75 % purity)	Lithium complex	CHCl3 diluted grease stirred with DMF-dissolved graphene	1 %	23.73 %	19.51 %
Wang [64]	Few-layer 10 μm flakes	Lithium complex	Dispersing sand mill at 900 rpm for 2 h	0.5 %	52.05 %	19.60 %
Kaiyue [16]	Few-layer	Lithium complex	Graphene oil converted into grease	0.1 % (only sample)	18.84 %	67.34 %
Liang [67]	Few-layer	Lithium complex	Graphene oil converted into grease	0.15 %	Increased coefficient of friction	22.76 %
Fu [68]	Multi-layer 3.46 μm flakes	Not listed	Mixed at 3500 rpm for 15 min	2 %	15.25 %	14.0 %
Zhang [70]	1–4 layers 2 μm flakes	Lithium	Ultrasonicated graphene oil then 900 rpm mixing with grease	2 %	15 %	60 %
Lin [71]	5 nm thick 1–3 μm flakes	Lithium	Graphene oil homogenized into grease at 750 rpm for 30 min	0.07 % %	19.6 %	19.1 %
Niu [65]	Few-layer 0.5–5 μm flakes	Titanium Complex	Graphene oil converted into grease	0.06 %	21.25 %	18.4 %
Fan [72]	Multilayer	Bentone	MLG-containing ethanol mixed in and then evaporated	0.1 %	10.4 %	25–50 %

crucial role in the dispersion of the graphene across the lubricant structure and can severely impact the performance of the final grease. Table 3 compares many of these important differences. The collage of images presented in Fig. 11 is derived from studies referenced in Table 3, showcasing various frictional and wear characteristics of graphene-enhanced lubricants.

It is clear that graphene-enhanced grease has incredible potential, but further research is still needed in many aspects of its manufacturing before its benefits can be realized. In the future, larger-scale analysis must be performed on flake shapes and mixing methods to properly analyze the impact of these key factors. Additionally, to fully understand the method by which graphene improves lubrication, further research into the interactions of thickener, base oil, and graphene must be made available. With more research, this new lubricant's incredible energy-saving potential should become accessible.

3.2. Graphene oxide

3.2.1. Fabrication of graphene oxide (GO) enhanced grease

Graphene Oxide can be synthesized using various methods, each yielding slightly different products [45]. Common synthesis methods include the Hummers' method and its modifications, which involve the chemical oxidation of graphite using strong acids and oxidants [73]. These processes introduce oxygen-containing functional groups such as hydroxyl, epoxy, and carboxyl groups onto the graphene sheets [74]. These functional groups not only improve the solubility of GO in water and other polar solvents but also significantly alter its chemical and physical properties compared to pristine graphene [75]. Fig. 12 provides a schematic representation of the oxidation process, illustrating how graphite is chemically transformed into graphene oxide through the introduction of these functional groups.

