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Review article

Magnetic Nanomaterials as Lubricant Additives: Tribological Mechanisms, Formulation Challenges, and Prospects for Electrified Powertrains

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A B S T R A C T

The development of advanced and electrified powertrains is creating new demands on lubricants for controlling friction, wear, heat generation, and interfacial interactions under increasingly complex operating conditions. Magnetic nanomaterials, particularly magnetite (Fe_3O_4), offer a potential route toward responsive lubricant formulations because their behavior can be influenced by external magnetic fields. This review critically examines the tribological mechanisms, material characteristics, formulation strategies, and application prospects of magnetic nanomaterials as lubricant additives. Particular attention is given to particle-mediated friction and wear reduction, tribofilm formation, magnetic-field-assisted particle transport, hybrid formulations, surface functionalization, dispersion stability, and compatibility with base oils and greases. The available studies are considered in relation to their material composition, formulation conditions, test configurations, and reported evidence, while distinguishing experimentally investigated effects from proposed mechanisms and prospective applications. The review also discusses the challenges of interpreting results obtained under different tribological conditions and translating laboratory-scale findings to bearings, gears, and other electrified-powertrain components. Priorities for future research include quantitative comparison of formulations, long-term stability assessment, realistic component-level validation, reproducibility, sustainability, and the potential application of artificial intelligence and machine learning to materials and formulation design. Magnetic nano-lubricants therefore represent a promising research direction, although their practical implementation requires more systematic experimental validation and a clearer understanding of coupled magnetic, mechanical, thermal, and electrical effects.

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1. INTRODUCTION

The rapid development of electrified powertrains is creating new demands on lubricants used in bearings, reduction gears, electric axles, and related drivetrain components. High rotational speeds, compact component designs, thermal loads, and electrical stresses require lubricants to maintain friction and wear control while providing adequate thermal performance, material compatibility, and long-term stability [1–5]. Nanotechnology has consequently attracted considerable attention as a means of developing multifunctional lubricant formulations. Investigated additives include graphene and its derivatives, carbon nanostructures, metal oxides, MXenes, and other engineered nanomaterials, whose effects depend on their physical characteristics, interfacial interactions, and compatibility with the carrier fluid [6–13].

Although nonmagnetic nanomaterials have demonstrated potential for modifying friction, wear, and surface interactions, their performance is strongly influenced by particle concentration, morphology, dispersion stability, surface functionalization, base-oil chemistry, and tribofilm development [8,14–18]. These considerations are particularly important under electrified operating conditions, where electrical conductivity, charge generation, electrical discharge, and bearing-current damage may interact with conventional tribological processes [5,19–25]. The development of advanced lubricants for electrified powertrains therefore requires consideration not only of conventional friction-reduction mechanisms but also of the coupled physical and chemical processes that govern lubricant behavior in service.

Magnetic nanomaterials introduce an additional design variable because their response to an external magnetic field may influence particle distribution and interfacial interactions. Among these materials, magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3) are of particular interest because of their magnetic properties, nanoscale surface characteristics, and potential for surface functionalization [26–27]. Research has examined Fe_3O_4-containing lubricant additives, core–shell structures based on Fe_3O_4, and hybrid systems combining magnetite with other nanomaterials [28–30]. Other investigations have considered functionalized magnetite in biodegradable grease formulations and magnetic fluids for specialized bearing applications [31–32]. These studies provide a basis for investigating the relationships among particle characteristics, lubricant formulation, magnetic-field conditions, and tribological performance.

A further research direction concerns the possible participation of magnetic nanoparticles in protective tribofilm formation. Experimental investigations have examined the formation of Fe_3O_4-associated tribofilms and the conditions influencing their development [33]. Surface functionalization and hybrid-additive approaches may also affect dispersion behavior, lubricant compatibility, and interfacial protection [28–31,34]. Nevertheless, these effects should be interpreted in the context of the individual materials and experimental conditions studied. A reduction in friction or wear does not, by itself, establish a particular lubrication mechanism, and the observation of a beneficial laboratory-scale response does not necessarily demonstrate long-term stability or component-level suitability. The contact-level concept is illustrated schematically in Fig. 1.

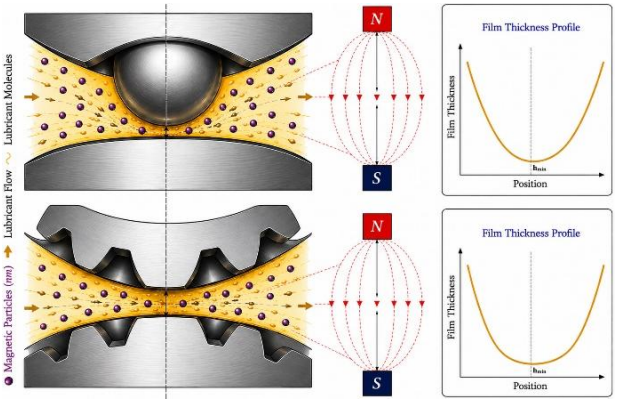


Fig. 1. Conceptual illustration of magnetically influenced lubricant films in bearing and gear contacts, based on [28–37].

