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Review article

2D Nanomaterials as Lubricant Additives for Electric Vehicle Propulsion: Tribological Mechanisms, Performance and Sustainability – A Review

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A B S T R A C T

Two-dimensional (2D) nanomaterials including graphene, MXenes, hexagonal boron nitride (h-BN), molybdenum disulfide (MoS_2), and phosphorene have emerged as strategically important additives for next-generation electric vehicle (EV) e-fluids. This review synthesizes the most recent advances in 2D-material-enhanced lubrication, with emphasis on their behavior in synthetic ester base stocks that dominate modern EV lubrication formulations. A comprehensive literature survey across global research clusters (USA, EU, China, Japan, South Korea) highlights significant variability in synthesis approaches, scalability, functionalization strategies, and additive performance. Comparative assessments reveal that graphene-based materials excel in shear-induced friction reduction, MXenes offer superior load-carrying capability and electrical responsiveness, and MoS_2 and h-BN contribute stability at elevated temperatures. Phosphorene, despite its promising anisotropic lubrication mechanisms, remains constrained by degradation and oxidation challenges. This review summarizes tribological performance metrics, production cost–scalability, environmental considerations, and concentration ranges in e-fluids. Critical research gaps identified in dispersion stability, rheo-electrical interactions, and long-term chemical compatibility within ester-rich formulations. An opportunities-focused outlook highlights pathways for integrating 2D materials into industrial-scale EV lubricants, emphasizing sustainable synthesis, hybrid additive architectures, and machine-learning-driven formulation design. The review concludes by outlining strategic directions for future work to accelerate translation of laboratory-scale tribological advances into robust, commercially viable e-fluid technologies.

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1. INTRODUCTION

1.1 Background and Motivation

The rapid electrification of transportation systems has fundamentally altered the operating ecosystem of tribological interfaces in electric vehicles (EVs), shifting tribology from component-level optimization toward integrated, vehicle-system performance involving bearings, transmissions, and EV lubrication systems [1–10]. These intensified operating conditions impose stringent—and often conflicting—requirements on advanced lubricant formulations, commonly referred to as e-fluids, including the increasing adoption of low-viscosity formulations to balance efficiency, friction, and wear in electrified powertrains [11]. Such fluids must simultaneously provide friction and wear mitigation, controlled electrical conductivity or insulation, thermal stability, and long service life under electrified environments [12–17]. These coupled mechanical–electrical responses are increasingly described within the framework of rheoelectricity, which captures the interdependence of viscosity, electrical conduction, dielectric breakdown, and tribological behavior under applied electric fields [7,18–19]. Recent efforts to standardize electric vehicle fluid testing further highlight that conventional lubricant evaluation protocols are insufficient for electrified drivetrains, necessitating dedicated methodologies that simultaneously address tribological, thermal, and electrical performance metrics [20].

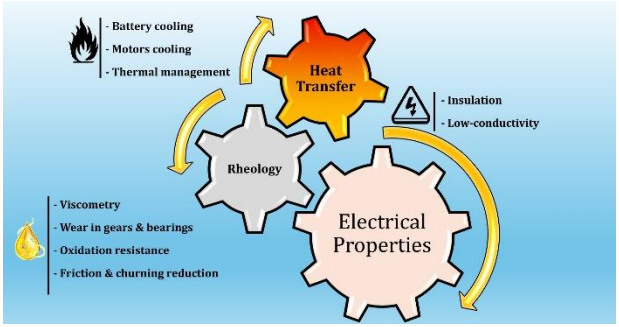


Fig. 1. Key functional requirements governing EV e-fluids, adapted from Refs. [21–22].

Conventional lubricant formulations originally optimized for internal combustion engine (ICE) systems frequently fail to meet these multifaceted demands, motivating the exploration of advanced base-oil chemistries and functional additives specifically tailored for EV tribological regimes [23–25]. The expanding scope of vehicle tribology—encompassing bearings, transmissions, drivetrains, and lubrication systems in electrified platforms—has been comprehensively highlighted in recent automotive-focused tribology compilations [8]. Authoritative monographs dedicated to electric vehicle tribology further consolidate the understanding that electrified drivetrains introduce fundamentally new lubrication, wear, and electro-tribological challenges that extend beyond conventional automotive paradigms [21]. Among emerging base oils, synthetic esters have gained considerable attention due to their favorable viscosity–temperature behavior, high dielectric strength, biodegradability, and tunable molecular architectures [7,17,26–29]. However, ester base oils alone may be insufficient to withstand extreme contact pressures, boundary lubrication conditions, or electrically induced degradation phenomena encountered in EV drivetrains [17,27-28]. Recent surveys emphasize that EV tribology should be treated as a coupled, system-level problem involving surfaces, interfaces, electrical fields, and lubricant chemistry [30].