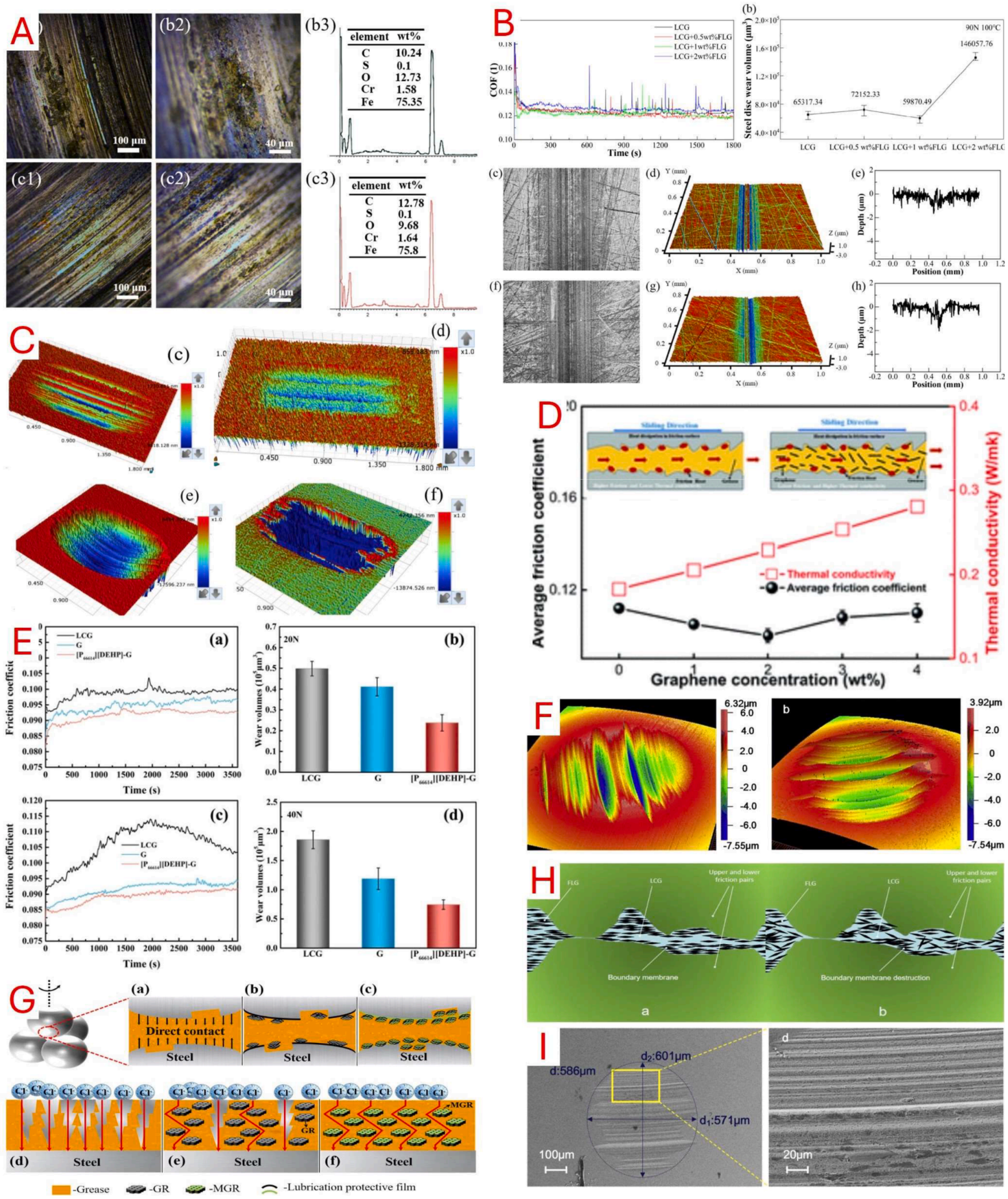

Fig. 11. (A) Optical microscopy and SEM-EDS analysis of the steel ball friction surface [67] (B) COF curves, the abrasion volume of the steel plate (SPAV), and two-dimension, three-dimensional and sectional views of abrasion scars on the plate surfaces [64] (C) Worn surfaces morphologies under different loads [62] (D) Comparison of graphene weight percentage with friction coefficient and thermal conductivity [68] (E) Friction coefficients and wear volumes of as-prepared grease [70] (F) WLI morphologies of wear scar lubricated by different greases samples at 392N for 60min [65] (G) Schematic diagrams of lubrication mechanism and schematic diagrams of corrosion mechanism [67] (H) Two states of FLG in LCG [64] (I) SEM morphologies of wear scar lubricated by different greases samples at 392N for 60 min [65].

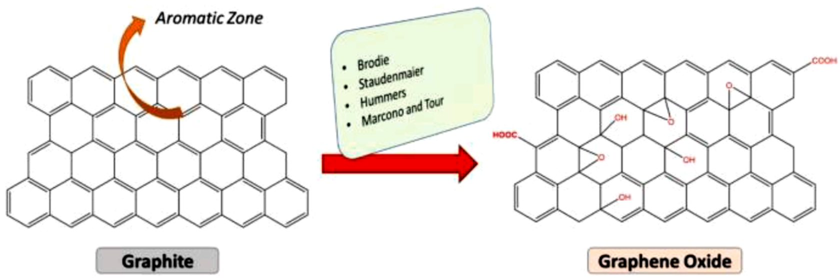

Fig. 12. Schematic representation of the oxidation process from graphite to graphene oxide [84].

In a study conducted by Ghosh et al, GO was synthesized using a modified Hummers' method [76]. The process involved the oxidation of graphite powder with a mixture of concentrated sulfuric acid and potassium perman- ganate. This mixture was then heated to 98 °C, followed by the gradual addition of hydrogen peroxide to terminate the reaction and form the graphene oxide. The resulting GO was then washed and purified through multiple centrifugation steps to remove residual acids and oxidants, resulting in high purity GO with a high degree of oxidation [76].

The dispersion of GO into the grease matrix is crucial for the fabrication of GO-enhanced grease. One effective method involves first dispersing the GO in a suitable solvent, such as water or ethanol, followed by mixing this GO solution with the base grease [77]. Ultrasonication is often used during this process to ensure a uniform dispersion of GO particles. The solvent is then evaporated, leaving behind a well-dispersed GO-enhanced grease. This approach was used in a study performed by Priyadarsini et al [78].