Despite growing interest in magnetic nano-lubricants, several issues require more critical evaluation. These include the distinction between magnetic-field-assisted particle transport and other nanoparticle-mediated lubrication mechanisms; the influence of particle size, concentration, surface chemistry, and carrier-fluid properties; the stability of formulations during storage and operation; and the extent to which reported laboratory results can be compared across different test configurations.

The relevance of these findings to electrified powertrains must also be assessed carefully because studies of specialized magnetic fluids or individual tribological contacts do not automatically establish performance in complete electric-vehicle bearings, gears, or e-axles. In addition, the possible contribution of artificial intelligence (AI) and machine learning (ML) to the design of magnetic nanomaterials and lubricant formulations remains an emerging research direction whose applicability must be distinguished from already demonstrated experimental outcomes.

Accordingly, this review critically examines magnetic nanomaterials as lubricant additives, with particular emphasis on Fe_3O_4-based systems, tribological mechanisms, magnetic-field effects, formulation and surface-functionalization strategies, and the limitations of the available evidence. It considers how material characteristics and formulation conditions may influence friction and wear behavior, particle distribution, and interfacial protection. It also evaluates the challenges associated with dispersion stability, compatibility, reproducibility, and translation from laboratory investigations to practical lubrication systems. Finally, the review identifies research priorities involving alternative magnetic materials, hybrid formulations, realistic operating conditions, industrial validation, sustainability, and the prospective use of AI/ML-assisted design. By distinguishing experimentally supported findings from proposed mechanisms and future applications, the review aims to clarify both the potential and the current limitations of magnetic nano-lubricants for advanced lubrication systems and electrified powertrains.

1.1 Review Scope and Literature Selection

This article adopts a narrative review approach to examine magnetic nanomaterials as lubricant additives, with emphasis on magnetite-based formulations, magnetic-field-assisted lubrication, tribological mechanisms, and prospective applications in electrified powertrains. The literature search focused on studies addressing the preparation and characterization of magnetic nanoparticles, their incorporation into oils or greases, their tribological performance, and the influence of magnetic fields on particle behavior or lubrication outcomes.

The literature was assessed according to its relevance to the review objectives, the type of magnetic material investigated, the lubricant formulation and experimental conditions reported, and the extent to which the findings supported claims concerning friction, wear, dispersion stability, tribofilm formation, or practical application. Studies of nonmagnetic additives and broader materials-design approaches were considered where they provided relevant context for formulation strategies, electrified tribology, or prospective AI/ML-assisted design. Particular attention was given to distinguishing direct experimental observations from proposed mechanisms and extrapolations to applications that have not been validated at component level.

2. MAGNETIC NANOMATERIALS AS LUBRICANT ADDITIVES

Magnetic nanomaterials comprise a diverse group of nanoscale materials whose magnetic response and interfacial properties depend on their composition, particle size, morphology, surface chemistry, and surrounding medium. Their potential use in lubrication arises from two related but distinct characteristics: their ability to interact with lubricated surfaces and their response to an externally applied magnetic field. Unlike conventional nonmagnetic nanoparticles, magnetic particles may provide an additional means of influencing their spatial distribution within a lubricated system. Nevertheless, this possibility should not be interpreted as evidence that all magnetic nanoparticles provide field-controlled lubrication under practical operating conditions [11,26]. Carbonaceous materials, metal oxides, MXenes, and other engineered nanostructures provide useful comparative context for understanding nanoparticle-based lubrication, but their behavior should not be treated as directly equivalent to that of magnetic additives [17,38].

Iron-oxide nanoparticles, particularly magnetite (Fe_3O_4), are prominent candidates because of their magnetic response and the possibility of modifying their surfaces to improve compatibility with lubricant formulations [26,28,33]. Maghemite (γ-Fe_2O_3) and other ferrite materials, including mixed-metal oxides, offer additional possibilities for tailoring magnetic and surface properties [27]. However,

the availability of a material with suitable magnetic or physicochemical characteristics does not, by itself, establish its effectiveness as a lubricant additive. The tribological relevance of each material must be assessed from evidence obtained in the corresponding lubricant formulation and contact conditions. In particular, findings from general studies of magnetic nanomaterials or ferrite ceramics should not be interpreted as direct demonstrations of friction or wear reduction in lubricating oils or greases unless such performance was actually evaluated.

Published investigations illustrate the diversity of formulations considered to date. These include Fe_3O_4-containing hybrid structures, such as Fe_3O_4–polydopamine-associated nanoparticles incorporated into a black-phosphorus-based additive [28], and heterogeneous core–shell nano/microspheres based on Fe_3O_4 and carbon [29]. Fe_3O_4/graphene-based formulations have also been investigated under magnetic-field-assisted lubrication conditions [30]. These hybrid systems combine magnetic constituents with other materials, meaning that their tribological performance cannot automatically be attributed to magnetite alone. The role of the magnetic phase must therefore be considered alongside the contribution of the supporting material, particle architecture, surface chemistry, and experimental configuration. In addition, magnetic fluids investigated across different lubrication regimes provide evidence relevant to field-dependent lubrication behavior, but their results must be interpreted in the context of the specific fluid and contact studied [39].

