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Nanoparticle-Enhanced Lubricants for Improved Friction and Wear Performance: A Critical Review

Nanoparçacık Katkılı Yağlayıcılar ile Sürtünme ve Aşınma Performansının İyileştirilmesi: Eleştirel Bir İnceleme

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Öz
Nanopartiküller, zorlu koşullar altında çalışan mekanik sistemlerde sürtünmeyi ve aşınmayı azaltmak için potansiyel çözümler sunan, yağlama yağlarında umut verici katkı maddeleri olarak ortaya çıkmıştır. Son çalışmalar, nano ölçekli malzemelerin yağlayıcılara dahil edilmesinin, yüzey filmi oluşumu ve mikro yapısal düzeyde etkileşim gibi mekanizmalar aracılığıyla tribolojik performansı önemli ölçüde iyileştirebileceğini göstermiştir. Grafen gibi iki boyutlu malzemelerin sürtünme katsayısını ve aşınma izi çapını sırasıyla yaklaşık %40 %30 oranında azalttığı bildirilirken, Al_2O_3 gibi üç boyutlu nanopartiküller sürtünme katsayısı değerini yaklaşık %15 oranında azaltmaktadır. Ancak, bu alandaki artan araştırmalara rağmen, birçok çalışma sınırlı nanopartikül tiplerine odaklanmaktadır veya sentez yöntemlerinin ve dispersiyon davranışının genel performans üzerindeki etkisini sistematik olarak incelememektedir. Özellikle, partikül tipleri, işleme yolları ve çalışma koşulları arasında kapsamlı karşılaştırmaların olmaması, endüstriyel uygulamalar için optimize edilmiş formülasyonların geliştirilmesini engellemektedir. Bu inceleme, sentez tekniği, tribolojik mekanizma ve performans sonucu arasındaki ilişkilere odaklanarak nanopartikül destekli yağlayıcılardaki son gelişmeleri analiz ederek bu boşlukları ele almaktadır. Literatürden elde edilen bulgular, nanopartiküllerin doğrudan teması en aza indirerek ve yüzey etkileşimlerini değiştirerek aşınmayı etkili bir şekilde azaltabileceğini ve bileşen ömrünü uzatabileceğini doğrulamaktadır. Bu faydalar ışığında, nanopartikül tiplerinin çeşitlendirilmesi, yeni hibrit yapıların araştırılması ve daha geniş ve daha verimli uygulamalar için yağlama sistemlerine işlevsel entegrasyonlarının hassas bir şekilde ayarlanması için daha fazla araştırma yapılması teşvik edilmektedir.

Anahtar Kelimeler
Nanopartiküller; Yağlayıcılar; Sürtünme; Aşınma; Tribofilm; Spinel Oksitler; MXene; ZnO; Triboloji; Katkı teknolojisi.

Abstract
Nanoparticles have emerged as promising additives in lubricating oils, offering potential solutions to reduce friction and wear in mechanical systems operating under demanding conditions. Recent studies have demonstrated that the inclusion of nanoscale materials in lubricants can significantly improve tribological performance through mechanisms such as surface film formation and interaction at the microstructural level. Two-dimensional materials such as graphene are reported to reduce the coefficient of friction and wear scar diameter by ~ 40% and 30%, respectively, while three-dimensional nanoparticles such as Al_2O_3 reduce to coefficient of friction value by ~ 15%. However, despite the growing body of research in this field, many studies focus on limited nanoparticle types or do not systematically examine the influence of synthesis methods and dispersion behaviour on overall performance. A lack of comprehensive comparisons across particle types, processing routes, and operating conditions hinders the development of optimized formulations for industrial applications. This review addresses these gaps by analysing recent advances in nanoparticle-enhanced lubricants, with a focus on the relationships between synthesis techniques (sol-gel, hydrothermal, chemical reduction), tribological mechanism, and performance outcome. The literature shows that nanoparticles can reduce wear and prolong component life by minimising direct contact and changing surface interactions. Considering these benefits, nanoparticle types, hybrid structures, and functional integration into lubricant systems should be studied for wider and more efficient applications.

Key Words
Nanoparticles; Lubricants; Friction; Wear; Tribofilm; Spinel Oxides; MXene; ZnO; Tribology; Additive Technology.