3.2.2. Performance of graphene oxide (GO) enhanced grease

3.2.2. Performance of graphene oxide (GO) enhanced grease The incorpo- ration of GO into lubricating greases has been shown to significantly improve their performance, particularly in terms of reducing friction and wear. For instance, Ghosh et al.found that incorporating GO into lithium grease resulted in a 30 % reduction in the coefficient of friction and a 40 % reduction in wear scar diameter compared to the base grease [76]. This improvement is attributed to the oxygen-containing groups in GO that facilitate the formation of a protective film.

Singh et al. observed that GO-enhanced grease could handle higher pressures and maintain structural integrity under extreme conditions, outperforming conventional greases [79]. The researchers suspected that the high thermal conductivity of GO aids in heat dissipation, which helps maintain the grease's performance at elevated temperatures [79]. Another study highlighted that GO-enhanced grease retained its lubricative properties at temperatures up to 150 °C, while the base grease without GO showed signs of degradation [80].

Singh Rawat et al. further explored the benefits of GO in paraffin grease, finding that GO addition reduced both the coefficient of friction and wear scar diameter by 20 % and 25 %, respectively [44]. The study attributed these improvements to the stable tribo-film formed by GO, which provided superior protection under high-load conditions. Lian et al. investigated a GO composite as a solid lubricant, demonstrating that GO significantly contributed to friction and wear reduction, particularly in high-temperature environments [81]. Their research showed that the GO component maintained the grease's performance under extreme conditions, highlighting its effectiveness in en- hancing grease formulations for demanding applications. As showcased in Fig. 13, the wear scar and Raman spectra of TiC/Graphene Oxide heterostructural coatings provide visual and analytical evidence of the improved lubrication and protective properties achieved with GO-based formulations.

In terms of wear resistance, graphene oxide enhanced greases significantly outperform traditional greases. The protective tribo-film formed by GO not only reduces friction but also shields the underlying surfaces from wear. For example, Kamel et al. demonstrated that GO-enhanced calcium grease exhibited a 25 % reduction in wear compared to the base grease, emphasizing the effectiveness of GO in enhancing the durability of lubricated components [82,83].

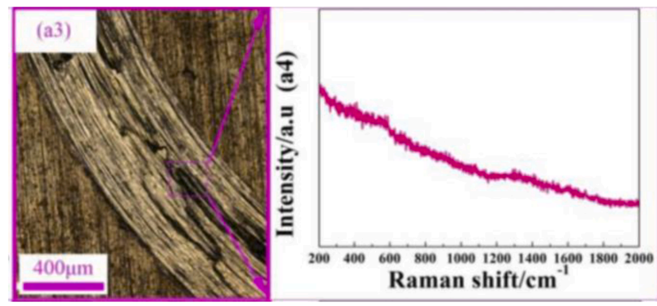

Fig. 13. Wear scar and raman spectra of TiC/graphene oxide heterostructural coating [81].

Uniform dispersion of GO within the grease matrix is crucial for consistent performance. Proper dispersion techniques, such as using solvents like ethanol and ultrasonication, ensure a homogeneous distribution of GO. Studies have shown that well-dispersed GO in grease provides better stability and performance over extended periods. For instance, in one study, GO was dispersed in ethanol and incorporated into lithium grease, resulting in superior lubrication performance [78, 84]. GO also enhances the corrosion resistance of greases. The functional groups in GO provide a barrier that protects metal surfaces from corrosive elements. Research indicates that GO-enhanced greases offer better protection against rust and corrosion, making them suitable for use in harsh environments [82]. Additionally, Wang et al. investigated the performance of GO-enhanced lithium complex grease and found that the grease performed optimally at 1 wt% GO, significantly re-ducing friction and wear [16]. Similarly, Prasad et al. reported that a GO concentration of 1 wt% in lithium-complex grease reduced the friction coeffi- cient by 19.5 % and wear scar diameter by 23.73 %. These findings underscore the potential of GO to enhance the performance of lubricating greases across various applications [85]. In summary, GO-enhanced greases has the potential to offer significant improvements in friction reduction, load-carrying capacity, thermal stability, wear resistance, and corrosion resistance.

These studies collectively highlight the versatility and effectiveness of graphene oxide as a lubricant additive, improving the performance of various types of grease across different applications. The following table, Table 4, provides a comparative analysis of key findings from these studies, illustrating the significant impact of GO on reducing friction and wear in lubricating greases. The collage of images presented in Fig. 14 is derived from studies summarized in Table 4, showcasing the tribological performance and characterization of graphene oxide (GO) as a lubricant additive in greases.

Table 4
Comparison of studies involving graphene oxide (GO) as an additive in lubricants.