The carrier medium is another important distinction among reported formulations. Magnetite nanoparticles have been investigated in biodegradable grease following surface functionalization [31], whereas silanized magnetite nanoparticles have been evaluated as an additive in a polyalphaolefin-based fluid intended for electric-vehicle transmission applications [40]. These examples represent different formulation environments and should not be compared as though grease and liquid oil were interchangeable carriers. The thickener structure and consistency of a grease, for example, introduce formulation considerations that differ from those of a circulating transmission fluid. Likewise, a study using an EV-relevant base fluid provides useful application-oriented evidence, but it does not by itself establish performance or durability in a complete electric-drive component. Magnetic fluids studied for specialized bearing applications, including space-related environments, should similarly be considered within their specific operating context rather than as direct evidence of suitability for automotive bearings or e-axles [32].

Surface functionalization, particle architecture, and carrier-fluid compatibility consequently form central considerations in the design of magnetic nano-lubricants. Surface treatments may be used to modify particle–fluid interactions and improve dispersion, while hybrid or core–shell structures may combine properties that are difficult to obtain from a single constituent [28–29,31,41]. However, improved initial dispersion should not be equated with long-term storage stability or stability under repeated mechanical and thermal loading. These outcomes require separate evidence, including appropriate stability measurements and, where relevant, assessment of particle aggregation, sedimentation, and changes in tribological performance during operation. Similarly, the presence of magnetic particles does not guarantee effective magnetic control: the response depends on the particle properties and the field configuration, as well as on the flow and geometry of the lubricated system.

Accordingly, magnetic nanomaterials should be classified not only by chemical composition but also by formulation type, surface treatment, carrier medium, and the level of experimental validation. The literature includes investigated oil-based additives, hybrid nanostructures, functionalized particles in grease, and magnetic fluids examined under specialized lubrication conditions. These categories provide complementary insights, but they do not establish the same level or type of evidence for practical use. The distinctive research opportunity lies in determining when magnetic responsiveness offers a measurable advantage beyond conventional nanoparticle-mediated lubrication, and whether that advantage can be maintained under realistic operating conditions. The following section therefore examines the proposed and experimentally investigated tribological mechanisms, distinguishing observed outcomes from mechanisms that remain inferred or require further validation.

3. TRIBOLOGICAL MECHANISMS OF MAGNETIC NANO-LUBRICANTS

Magnetic nano-lubricants may influence friction and wear through several interacting processes, including particle-mediated separation of contacting asperities, deposition of particles at the interface, formation of protective surface layers, and field-dependent redistribution of magnetic particles. The relative importance of these processes depends on particle characteristics, formulation chemistry, contact geometry, lubrication regime, and magnetic-field configuration. Importantly, a measured reduction in friction or wear does not, by itself, establish which mechanism is responsible. Mechanistic interpretations should therefore be distinguished from processes supported by direct characterization of particles, lubricant films, or worn surfaces.

3.1 Particle-Mediated Contact and Friction Reduction

Nanoparticles dispersed in a lubricant may influence contact mechanics by entering surface valleys, modifying local contact conditions, or contributing to the separation of opposing surfaces. A rolling or sliding contribution is sometimes proposed for particles with suitable size and morphology. However, the presence of approximately spherical particles does not establish that they act as rolling elements during a tribological test. Direct evidence is needed to distinguish rolling from sliding, particle deformation, fragmentation, surface deposition, or other contact-mediated effects [28–29,42].

The effectiveness of particle-mediated lubrication also depends on the relationship between particle size and the dimensions of the contact and surface roughness. Particles that are too large, poorly dispersed, or present at excessive concentrations may interfere with contact rather than improve it. Accordingly, rolling should be treated as a possible mechanism whose contribution depends on the material and operating conditions, rather than as a universal explanation for the performance of magnetic nano-lubricants.

3.2 Interfacial Deposition and Tribofilm Formation

A second possible mechanism is the deposition or retention of nanoparticles at the rubbing interface, where they may contribute to a surface layer that modifies direct asperity contact. Evidence for this process is stronger when post-test surface characterization identifies deposited material and relates its distribution or composition to the tested formulation. Friction and wear measurements alone can establish a performance change, but cannot independently confirm the composition, continuity, or protective function of a tribofilm.

Studies of magnetic fluids containing Fe_3O_4 nanoparticles have reported field-dependent deposition at the contact and used worn-surface analysis to investigate the associated lubrication behavior [39]. These findings support a role for particle delivery and interfacial deposition under the tested conditions. They should not, however, be generalized to every magnetic additive, carrier fluid, or lubrication regime without further evidence.

Recent experimental work has directly investigated tribofilm formation by Fe_3O_4 nanoparticles used as lubricant additives, providing microscopic insights into the growth conditions and underlying interfacial mechanisms [33].

3.3 Magnetic-Field-Assisted Particle Transport and Retention

Magnetic-field assistance introduces a control variable that is not available in the same form for conventional nonmagnetic additives. Depending on the magnetic properties of the particles and the field configuration, magnetic forces may redistribute particles within the lubricant and influence their delivery to or retention near a tribological contact. The resulting response depends not only on field strength but also on the spatial field gradient, particle magnetization, particle concentration, lubricant viscosity, flow conditions, and contact geometry.

Particle transport toward a contact must be distinguished from field-induced alignment,

chaining, or local aggregation. These processes are related but not equivalent. Transport concerns the movement and redistribution of particles; alignment or chaining concerns their arrangement under the applied field; and aggregation may alter their effective size and dispersion state. Depending on the formulation and operating conditions, these effects may promote local particle availability or instead produce nonuniform distributions and reduce dispersion stability.