1. Introduction

In modern industrial systems, mechanical components frequently operate under high loads, elevated temperatures, and continuous sliding motion—conditions that lead to significant friction-induced energy losses and surface degradation over time (Gul, Demirsöz, Kabave Kilincarslan, Polat, & Cetin, 2024; B. Li, Li, Zhou, Feng, & Zhou, 2022; G. Zhang et al., 2024). These effects are particularly pronounced in commonly used metals such as steel, aluminum, and magnesium alloys, where direct contact at moving interfaces causes deformation and wear, ultimately compromising the service life of components (D. Kumar, Idapalapati, Wang, & Narasimalu, 2019; Saraçoğlu et al., 2024; Zhai et al., 2021). While various strengthening techniques have been developed to improve the mechanical robustness of such materials, enhancing their tribological performance—especially under lubricated conditions—remains a key challenge (Findik, 2014; Polat, Sun, Çevik, & Colijn, 2019; X. Zhang, Ren, & Li, 2023). In recent years, the incorporation of nanoparticles into lubricating oils has attracted significant attention as a strategy to improve the tribological performance of mechanical systems (Cetin & Kabave Kilincarslan, 2020; Cetin, Kesen, Korkmaz, & Kabave Kilincarslan, 2020; Krishna Sabareesh, Gobinath, Sajith, Das, & Sobhan, 2012; Y. Li, Liu, Zhang, Zhang, & Zhang, 2018; Samylingam et al., 2024). Friction and wear are among the primary causes of energy loss and material degradation in moving components, leading to reduced efficiency, increased maintenance costs, and shortened service life (Gul, Gokkaya, Kondul, & Cetin, 2022; Z. Li et al., 2024; Polat, Sun, & Cevik, 2021; Polat, Sun, Çevik, Colijn, & Turan, 2019). Conventional lubricant additives, while effective to a degree, often fail to provide adequate protection under high loads and extreme boundary lubrication conditions (Kulkarni, Toksha, Chatterjee, Naik, & Autee, 2023). Therefore, the development of advanced additives that can operate reliably under such conditions is critically needed. Nanoparticles—owing to their high surface area, tunable surface chemistry, and ability to interact with sliding surfaces at the nanoscale—have shown promise in minimizing direct metal-to-metal contact, thereby reducing friction coefficients and wear rates in various tribological systems (Kulkarni et al., $_2$023; Loo et al., 2023; Singh, Sharma, Singh, & Singla, 2019).

Numerous experimental studies have confirmed that both metal oxide and carbon-based nanoparticles can significantly improve lubrication performance through mechanisms such as tribofilm formation, mending of surface defects, and rolling or polishing effects, Spinel-type oxides like Fe_3O_4, ZnO, and $ZnAl_2O_4$, as well as two-dimensional materials like graphene and MXene, have been particularly effective in enhancing anti-wear and friction-reducing characteristics (Gul, Polat, Cetin, Kabave Kilincarslan, & Polat, 2025; Karaca, Polat, & Esen, 2024). Reported results show reductions in coefficient of friction by up to 60% and notable decreases in wear scar diameter, depending on nanoparticle type, concentration, and dispersion method (Shahnazar, Bagheri, Bee, & Hamid, 2016). However, the effectiveness of these additives is highly sensitive to their synthesis method and stability within the base oil. Among various production techniques, hydrothermal synthesis has emerged as a favourable route due to its ability to produce crystalline, monodispersed, and morphologically uniform nanoparticles with high surface reactivity (Boruah, Mohan, Choudhury, & Chowdhury, 2025; Lefdhil, Polat, & Zengin, 2023; Mbebou, Polat, & Zengin, 2023).

This study aims to explore the role of nanoparticles in enhancing the tribological properties of lubricants, focusing on their ability to reduce friction and wear. The work also provides a comparative evaluation of different nanoparticle systems. It provides quantitative insights into their effects on wear reduction and friction coefficient, based on recent findings in the literature.