Paper	GO Con- centration (wt %)	Base Grease	Mixing Method	Coefficient of Friction Reduction	Wear Scar Diameter Reduction
Ghosh [76]	1	Lithium	Ultrasonication, Solvent Evaporation	30 %	40 %
Singh [79]	1	Lithium complex	Ultrasonication, Mechanical stirring	28 %	35 %
Singh Rawat [44]	0.5	Paraffin	Ultrasonication, Solvent Evaporation	20 %	25 %
Lian [81]	0.5	Dry	Mechanical stirring	18 %	22 %
Kamel [83]	1	Calcium Grease	Ultrasonication, Solvent Evaporation	25 %	25 %
Prasad [85]	1	Lithium complex	Ultrasonication, Solvent Evaporation	19.5 %	23.73 %
Liu [73]	1	Lithium complex	Mechanical stirring	21.25 %	18.4 %

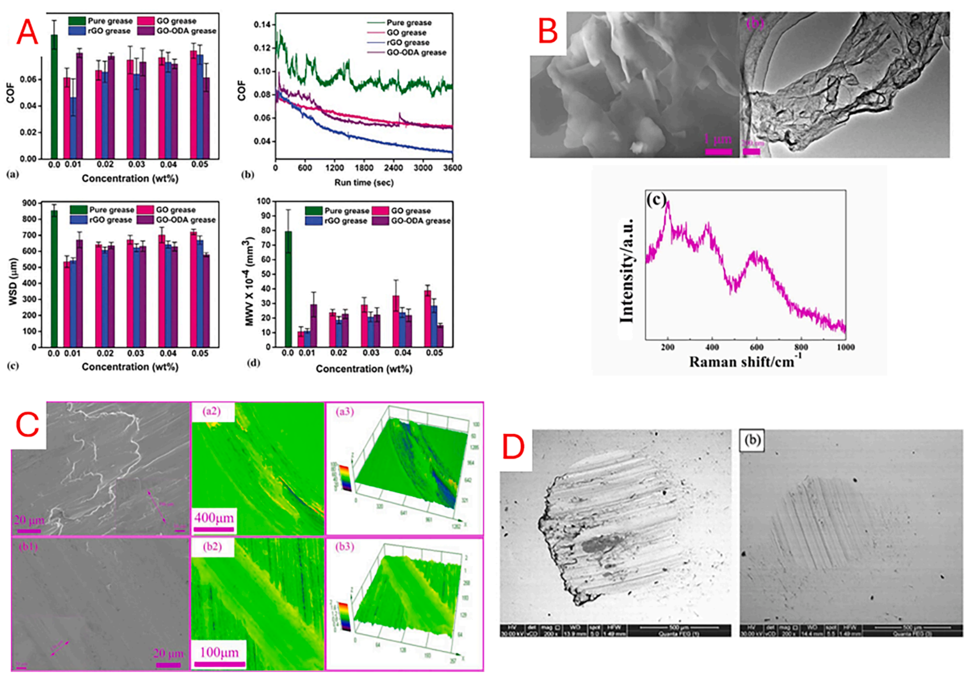

Fig. 14. (A) Tribological Performance of Graphene-Based Additives in Grease: COF, WSD, and MWW at Different Concentrations [44] (B) Morphological and Raman Spectroscopic Analysis of Graphene Nanosheets [82] (C) Surface Morphology and Topographical Analysis of Worn Surfaces [82] (D) SEM Micrographs of Wear Scars [84].

3.3. Reduced graphene oxide

3.3.1. Fabrication of reduced graphene oxide (rGO) enhanced grease

Reduced graphene oxide (rGO) is produced when graphene oxide (GO) is chemically reduced. This creates a graphene product that has a combination of the advantages of pure graphene and graphene oxide [86]. Unfortunately, rGO often has defects that hinder its performance compared to other forms of graphene [86]. More research is still needed to find a synthesis route that produces pure rGO with a low defect rate [86]. Like with other carbon-based additives, further research is still needed to optimize the dispersion of rGO [87]. One advantage of rGO compared to other graphene derivatives is that the synthesis method is replicable at a larger scale [86]. In order to capitalize on the scalability of this product, many companies hope to develop energy-efficient lubricants that rely on the frictional benefits of rGO. Fig. 15 provides TEM images of rGO, illustrating its structure at 50,000× and 150,000× magnification, which reveals the defects and surface morphology that can affect its performance in lubrication applications.