Consequently, the incorporation of nanoscale additives—particularly two-dimensional (2D) materials—has emerged as a promising strategy to enhance lubricant performance without compromising rheological or electrical characteristics [7,15,18,31–33]. Recent studies indicate that synthetic ester-based e-fluids, when combined with functional nanomaterials, can actively modify lubricant film structure, electrical conduction pathways, and interfacial energy dissipation, rather than acting merely as passive friction modifiers [34–38]. These findings reinforce the suitability of ester-based e-fluids for next-generation EV propulsion systems operating under coupled thermo–rheo–electrical stresses [7,17].

Beyond classical lubrication challenges, electrified powertrains increasingly demand fluids that function as multifunctional media, simultaneously mediating mechanical contact, heat transport, and charge conduction or insulation. Recent system-level studies on EV bearings, greases, and drivetrain fluids demonstrate that lubricant performance is inseparable from electrical discharge mitigation, thermal stability, and long-term material compatibility under high-speed operation [39–49]. These insights reinforce the necessity of

designing e-fluids not merely as tribological agents, but as integrated electro-thermo-mechanical components of the EV powertrain.

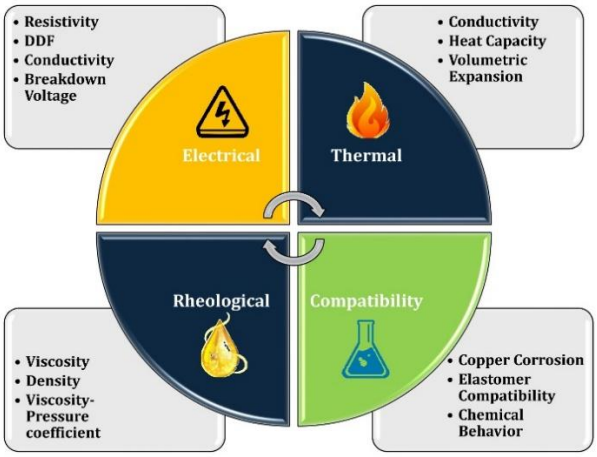


Fig. 2. Coupled electrical, thermal, and rheological domains governing EV fluids, adapted from Refs. [18–19,21].

1.2 Emergence of Two-Dimensional Materials in Tribology

Two-dimensional materials, defined by atomic-scale thickness and extended in-plane dimensions, exhibit exceptional mechanical strength, high surface-to-volume ratios, anisotropic electrical properties, and distinctive interfacial chemistries [50–52]. Since the isolation of graphene, an expanding family of 2D materials—including graphene derivatives, transition-metal dichalcogenides (TMDs), MXenes, hexagonal boron nitride (h-BN), and phosphorene—has emerged as a compelling class of functional materials for tribological applications [53–55]. Beyond tribology, 2D nanomaterials also exhibit highly tunable optical, electronic, and surface-sensitive behaviors that have been extensively explored in biosensing and imaging platforms, underscoring their multifunctional potential across coupled physical domains [56].

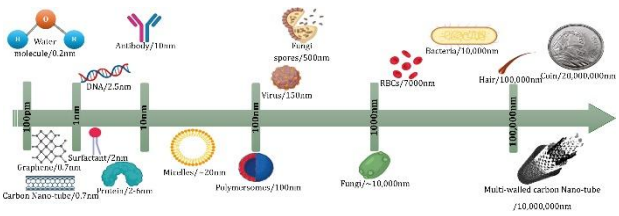


Fig. 3. Comparative size scale spanning molecular, nanoscale, and microscale regimes, highlighting the dimensional domain of 2D-nanomaterials in tribological/lubrication applications, adapted from representative literature [39,56–58].

As illustrated in Figure 3, two-dimensional materials occupy a unique dimensional regime between molecular species and conventional particulate additives, which underpins their distinct interfacial and tribological behavior. These materials share layered crystal structures that facilitate low interlayer shear strength, rendering them inherently suitable for both solid lubrication and dispersed lubricant additive applications [59–61]. Over the past decade, 2D materials have attracted increasing attention as multifunctional solutions capable of addressing friction reduction, wear mitigation, heat transfer enhancement, and electrical functionality within next-generation EV powertrains [6,32,55,62–64]. Their ability to participate in tribo-chemical adaptation under complex thermo–rheo–electrical conditions distinguish them from conventional additive technologies [1–3,12,65–68]. Figure 4 illustrates a conceptual timeline highlighting the emergence and adoption of key 2D materials for lubrication and tribological applications relevant to EV e-fluids, synthesized from foundational and recent literature on material synthesis, tribological mechanisms, and lubricant integration [32–33,54–55,63,69–71].