2. Synthesis, Functional Role, and Dispersion of Nanoparticles in Lubricant Systems

The use of nanoparticles as lubricant additives has grown in popularity, especially in boundary lubrication situations where traditional additives frequently fall short in terms of protection (Shahnazar et al., 2016). By creating protective layers between contacting surfaces, these nano-additives can minimise wear and lower friction coefficients (COF). Numerous factors, such as chemical composition, particle size, morphology, concentration, and dispersion stability within the lubricant matrix, affect their tribological performance. Metal oxide nanoparticles—especially those with spinel structures such as Fe_3O_4 and ZnO—have shown promising results in this regard (Ran, Yu, & Zou, 2017; Tsuzuki, 2021). These oxides can form durable tribofilms on metal surfaces that reduce direct contact and suppress abrasive wear (Tomala et al., 2019). ZnO nanoparticles, in particular, are noted for their excellent thermal stability (with decomposition temperatures exceeding 1975 °C) and surface compatibility (with a specific surface area of ~40 m²/g and particle sizes around 20 nm), making them suitable for a range of operating conditions (Hernandez Battez et al., 2006; Ren et al., 2020). Additionally, layered carbon-based nanomaterials such as graphene (Eswaraiah, Sankaranarayanan, & Ramaprabhu, 2011), carbon nanotubes (CNTs) (Hwang et al., 2011), and $g\text{-}C_3N_4$ (Boruah et al., 2025), along with two-dimensional materials like MXenes (Gul et al., 2025), contribute to enhanced lubrication via their high strength and anisotropic architectures, which support rolling and sliding effects at the interface.

The synthesis method plays a crucial role in determining the structural and functional properties of nanoparticles. Common techniques include co-precipitation (Ingole et al., 2013), sol-gel techniques (Parashar, Shukla, & Singh, 2020), mechanochemical milling (Tsuzuki, 2021), and microwave-assisted synthesis (Sreeram, Nidhin, & Nair, 2008). Among them, the hydrothermal method is particularly favoured for producing well-defined crystal structures with uniform morphology (Gul et al., 2025; Lefdhil et al., 2023; Mashrah & Polat, 2023). Hydrothermally synthesized nanoparticles also exhibit high surface energy, which enhances their interaction with lubricant matrices and increases their ability to form stable tribofilms (Polat & Faris, 2022). For example, $ZnAl_2O_4$ nanoparticles synthesized via a solvothermal process and modified with oleic acid demonstrated superior dispersion behaviour and anti-wear properties compared to individual ZnO or Al_2O_3 counterparts (Song et al., 2012). This highlights the hydrothermal route as a versatile and efficient approach to tailor both the structure and surface chemistry of nanoparticles for lubricant applications. Moreover, various metal oxides can be readily synthesized together with carbon-based materials such as graphene or g-C_3N_4 using hydrothermal routes, enabling the formation of hybrid nanostructures with synergistic tribological properties (Khan et al., 2015; Polat & Mashrah, 2022; Polat, Mashrah, & Maksur, 2024). This demonstrates that the hydrothermal route is a versatile and effective way to modify the surface chemistry and structure of nanoparticles for lubricant applications.

There are four main processes that control the ability of nanoparticles to reduce wear and friction. First, they can form protective tribofilms on sliding surfaces that prevent direct metal-to-metal contact (Shahnazar et al., 2016). Second, they can fill microcracks or surface defects through a mending effect, enhancing surface integrity (Liu et al., 2004). Third, their spherical or layered morphologies induce rolling or sliding effects that reduce shear stress and surface damage (Ingole et al., 2013). Fourth, their presence can result in a polishing effect that smoothens surface asperities and mitigates abrasive wear (Ingole et al., 2013; Wu, Tsui, & Liu, 2007). These combined mechanisms have been shown to lower COF values by 15–60% and significantly reduce wear scar diameters by ~ 20-35 % under various test conditions (Boruah et al., 2025; Shahnazar et al., 2016). However, to achieve these benefits, the nanoparticles must be uniformly and stably dispersed in the base oil. Agglomeration caused by van der Waals forces remains a major challenge, often addressed through surface functionalization, surfactant-assisted dispersion, or chemical modification of the lubricant to improve compatibility and suspension stability (Boruah et al., 2025).