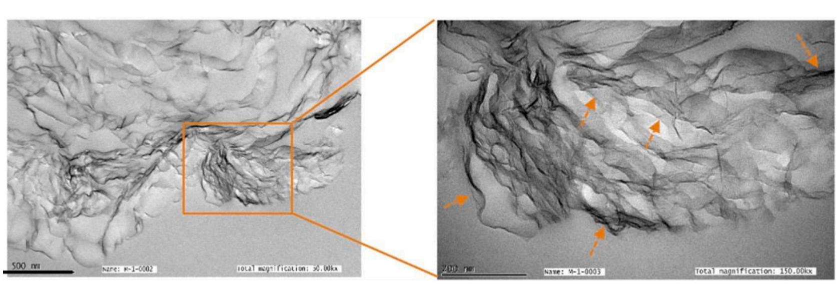

Fig. 15. TEM images of reduced graphene oxide under 50,000× and 150,000× magnification [92].

3.3.2. Performance of reduced graphene oxide (rGO) enhanced grease

Researching the impacts of rGO on the frictional properties of greases, Singh et al. used “rGO nano-sheets with an interlayer spacing of 0.35 nm and average size of around 500 nm” combined with pure base grease [88]. By dispersing the nano-sheets in toluene, they were able to mix the rGO into the grease and then evaporate the remaining toluene to achieve an even dispersion. They found that the rGO at 0.4 wt% significantly improved the elastic recovery of the grease, which indicates higher stability and less damage to the fibrous network after mechanical work [88]. This research suggests that incorporating rGO into lubrication products can help improve their lifespan, leading to long-term energy savings.

Rawat et al. investigated both the impact on microstructure and lubricating properties various forms of graphene would have on base lithium grease [89]. They found an optimal sample at 0.03 wt% rGO with an 18 % reduction in friction [89]. The researchers suggested this is due to the fact that rGO had the weakest interlayer forces, which allowed easy shear across the plane and the creation of an even lubricating film. They also noted that the grease thickener structure enhanced by rGO was less dense than the non-enhanced structure, which allows it to store oil more efficently [89].

Due to the novelty of rGO, many researchers are still working to optimize the synthesis method [86]. Jin et al. worked on the impact of ultra-flat reduced graphene oxide nanosheets synthesized for lubricant applications [90]. Their research revealed that 0.5 wt% of graphene nanosheets had the capacity to reduce the coefficient of friction by 49 % and the wear scar depth by 93 %. This investigation found significant differences in the performance of various synthesized graphite byproducts and large gaps in the optimal additive range depending on the synthesis method. The researchers also noted that at high temperatures, rGO demonstrated significant variance in its lubricating properties, likely due to a loss in stability of the oil film caused by increased temperatures [90].

Nassef et al. explored the effects of incorporating rGO nanosheets into lithium grease to assess vibrational, ultrasonic and thermal properties [91]. Their results showed that a 5 wt% sample led to a 52 % improvement in damping ratio, though vibrations increased by 80 %, likely due to graphene aggregation impeding grease flow [91]. A 1 wt% sample reduced vibrations by 38 %, with a slight enhancement in the damping ratio. They also found that all graphene concentrations decreased ultrasonic emissions, with rGO showing slightly lower performance compared to graphite [91]. Notably, a 2 wt% graphene sample decreased energy production by 57 %, likely through friction reduction and heat absorption [91]. Furthermore, a Timken load test revealed a 100 % increase in load-bearing capacity for the 5 wt% sample, with similar improvements for other concentrations [91]. These findings suggest that rGO may enhance the performance and noise reduction of rolling bearings. Fig. 16 illustrates the XRD pattern, Raman spectrum, and TEM analyses, confirming the structural features of rGO at varying resolutions.

Rawat et al. performed an extensive series of tests on GO-, rGO- and modified rGO-enhanced greases to determine their effectiveness [44]. They noted, “the graphene-based nano additives trapped in the fibrous cross-linked network of thickener furnished larger void area and decreased the structural compactness of pure grease,” which allowed oil to escape more easily and improve lubrication [44]. Of the three, rGO showed the most overall promise, with a reduction in the coefficient of friction of 50.3 %, a reduction in wear volume of 85.4 % and an improved energy conservation of 50.3 % [44]. These properties occurred at an optimal sample of 0.01 wt% rGO.

A study by Patel et al. explored the tribological performance of rGO as an additive in oil-based lubricants, specifically investigating concentrations of 0.01 %, 0.05 % and 0.1 % by weight. They found that 0.05 wt% of rGO provided the best balance, with a reduction in friction of 51.85 % and significant improvements in wear resistance without affecting the lubricant’s physical properties, such as viscosity and oxidation stability [92]. Another study by Patel et al. demonstrated that adding 0.5 wt% rGO to synthetic lubricants significantly improved both friction reduction and thermal stability [93]. These results, highlighted in Fig. 17, further emphasize rGO’s versatility as an additive in both solid and liquid lubrication systems, with potential to enhance performance in harsh operating conditions.