Experimental findings demonstrate that the effect of a magnetic field can vary with lubrication regime. In a study of magnetic fluids containing Fe_3O_4 nanoparticles, the application of a magnetic field improved the measured tribological performance in both boundary and mixed lubrication, with a particularly pronounced response in boundary lubrication. For the formulation containing 1 wt.% Fe_3O_4, the reported friction reduction was 41.2% and the wear-volume reduction was 94.7% under the tested boundary-lubrication conditions [39]. These values are specific to the investigated fluid, test configuration, and comparison conditions; they should not be interpreted as general performance factors for magnetic nano-lubricants.

Magnetic-field-assisted minimum-quantity lubrication using an Fe_3O_4/graphene nano-lubricant has also been investigated in grinding [30]. This study provides evidence relevant to magnetic assistance in a particular manufacturing-lubrication configuration, but its results should not be presented as direct validation for automotive bearings, gears, or e-axles. Overall, field-assisted lubrication is best understood as a condition-dependent process whose benefits and limitations must be evaluated experimentally for each formulation and contact.

3.4 Hybrid Additives and Potentially Complementary Mechanisms

Hybrid formulations combine magnetic nanoparticles with other materials to obtain a combination of properties that may be difficult to achieve with a single constituent. For example, Fe_3O_4/graphene systems combine a magnetic phase with a carbon-based material and have been investigated under magnetic-field-assisted grinding conditions [30]. Fe_3O_4-based core–shell structures incorporating carbon and other hybrid architectures have also been explored as lubricant additives [28–29].

Such combinations may affect particle distribution, interfacial interactions, deposition, and surface protection. Nevertheless, improved performance of a hybrid formulation does not automatically demonstrate synergistic behavior. Establishing synergy requires suitable controls—for example, comparison with the base lubricant and with formulations containing the individual constituents under equivalent test conditions. Without such comparisons, the relative contributions of the magnetic phase, the secondary material, and the hybrid architecture remain uncertain.

Hybrid formulations should therefore be evaluated using both performance measurements and evidence that helps explain the observed response. Relevant factors include additive concentration, particle morphology, surface treatment, carrier-fluid compatibility, dispersion stability, and the presence or absence of an external magnetic field. This approach is necessary to distinguish genuine complementary effects from improvements attributable primarily to one constituent or to differences in formulation and testing.

Table 1 summarizes the principal mechanisms discussed in this section, the evidence that can support them, and the limitations that should be considered when interpreting reported results. The mechanisms are not mutually exclusive, and the available evidence does not establish that every mechanism operates simultaneously in every magnetic nano-lubricant. Table 1 does not imply that all listed mechanisms have been directly verified in every cited study.

Figure 2 provides a conceptual overview of the possible relationships among magnetic-field effects, particle behavior, interfacial processes, and tribological performance. The schematic should be interpreted as a framework for organizing the mechanisms, not as proof of a universal sequence of events.

Table 1. Principal mechanisms proposed or investigated in magnetic nano-lubricants, their supporting evidence, and key limitations.

Mechanism	Physical basis	Evidences	Limitations	Refs.
Particle-mediated contact	Particles may reduce direct asperity contact	Friction and wear measurements under controlled conditions	Rolling is not confirmed by friction reduction alone	[28–29,42]
Interfacial deposition	Particles may accumulate on contacting surfaces	Surface analysis after tribological testing	Film formation requires direct experimental evidence	[39]
Tribofilm formation	Deposited material may contribute to a protective interfacial layer	Chemical and morphological analysis of the worn surface	Film formation requires direct experimental evidence	[33,39]
Field-assisted particle redistribution	Magnetic fields may alter particle transport within the contact	Tests under controlled magnetic-field conditions.	Results depend on field configuration and contact conditions	[30,39]
Hybrid-additive effects	Different additives may provide complementary functions	Comparison with individual-additive controls	Improved performance alone does not prove synergy	[28–30]
Field-induced aggregation	Magnetic interactions may promote particle chaining or aggregation	Particle-distribution observations under applied fields	Aggregation may impair dispersion and lubricant delivery	[30,39]

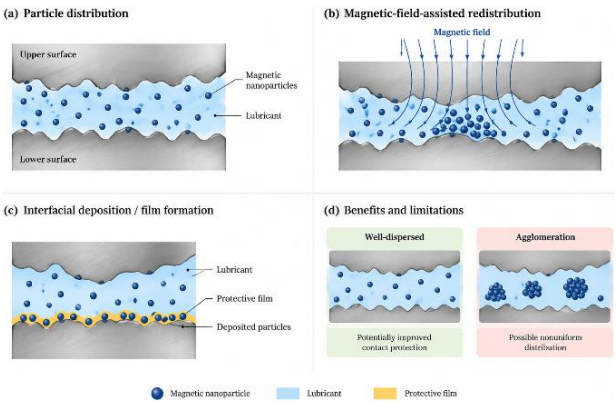


Fig. 2. Conceptual illustration of magnetic nanoparticle distribution, field-assisted redistribution, interfacial deposition, and agglomeration in lubricated contacts (based on mechanisms discussed in [28–30,39]).