3. Tribological Performance: Effect on Friction and Wear Properties

Friction and wear occur as a result of direct contact between interacting surfaces under relative motion, often leading to material degradation, heat generation, and energy loss. In dry or poorly lubricated environments, these effects are significantly intensified, causing rapid surface damage and reduced component lifespan (Karaca et al., 2024; Rundora et al., 2024). The integration of nanoscale additives into lubricating oils has emerged as a promising approach for enhancing tribological performance, particularly under boundary and mixed lubrication regimes (Kulkarni, Toksha, & Autee, 2024). Among various nanoparticles, metal oxides such as TiO_2, ZnO, and $ZnAl_2O_4$ have garnered significant attention due to their ability to form protective tribofilms that minimize metal-to-metal contact (Shahnazar et al., 2016). For instance, the incorporation of TiO_2 nanoparticles—especially in anatase form—has demonstrated a consistent reduction in the coefficient of friction (COF) and wear scar diameter (WSD), with reported friction decreases exceeding 15% at optimal concentrations (~0.01–0.25 wt%) (Ingole et al., 2013). Similarly, ZnO nanoparticles, characterized by high surface energy and reactivity, not only improve wear resistance but also enhance thermal stability. However, their oil dispersion stability requires surface functionalization, often achieved using surfactants such as SDS or oleic acid (Nozawa, Ferdows, Murakami, & Ota, 2009).

More advanced oxide systems such as $ZnAl_2O_4$ have shown superior performance over single oxides. Their high thermal and mechanical stability makes them ideal for forming stable lubricating layers at elevated temperatures. Modified $ZnAl_2O_4$ nanoparticles have been reported to deliver optimal anti-wear properties at just 0.1 wt%, outperforming both ZnO and Al_2O_3 under similar conditions (Song et al., 2012).

Carbon-based additives, including graphene and carbon nanotubes (CNTs), function through a different mechanism, where their layered or tubular morphologies facilitate interfacial sliding and reduce abrasive contact. These materials act as solid lubricants, reducing both shear stress and oxidation. For example, surface-modified graphene nanoplatelets were shown to reduce wear scar diameter (WSD) by up to 33% and coefficient of friction (COF) by 80% at concentrations as low as 0.025 mg/mL (Eswaraiah et al., 2011). Similarly, multi-walled CNTs, when functionalized with stearic acid, exhibited stable dispersion in oil and improved wear resistance up to 0.1 wt%, beyond which agglomeration begins to impair performance (Chen, Liu, & Yu, 1998). Fullerenes (0D) have also shown pressure resistance and COF reduction, especially in low-viscosity base oils (Ku et al., 2010). Hybrid systems that combine metal oxides with carbon nanostructures have revealed synergistic effects. For example, composites like Al_2O_3/TiO_2 or ZnO/graphene provide enhanced tribological behaviour by simultaneously offering surface passivation, mechanical cushioning, and heat dissipation (W. Zhang et al., 2011). These systems outperform their single-component counterparts, both in friction mitigation and anti-wear efficiency.

Despite these advancements, the concentration of nanoparticles remains critical. While low loading (<0.01 wt%) may not sufficiently modify surface interactions, higher concentrations (>1.0 wt%) can lead to aggregation, increased viscosity, or even abrasive behaviour (Krishna Sabareesh et al., 2012). Therefore, achieving stable dispersions at optimal loadings remains central to maximizing performance. Post-test surface analyses such as SEM and XPS confirm the formation of nanoparticle-derived tribofilms and indicate a transition in wear mechanism—from severe abrasive to mild adhesive or oxidative wear—when nano-additives are employed (Wu et al., 2007).

4. Comparative Literature Summary

Table 1 provides a comparative overview of a few chosen literature reports in order to better contextualise the tribological performance of different nanoparticle additives. The table lists important variables that affect wear scar diameter (WSD) and coefficient of friction (COF), including nanoparticle type, synthesis method, test setup, and operating conditions. Numerous studies (Kotia, Ghosh, Srivastava, Deval, & Ghosh, 2019; Z. Li et al., 2024; Ren et al., 2020) report COF reductions up to 78% and WSD reductions up to 44% under specific conditions. Together, these studies show that, particularly in boundary lubrication conditions, optimum concentration nanoparticle-lubricant systems can result in a notable decrease in friction and wear reduction.