Considering the above studies, it is likely that rGO can provide enormous benefits to many important lubricant properties. Further research is still needed to find optimal mixing methods of rGO and bulk synthesis routes. This additive shows great promise in reducing friction, noise, and wear, which would allow parts to survive much longer under harsh conditions and improve the lifespan of many machines. The

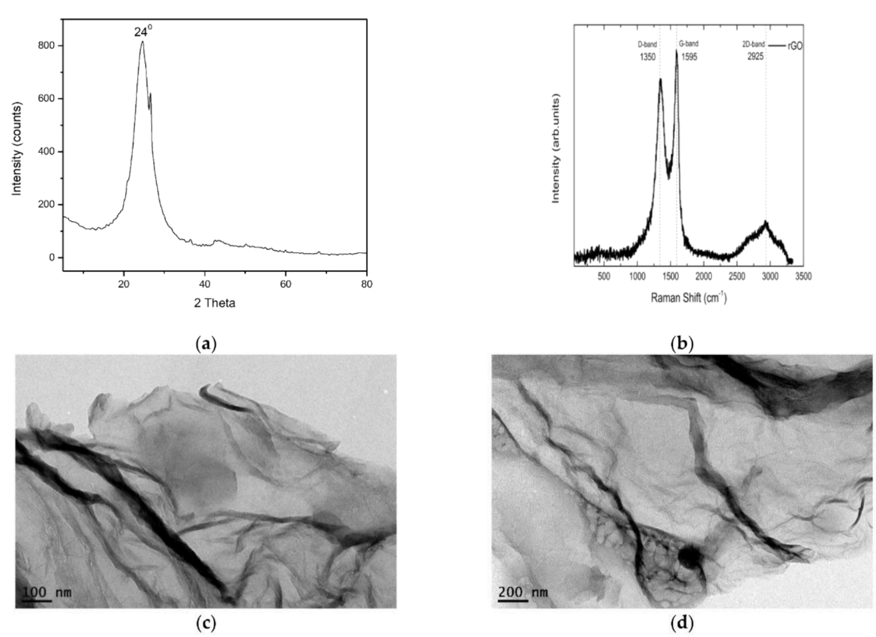

Fig. 16. (a) XRD pattern of reduced graphene oxide, (b) Raman spectrum of rGO sample, (c) TEM analysis of rGO structure with a resolution of 100 nm, (d) TEM analysis of rGO structure with a resolution of 200 nm [91].

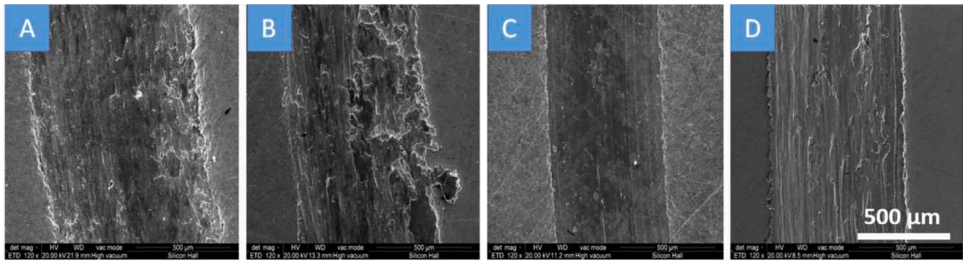

Fig. 17. SEM of specimen wear tracks at different 500 μm and 120× for pure oil mixed with reduced graphene oxide [92].

collage of images presented in Fig. 18 is derived from studies summarized in Table 5, highlighting the tribological performance and surface analysis of rGO-based lubricants under various conditions. (C) Ultrasound signal for test bearing with base grease lubrication in time domain and frequency domain [91] (D) Wear rate for pure oil and three nano lubricants [92] (E) TEM images of graphene, titanium dioxide and graphene and titanium dioxide mixed together in powder form at 1 m scale and 25.00 kx magnifications [93]