Similarly, core–shell structures based on Fe_3O_4 and carbon provide opportunities to tailor particle morphology, surface interaction, and tribofilm formation [29].

Overall, magnetic nano-lubrication should be viewed as a coupled particle–surface–field system, rather than simply a conventional nano-lubricant containing magnetic particles. The interaction between nanoparticle characteristics, lubricant chemistry, contact conditions, and magnetic-field parameters ultimately determines whether magnetic control produces improved lubrication or undesirable particle aggregation [27–34].

4. FORMULATION AND SURFACE FUNCTIONALIZATION OF MAGNETIC NANO-LUBRICANTS

The tribological performance of magnetic nanomaterials depends not only on their intrinsic properties but also on their dispersion state, surface chemistry, concentration, and compatibility with the carrier lubricant. Magnetic attraction and interparticle interactions can promote agglomeration, while differences in particle–fluid affinity may contribute to sedimentation or nonuniform distribution. These effects can reduce the effective particle concentration reaching the contact and make the measured friction and wear responses less reproducible. Consequently, particle characteristics, formulation conditions, and carrier-fluid properties should be considered together when designing magnetic nano-lubricants [11,28,31,40,43–45].

Surface functionalization is one strategy for improving particle dispersion and compatibility with the surrounding fluid. Organic coatings, including silane-based and fatty-acid-based treatments, can modify particle-surface interactions and influence the stability of the resulting formulation. Silanized Fe_3O_4

nanoparticles have been investigated in a polyalphaolefin (PAO)-based fluid intended for electric-vehicle transmission applications [40], while stearic-acid-functionalized magnetite has been studied in biodegradable grease [31]. These examples illustrate the importance of matching surface treatment to the carrier formulation. However, improved initial dispersion or favorable tribological results do not, by themselves, establish long-term storage stability or reliable performance under prolonged operating conditions. Such conclusions require stability measurements over defined periods and, where relevant, under representative temperature, shear, and magnetic-field conditions.

Particle architecture provides another means of tailoring magnetic and interfacial behavior. Fe_3O_4/carbon core–shell structures have been investigated as a way to combine a magnetic component with a carbon-based surface [29]. Hybrid formulations containing magnetic nanoparticles and materials such as graphene may also provide complementary functions, including changes in interfacial contact and particle transport [28,30]. Nevertheless, the performance of a hybrid formulation cannot automatically be attributed to synergy: comparisons with the individual components, tested at appropriate concentrations and under equivalent conditions, are needed to establish whether the combined system provides an additional benefit.

The carrier fluid is equally important because viscosity, polarity, thermal behavior, and additive compatibility influence particle dispersion and transport through a lubricated contact. These considerations are particularly relevant to electrified powertrains, where a lubricant may need to provide friction and wear control while meeting thermal and electrical requirements [3–5,23–24,43,46–47]. Studies involving low-viscosity lubricants and nanoparticle-enhanced electric-vehicle transmission oils provide relevant context for these formulation challenges [46–47]; however, findings from nonmagnetic nanoparticle systems should not be interpreted as direct evidence of the performance of magnetic nano-lubricants.

A further challenge is the distinction between dispersion stability in the absence of a magnetic field and stability during field-assisted operation. An applied field may redistribute magnetic particles toward particular regions of a contact, but it may also promote particle chaining or aggregation, depending on particle properties, field configuration, fluid motion, and contact geometry. Therefore, particle retention near a contact should not be equated automatically with stable dispersion or improved lubrication. These effects require evaluation under clearly defined magnetic and operating conditions.

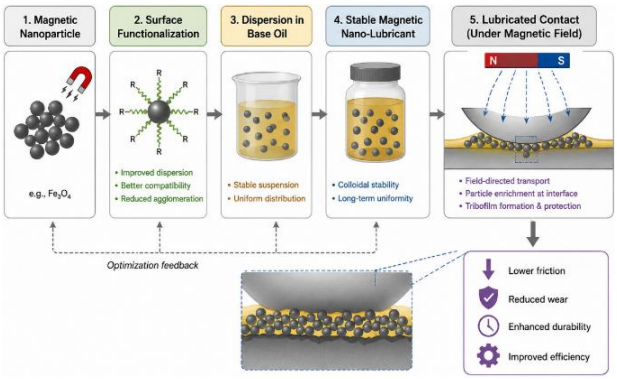


Fig. 3. Formulation and validation pathway for magnetic nano-lubricants.

Overall, the formulation of magnetic nano-lubricants requires an integrated assessment of particle composition, surface functionalization, carrier-fluid compatibility, concentration, and magnetic-field conditions. Future investigations should distinguish initial dispersion, storage stability, and operational stability; report the methods and duration used to assess each; and evaluate friction and wear alongside evidence of particle distribution and post-test surface condition. Such an approach would provide a stronger basis for comparing formulations and assessing their potential for practical transmission, bearing, and other electrified-powertrain applications. The principal formulation and validation stages are summarized in Fig. 3.

5. MAGNETIC-FIELD-ASSISTED LUBRICATION

An external magnetic field introduces an additional control variable into magnetic nanolubrication by influencing the distribution and movement of magnetic particles within the lubricant. Depending on the formulation and field configuration, this influence may increase particle concentration near a tribological contact and facilitate interfacial deposition. However, particle transport toward a contact should be distinguished from particle alignment, chaining, or aggregation, as these processes may produce different effects on lubricant delivery and tribological performance [30,32,39].