Table 1. Summary of Tribological Performance of Selected Nanoparticles Used in Lubricants

Nanoparticle	Synthesis Method	Load / Temp	Concentration (wt%)	COF Reduction (%)	WSD Reduction (%)	Geometry	Reference
TiN	Sol-gel	392 N / RT	0.4	~15	~23	3D	(Z. Li et al., 2024)
CuO	Ultrasonic dispersion	392 N / 75°C	0.6	~25	~13	3D	(Zheng, Zhou, Jia, & He, 2020)
n-Ag	Chemical reduction	618 N / 120°C	2	~16	~13	3D	(Prabu, Saravanakumar, & Rajaram, 2018)
ND	-	100 N / RT	0.4	~16	-	3D	(Raina & Anand, 2018)
Al_2O_3	-	40 kg / 75°C	0.1	~3	~22	3D	(Loo et al., 2023)
Graphene	Liquid-phase exfoliation	40 kg / RT	0.02	~17	~9	2D	(W. Zhang et al., 2011)
Sc–Ni/GO	Chemical deposition	150 N / RT	0.08	~32	~42	2D	(Meng, Su, & Chen, 2015)
Cu NP	-	40 kg / 75°C	0.3	~60	~20	3D	(Guzman Borda, Ribeiro de Oliveira, Seabra Monteiro Lazaro, & Kalab Leiróz, 2018)
Cu NP	-	40 kg / 75°C	1.6	~40	~24	3D	(Y. Li et al., 2018)
Al_2O_3	-	98 N / RT	0.3	~33	~15	3D	(Kotia et al., 2019)
SnO_2	-	50 N / RT	3	~35	~42	3D	(B.-X. Wang et al., 2022)
ZnO	-	500 N / RT	0.5	~26	~12	3D	(Ran et al., 2017)
Fe_3O_4	Chemical precipitation	10 N / RT	2	~25	-	3D	(Zhou et al., 2013)
GO	Chemical exfoliation	3 N / RT	0.5	~78	-	2D	(Xie et al., 2018)
Al_2O_3/TiO_2	Hydrothermal	147 N / 75°C	0.1	~21	~44	3D	(Luo, Wei, Zhao, Cai, & Zheng, 2014)
$CaCO_3$	Hydrothermal	40 kg / 75°C	0.1	~2	~34	3D	(Kulkarni et al., 2024)
CeO_2	-	3000 N / RT	0.05	~70	~40	3D	(Pena-Paras, Maldonado-Cortes, Taha-Tijerina, Irigoyen, & Guerra, 2018)
EC-CNT	Etching	100 N / RT	1	~58	~33	1D	(Opia et al., 2022)
BN	-	392 N / 75°C	0.6	~17	~10	2D	(T. Wang, Li, Li, & He, 2020)
Al_2O_3	-	50 N / 125°C	0.075	~48	~18	3D	(Singh et al., 2019)
ZnO@Graphene	Hydrothermal	392 N / RT	0.5	~35	~32	2D	(Ren et al., 2020)
$Mn_3B_7O_{13}Cl$	Sol-gel	392 N / 75°C	0.2	~26	~25	3D	(Xiong, Liang, Wu, & Zhang, 2020)
MoS_2	Microwave Synthesis	392 N / 75°C	0.05	~10	~10	2D	(Nagarajan, Khalid, Sridewi, Jagadish, & Walvekar, 2022)
$CaCO_3$	Hydrothermal	392 N / 75°C	0.3	~29	~30	3D	(Kulkarni et al., 2023)
RTS (rubber tube soot)	Hydrothermal	40 kg / RT	0.1	~9	~17	3D	(Nowduru et al., 2022)

Cu@C	Hydrothermal	392 N / RT	0.1	~62	~38	3D	(B. Kumar et al., 2020)
Graphene	Chemical exfoliation	50 N / RT	0.05	~50	~4	2D	(Raghavulu & Govindha Rasu, 2022)

It has been demonstrated that adding nanoparticles to lubricants lowers the wear scar diameter (WSD) and coefficient of friction (COF). In this regard, Table 1 presents a comparative overview of different nanoparticles with distinct geometries (1D, 2D, and 3D), along with information on their synthesis techniques, concentration ratios, and testing parameters. According to the literature review data given in Table 1, the optimum addition rates of nanoparticles in lubricants vary widely, with a commonly referenced optimal range between 0.4% and 0.6%. However, as Table 1 shows, tested concentrations span from as low as 0.05% to as high as 3.0%, reflecting a broader experimental scope. It has been observed that even such low nanoparticle additive rates (0.05-0.5 wt%) significantly reduce the wear values (78% COF and 44% WSD) of tribological systems.