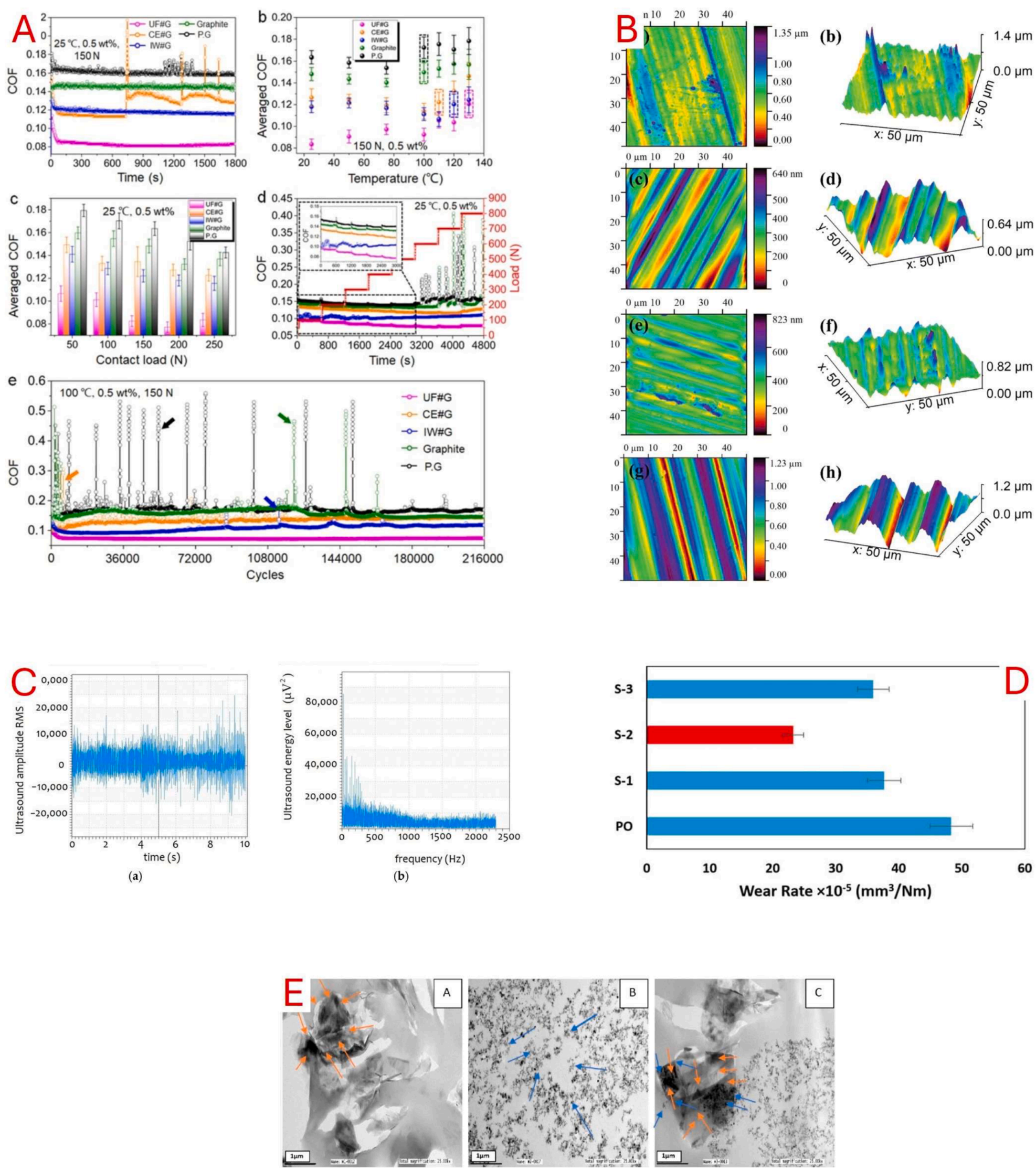

Fig. 18. (A) COF time-varying curves of different lubricants at 25 °C, 150 N, influence of temperature on the tribological properties, influence of contact load on the tribological properties, extreme pressure performance test at ambient temperature (100–800 N) and long-operating of 216,000 cycles (three hours) friction test at high temperature of 100 °C[90] (B) Surface roughness and 3D topography of wear tracks on steel surfaces [44].

Table 5
Performance of reduced graphene oxide (rGO) as a lubricant additive in greases and oils.

Study	rGO Con- centration (wt %)	Base Lubricant (Oil/ Grease)	Mixing Method	Coefficient of Friction Reduction	Wear Scar Diameter Reduction
Singh et al. [88]	0.4	Composite Grease	Toluene dispersion, evaporation	20–30 %	-
Rawat et al. [89]	0.03	Paraffin Grease	Mechanical Stirring	18 %	-
Jin et al. [90]	0.5	Pure Grease	Ultrasonication	49 %	93 %
Nassef et al. [91]	1 - 5	Lithium Grease	Modified Hummers	52 % increase in damping	80 % increase in vibrations
Rawat et al. [44]	0.01–0.05	Paraffin Grease	Ultrasonication	50.3 %	85.4 %
Patel [92]	0.05	Mineral Oil	Mechanical Mixing, Ultrasonication	51.85 %	Significant Decrease
Patel [93]	0.5	Synthetic Oil	Mechanical Mixing	Significant improvement	25.65 %

4. Conclusion

4.1. Conclusions

The application of carbon-based additives, such as graphene, graphene oxide and reduced graphene oxide, in lubricating greases has shown significant promise in enhancing tribological performance. These additives have demonstrated their ability to reduce friction, improve wear resistance, and enhance thermal stability, making them valuable for various industrial ap- plications. This review has provided a comprehensive overview of the current state of research, highlighted the benefits and limitations of different graphene derivatives, and explored the impact of graphene on other aspects of lubricant performance.