The response to a magnetic field depends on more than field strength alone. Relevant factors include the field gradient and orientation, particle magnetization and concentration, carrier-fluid viscosity, flow conditions, and contact geometry. The resulting behavior also depends on the lubrication regime. For example, Wang et al. [39] investigated Fe_3O_4-based magnetic fluids under boundary and mixed lubrication and reported different responses to magnetic-field application. For a formulation containing 1 wt.% Fe_3O_4, the authors reported reductions of 41.2% in friction and 94.7% in wear volume under the investigated field-assisted boundary-lubrication conditions. These results demonstrate the potential of magnetic-field assistance in that particular experimental system; they should not be treated as universal performance improvements for other formulations or operating conditions.

A complementary approach combines magnetic particles with other functional nanomaterials. The Fe_3O_4/graphene formulation investigated in reference [30] used magnetic traction to improve lubricant delivery in minimum-quantity lubrication grinding. The reported findings support the potential of combining magnetic-field-assisted transport with a hybrid additive architecture. Nevertheless, grinding conditions differ substantially from those encountered in enclosed transmission systems and electric-motor bearings. The study therefore provides relevant evidence for magnetic-assisted lubrication, but not direct validation of an EV drivetrain component.

Magnetic attraction may also have adverse effects. Depending on the field configuration and formulation, particle chaining or aggregation may produce a nonuniform distribution, potentially limiting lubricant delivery to parts of the contact. Consequently, increasing field strength cannot be assumed to improve lubrication continuously. A useful operating range must be established experimentally by examining particle distribution, friction, wear, and surface condition under defined field and contact conditions [30,39].

From an engineering perspective, magnetic-field-assisted lubrication offers a possible route toward actively controlled particle delivery rather than relying entirely on passive dispersion. Future systems could investigate field control in response to changing load, speed, temperature, or lubrication regime. However, such adaptive operation remains a prospective application until demonstrated under representative component conditions. Validation should include repeatability, long-term dispersion stability, thermal behavior, and compatibility with the electrical and mechanical requirements of the intended system [3–5,19,23–25].

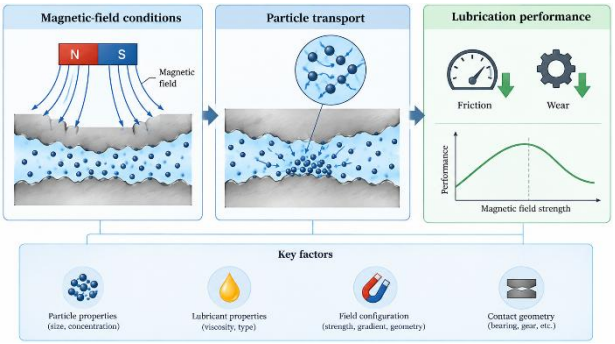


Fig. 4. Conceptual relationship between magnetic-field conditions, particle transport, and lubrication performance.

Accordingly, future investigations should report field strength, field gradient and geometry, particle concentration, lubricant properties, and contact conditions in sufficient detail to enable meaningful comparison. Where possible, field-assisted tests should be compared with otherwise equivalent tests without an applied field. Such controls are essential for determining whether an observed improvement arises from magnetic-field-induced particle transport, the additive formulation itself, or an interaction between these factors. The conceptual relationships among these parameters, particle transport, and lubrication performance are summarized in Fig. 4.

6. APPLICATIONS AND CHALLENGES

Magnetic nano-lubricants may offer advantages in applications where lubricant distribution, interfacial protection, and friction control are important under demanding operating conditions. Their potential relevance to electrified powertrains arises from the possibility of influencing magnetic-particle distribution through an external field. However, this potential should be distinguished from demonstrated component-level performance. Evidence obtained from laboratory tribological contacts, specialized bearing systems, greases, or grinding operations does not by itself establish suitability for electric-motor bearings, reduction gears, or e-axles [1–5,23,28–32,34,40].

6.1 Potential Applications in Electrified Powertrains

Electric-motor bearings and transmission gears are potential targets for magnetic nano-lubricant research because these components require reliable friction and wear control under changing mechanical and thermal conditions. Magnetic-field-assisted particle transport could, in principle, provide an additional means of controlling lubricant delivery near a contact. Nevertheless, practical implementation would require evidence that the particles can be delivered reproducibly without compromising lubricant supply, bearing or gear performance, or material compatibility.

Reference [40] investigated silanized magnetite nanoparticles as an additive for a PAO-based electric-vehicle transmission base fluid. This work provides a relevant formulation-level example, but it should not be interpreted as validation in a complete EV transmission or vehicle. Similarly, reference [30] concerns magnetic-field-assisted minimum-quantity lubrication in grinding, while reference [31] investigates a biodegradable grease formulation. These studies contribute evidence about specific materials and lubrication configurations, but their findings cannot be transferred directly to EV bearings or e-axles without additional testing.

6.2 Dispersion Stability and Formulation Compatibility

Dispersion stability remains a central challenge for practical magnetic nano-lubricants. Agglomeration and sedimentation can change the local particle concentration, reduce formulation uniformity, and potentially alter rheological and tribological behavior. Surface functionalization, particle concentration, and compatibility between the particle coating and carrier lubricant must therefore be considered together [11,16,28,31].