As observed from the summary in Table 1, structures like carbon nanotubes (EC-CNT), Cu@C nanohybrids, CeO_2, ZnO@graphene, and Sc-Ni/GO stand out in particular for their capacity to drastically lower COF. For example, adding CeO_2 to a block-on-ring tribotest under high load conditions reduced the COF by ~ 70% and the WSD by ~ 40%. The development of a tribofilm layer on the contact surface, the rolling action of the nanoparticles, and the tribochemical reactions during sliding are all responsible for this improvement.

Two-dimensional (2D) nanoparticles like graphene, MoS_2, and MXene ($Ti_3C_2T_x$) can prevent direct contact between materials and reduce friction by creating a physical barrier between sliding surfaces, because of their large surface areas. For instance, the COF was lowered by 32% and the WSD by 42% upon adding the Sc-Ni/GO hybrid composite at a concentration of 0.08%. Interestingly, although GO was tested at a very low load, its addition led to a 78% decrease in COF. According to these findings, 2D structures greatly improve the tribological performance of sliding interfaces by forming thin film layers.

Table 1 discusses three-dimensional (3D) nanoparticles, specifically additives like AlO_3, TiN, CuO, and $CaCO_3$. Rolling mechanisms and surface repair processes are the main causes of these additives' tribological effects, and they usually have a spherical morphology. For example, adding SnO_2 (3 wt%) and CuO (0.6 wt%) increased COF by about 35% and 25%, respectively. Furthermore, adding Al2O3 nanoparticles at low concentrations (0.1–0.3 wt%) decreased WSD values by 15–22%, demonstrating their efficacy even at low dosages.

In COF and WSD, hybrid structures—which are composed of nano-additives with multiple phases or components—such as ZnO@graphene, Cu@C, and AlO_3/TiO_2—have shown promising results. For example, in the case of ZnO@graphene, the hybrid additive improved tribological behaviour and tribofilm formation by leveraging the beneficial qualities of both constituents.

One-dimensional (1D) nanoparticles, like EC-CNTs, offer a structure that makes sliding along the friction interface easier because of their linear morphology. Due to their large surface coverage, two-dimensional (2D) additives are crucial in avoiding metal-to-metal contact. On the other hand, three-dimensional (3D) nanoparticles mainly improve tribological performance by contributing to a rolling effect on the contact surface and serving as fillers embedded in surface asperities.

The summarized data in the Table 1 demonstrate that the morphology, dispersion quality, and compatibility with test conditions of nanoparticle additives are all strongly correlated with their tribological performance, which is not only influenced by their concentration and synthesis method. Even at low concentrations, 2D nanoparticles can perform well in this situation. On the other hand, attaining appropriate concentration levels and guaranteeing sufficient dispersion within the lubricant matrix are crucial for the efficacy of 3D nanoparticles.

5. Conclusion

Nanoparticles have demonstrated considerable effectiveness in enhancing the tribological properties of lubricants, primarily by reducing friction and wear through mechanisms such as tribofilm formation, surface mending, and interfacial rolling. This review highlighted how factors like nanoparticle type, synthesis route, morphology, and dispersion quality collectively determine performance outcomes. Particularly, hydrothermal synthesis methods have shown promise in producing uniform, crystalline nanoparticles with improved surface reactivity and compatibility with lubricant matrices. Moreover, hybrid nanostructures incorporating metal oxides and carbon-based materials have provided synergistic benefits, such as enhanced thermal stability and interfacial protection.

For future research, several practical challenges must be addressed. A critical issue remains the stable and uniform dispersion of nanoparticles within the lubricant medium, as agglomeration and sedimentation can significantly reduce their effectiveness. This necessitates advancements in both synthesis strategies and dispersion techniques. For instance, modifying hydrothermal methods to produce surface-functionalized nanoparticles that resist aggregation, or integrating surfactant-assisted or in-situ modification during synthesis, could enhance long-term stability. Additionally, high-shear mixing, ultrasonication, or magnetic stirring protocols tailored to specific nanoparticle systems may provide improved homogeneity in the lubricant matrix. Investigating these parameters in a systematic and application-specific context is crucial. Furthermore, comparative studies assessing how dispersion quality influences tribological behaviour across various load and temperature conditions would contribute to developing standardized, industry-ready nano-lubricant formulations.

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