4.1.1. Challenges

Despite the progress, there are still challenges that need to be addressed to fully utilize these new lubricant additives;

Dispersion and Stability: Ensuring uniform dispersion of graphene, GO, and rGO within grease matrices remains a significant challenge. Researchers in this field have struggled to find a way to evenly disperse graphene with limited agglomeration. The agglomeration of particles has been shown to reduce the effectiveness of these additives, which is why this is a key issue that must be addressed.

Synthesis and Scalability: Developing cost-effective, scalable methods for synthesizing high-quality graphene derivatives is critical for their widespread adoption in industrial applications. Due to graphene's high cost, many industries have been hesitant to explore its energy-saving potential. Cost-effective bulk synthesis methods would allow for easier access to the material and limit the cost of implementation for large-scale companies like those in the mining and energy generation industries.

Additive Compatibility: Commercial greases come standard with up to 10 % additive content. Ensuring that graphene can be incorporated into greases without reducing the effectiveness of these other additives is critical. It is also important to consider how graphene interacts with the grease thickener structure, which plays a key role in performance. Further study is needed on the interactions between graphene and other additives to limit the effect they have on overall grease performance.

Limited Comprehensive Tests: Currently, few large-scale studies available on graphene-enhanced grease address multiple forms of graphene, mixing, and mechanical contact. More extensive testing under diverse operating conditions is required to fully understand the long-term impacts of these additives on grease performance and component longevity. By testing graphene outside of hyper-controlled lab conditions and for longer service windows, researchers will be able to gain insight into its long-term impact on energy savings and mechanical systems.

4.1.2. Future goals

In the future, as researchers begin to tackle the challenges presented by graphene as a lubricant additive, there are many areas that should be the focus of new research. Future studies could focus on;

Innovative Dispersion Techniques: Research should focus on developing advanced dispersion methods to ensure uniform distribution of graphene in greases. Techniques such as functionalization, use of surfactants, and mechanical mixing can be used to further this development. Consistent methods that are applicable on a large scale are critical if graphene enhanced lubricants are to be widely adopted.

Application-Specific Formulations: Tailoring graphene-enhanced greases for specific applications, such as high-temperature environments or heavy-load conditions, can maximize their benefits. Custom formulations utilizing various graphene shape, type and quantity combinations can address unique challenges faced in different industrial sectors.

Environmental and Economic Impact: Further research should evaluate the environmental benefits and economic feasibility of using graphene additives. This includes lifecycle assessments to determine the overall impact on sustainability and any environmental risks associated with introducing the nanomaterial to grease.

4.1.3. Final thoughts

The incorporation of carbon-based additives, specifically graphene, graphene oxide (GO), and reduced graphene oxide (rGO), into lubricating greases offers a significant opportunity to enhance tribological performance across various industrial applications. These materials have demonstrated the ability to reduce friction, improve wear resistance, and increase thermal stability, which can substantially extend the lifespan and efficiency of machinery. Despite these promising benefits, challenges such as achieving uniform dispersion, developing scalable synthesis methods, and ensuring compatibility with existing grease formulations remain key obstacles that must be addressed for these advanced materials to see widespread adoption.

This review has provided a comprehensive analysis of the current state of research, highlighting both the advantages and limitations of graphene-based additives. The findings emphasize the need for continued research into advanced dispersion techniques, the development of application-specific formulations, and a deeper understanding of the interactions between graphene additives and grease matrices. Overcoming these challenges is essential for unlocking the full potential of graphene-enhanced greases and driving the creation of next-generation lubricants that meet the evolving demands of modern industrial processes. As the global push for high-efficiency lubricants continues, the insights presented in this paper will serve as a foundation for future innovation, ultimately contributing to more efficient, durable, and sustainable industrial operations.

CRediT authorship contribution statement

Ethan Stefan-Henningsen: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis. **Nathan Roberts:** Writing – review & editing, Writing – original draft, Formal analysis. **Amirkianoosh Kiani:** Writing – review & editing,

Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

Amirkianoosh Kiani reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Ethan Stefan-Henningsen reports financial support was provided by Mitacs Canada. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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