Stability should be evaluated at three distinct levels: initial dispersion after preparation, storage stability over a defined period, and operational stability during repeated or prolonged use. A formulation that remains dispersed during a short laboratory test cannot automatically be considered stable during storage or under sustained shear, elevated temperature, and an applied magnetic field. Where evidence is available, these conditions should be reported separately rather than summarized by a general claim of improved stability.

Compatibility with the existing lubricant formulation is equally important. The effects of magnetic particles on viscosity, thermal behavior, oxidation stability, and conventional extreme-pressure or anti-wear additive packages require assessment. For electrified powertrains, electrical properties and compatibility with the materials encountered in the intended component must also be established. Favorable friction and wear results alone are insufficient to demonstrate that a magnetic nano-lubricant meets the complete requirements of an EV application [3–5,23–25,48–49,41].

6.3 Magnetic-Field Control and Component-Level Validation

External-field control introduces opportunities as well as engineering constraints. The response of a magnetic nano-lubricant depends on field strength, field gradient and geometry, particle characteristics, carrier-fluid properties, and the prevailing lubrication regime. Excessive particle attraction may encourage chaining or aggregation, whereas a field configuration that produces little effective particle transport may offer limited practical benefit [30,32,39].

Future component-level studies should therefore compare field-assisted operation with equivalent tests conducted without an applied field. Relevant measurements include friction, wear, particle distribution, lubricant temperature, and post-test surface condition. For electrified applications, testing should additionally address electrical behavior, temperature-dependent performance, and compatibility with bearing, gear, seal, and other relevant materials. These assessments are necessary before potential benefits can be translated into reliable component specifications.

6.4 Environmental, Manufacturing, and Scale-Up Considerations

Practical development also requires consideration of manufacturing reproducibility, formulation cost, environmental impact, and the management or recovery of nanoparticle-containing lubricants. Surface treatments and hybrid architectures may improve particular formulation properties, but their overall value must be assessed alongside processing requirements, service life, and end-of-life considerations [9–11,50–53].

Overall, magnetic nano-lubricants offer a promising research direction for externally responsive lubrication, but their practical readiness remains dependent on the specific formulation and application. Progress will require more than demonstrating friction or wear reduction in isolated experiments. Reproducible field-controlled particle transport, well-characterized dispersion stability, compatibility with complete lubricant formulations, and validation under realistic component conditions are essential steps toward practical implementation.

7. RESEARCH GAPS AND FUTURE PERSPECTIVES

Despite encouraging laboratory findings, several scientific and engineering challenges remain before magnetic nano-lubricants can be considered reliable solutions for practical machinery and electrified powertrains. Priorities include expanding the range of investigated magnetic materials, understanding coupled operating conditions, improving formulation stability, developing reproducible testing protocols, and establishing application-specific performance requirements. Artificial intelligence and machine learning may eventually support these efforts, but their value will depend on the availability of reliable, relevant, and sufficiently documented experimental data.

7.1 Expansion beyond Fe_3O_4

Research on magnetic nano-lubricants has concentrated substantially on magnetite (Fe_3O_4). Other magnetic oxides, including maghemite (γ-Fe_2O_3) and spinel ferrites such as $CoFe_2O_4$, $NiFe_2O_4$, $MnFe_2O_4$, and $ZnFe_2O_4$, provide potential candidates for further investigation [11,26–27]. However, magnetic properties alone do not establish suitability as lubricant additives. Each candidate requires evaluation of particle morphology, surface chemistry, dispersion behavior, compatibility with the carrier fluid, and performance under relevant tribological conditions.

Future studies should compare alternative ferrites using consistent particle characterization, formulation procedures, concentrations, contact configurations, and testing conditions. Such comparisons would help establish whether differences in magnetic response or surface chemistry translate into measurable improvements in friction and wear. Magnetic ceramic nanocomposites and hybrids incorporating two-dimensional materials also warrant investigation, provided that the contribution of each component can be distinguished through appropriate controls [12,28–30].

7.2 Multiphysics and Realistic Operating Conditions

Many laboratory investigations examine only a limited combination of load, speed, temperature, and magnetic-field conditions. In practical machinery, these variables may interact with lubricant flow, electrical stresses, and changing contact conditions. Future work should therefore move toward coupled magnetic–mechanical–thermal–electrical–tribological investigations relevant to bearings, gears, and electrified powertrains [4–5,19,23–25,46,54].

Particular attention should be given to the relationship between field configuration, particle concentration, lubricant properties, and measured friction and wear. Researchers should also distinguish particle transport toward a contact from aggregation, retention, and the formation of a protective interfacial layer. Direct surface characterization and controlled comparisons are needed to establish which mechanisms occur under each set of operating conditions [30,33,55].

For prospective EV applications, testing should additionally address temperature-dependent lubricant properties, electrical behavior, and compatibility with relevant component materials. Results from a laboratory contact should not be considered sufficient evidence of component-level performance. Validation in representative bearings, gears, or other intended components remains an essential research priority.

7.3 AI/ML-Assisted Magnetic Nano-lubricant Design

Artificial intelligence and machine learning may provide useful tools for organizing experimental data, identifying relationships among formulation variables, and prioritizing candidate magnetic nano-lubricants for testing. Potential input variables include particle composition and morphology, surface functionalization,

concentration, carrier-fluid properties, magnetic-field parameters, and operating conditions. Possible outputs include friction, wear, dispersion stability, and other measured formulation properties.

However, the application of AI/ML to magnetic-nano-lubricant design should currently be treated as a research opportunity rather than an established capability unless directly relevant studies demonstrate otherwise. Models trained on unrelated nanomaterials or general tribological datasets cannot automatically be assumed to predict magnetic-field-dependent lubricant behavior. Similarly, a model's apparent predictive accuracy does not establish its reliability outside the range of its training data.

A credible research framework would begin with a curated dataset containing clearly defined formulations, experimental conditions, measurement methods, and uncertainty information. Model evaluation should use appropriate validation procedures, prevent data leakage between closely related experiments, and assess performance on independent data where feasible. Interpretability and uncertainty estimation would also be valuable when identifying influential formulation variables or selecting experiments for further investigation. Ultimately, AI/ML should complement—not replace—experimental verification of dispersion, magnetic response, friction, wear, and material compatibility.

7.4 Scale-Up, Reproducibility, and Industrial Validation

Differences in nanoparticle synthesis, surface functionalization, dispersion procedures, magnetic-field configurations, and tribological testing can make results difficult to compare across studies. Standardized reporting should include particle characteristics, additive concentration, carrier formulation, preparation procedure, field conditions, contact geometry, test duration, control formulation, and measurement uncertainty wherever applicable.

Stability assessment also requires clearer distinctions between initial dispersion, storage stability, and stability during repeated or prolonged operation. Reporting only an initial particle distribution or a short friction test is insufficient to establish long-term formulation reliability. Where applicable, researchers should investigate the effects of temperature, shear, oxidation, and applied magnetic fields over defined periods [9–11,50–53].

Industrial validation should progress from laboratory screening to tests using complete lubricant formulations and representative components. These studies should evaluate not only friction and wear but also lubricant service life, compatibility with conventional extreme-pressure and anti-wear additive packages, manufacturing reproducibility, and the practical requirements of the intended application [48–49,56–59]. Claims of readiness for EV bearings, gears, or e-axles should be supported by evidence from the corresponding application level.

7.5 Sustainability and Formulation Compatibility

The environmental and practical implications of magnetic nano-lubricants require consideration alongside their tribological performance. Relevant questions include the environmental fate of released nanoparticles, the effects of surface treatments, the durability of the formulation, and the feasibility of recovering or recycling nanoparticle-containing lubricants. These aspects should be evaluated for the complete formulation rather than inferred solely from the composition of the magnetic particle.

Compatibility with the carrier lubricant and its existing additive package is another priority. Surface functionalization and hybrid architectures may improve selected properties, but they should be assessed against potential changes in viscosity, oxidation stability, electrical behavior, and service life. Formulation development should therefore seek a balance among friction and wear control, stability, compatibility, environmental considerations, and manufacturability [12,41].

Overall, the next stage of magnetic-nano-lubricant research should prioritize reproducible formulation data, systematic comparisons across materials, coupled-condition testing, and application-specific validation. AI/ML may assist in identifying promising candidates and optimizing experimental programs, while practical adoption will depend on demonstrated performance, stability, compatibility, and reliable manufacturing.

8. CONCLUSIONS

Magnetic nanomaterials offer a promising approach to developing multifunctional lubricants with potentially controllable particle distribution and interfacial behavior. Among the materials considered, Fe_3O_4-based systems have received particular attention because of their magnetic response and their potential to contribute to friction and wear control. Hybrid architectures, surface functionalization, and magnetic-field-assisted lubrication provide additional opportunities to tailor formulation properties and lubrication performance.

The effectiveness of magnetic nano-lubricants depends on the combined influence of particle characteristics, surface chemistry, carrier-fluid compatibility, dispersion stability, contact conditions, and magnetic-field configuration. Although encouraging laboratory results have been reported, proposed mechanisms—including particle-mediated contact, interfacial deposition, and protective-film formation—must be distinguished from processes directly confirmed by experimental evidence. Similarly, improvements demonstrated in specific laboratory contacts should not be interpreted as proof of performance in complete electrified-powertrain components.

Several challenges therefore remain before practical implementation can be established. These include maintaining dispersion stability during storage and operation, controlling field-induced particle redistribution and aggregation, ensuring compatibility with complete lubricant formulations, and validating performance under coupled mechanical, thermal, magnetic, and electrical conditions. Reproducible testing, realistic component-level assessment, and consideration of environmental impact and manufacturing requirements are also essential.

Future research should expand systematic comparisons to alternative magnetic ferrites and hybrid materials, establish more consistent experimental reporting, and investigate application-specific performance requirements. Artificial intelligence and machine learning may eventually assist in materials screening and formulation optimization, provided that reliable experimental datasets and rigorous independent validation are available.

In conclusion, magnetic nano-lubricants should be regarded as a promising but still developing approach to responsive lubrication. Their successful application will depend not simply on achieving lower friction or wear in individual experiments, but on demonstrating stable formulations, reproducible magnetic-field control, reliable component performance, and compatibility with the broader requirements of practical lubrication systems.

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