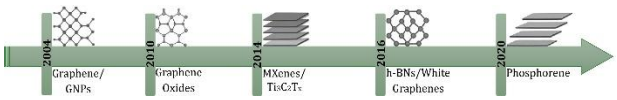


Fig. 4. Emergence timeline of key 2D-materials in lubricative/tribological applications, adapted from Refs. [1,6,32–33,51,54–55,63,69–71].

Accordingly, dispersed 2D materials have gained significant attention as additive candidates for synthetic ester-based e-fluids optimized for use in e-axles, high-speed bearings, and integrated motor–transmission architectures [4–5,7,23–25,62,70]. Nanofluids are defined as base fluids containing a stable dispersion of nanoscale solid particles, which can significantly modify the thermal, rheological, and transport properties of the host fluid compared to conventional lubricants [72–73]. Owing to their atomic-scale thickness, large specific surface area, and tunable surface chemistry, 2D materials exhibit unique tribological behavior through low-shear interlayer sliding, tribofilm formation, and favorable interfacial interactions with lubricant molecules, making them promising multifunctional additives for EV lubrication systems [33,36,63,74–75].

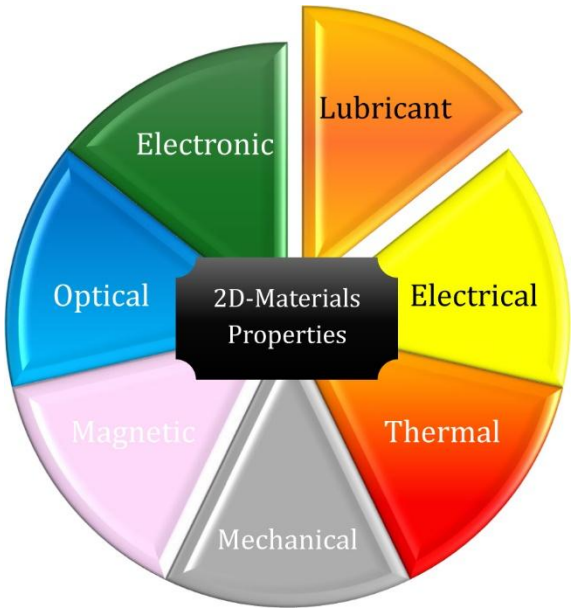


Fig. 5. Mechanical, thermal, electrical, and surface property domains of 2D-materials in advanced lubrication and electro-tribological applications, adapted from Ref. [56].

The rapid expansion of two-dimensional material families has been driven not only by tribology but also by parallel advances in energy storage, electrochemical systems, and defect-engineered nanostructures. Studies on MXenes, layered carbides, and hybrid 2D architectures demonstrate that surface terminations, defects, and interlayer coupling critically govern charge transport, thermal dissipation, and interfacial stability [76–85]. Together, these cross-disciplinary insights highlight the complex, coupled interactions governing 2D-material behavior under electrified and mechanically loaded conditions and motivate the conceptual framework summarized in Figure 6, which integrates these effects within the context of electric-vehicle lubrication.

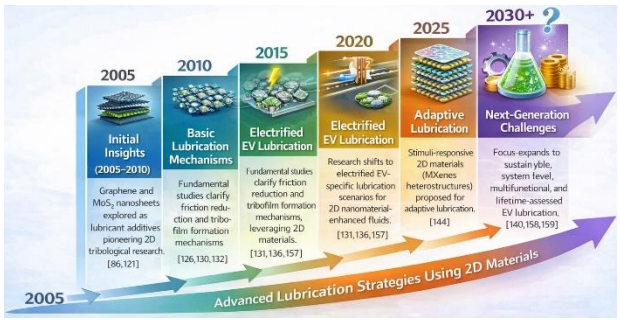


Fig. 6. Emergence timeline of 2D-material-based lubrication strategies for EVs, adapted from Refs. [70,80,85–96].

Recent studies indicate that the integration of 2D materials into EV lubricants has evolved from simple friction-reducing additives toward multifunctional components capable of interacting with electrical, thermal, and chemical fields at the interface. Experimental and theoretical investigations have highlighted the roles of interfacial charge transport, mechanochemical reactions, and tribofilm dynamics in governing lubrication performance under electrified and temperature-variable conditions relevant to EV powertrains [68,80,86–90]. In parallel, growing attention has been directed toward sustainable base oils and ester-based formulations, as well as electrically compatible additive systems, to address the coupled demands of efficiency, durability, and environmental compliance in EV lubrication systems [91–96].

Collectively, these trends suggest that lubrication in electric vehicles is transitioning toward a systems-level design paradigm, where material selection, interfacial phenomena, and operating conditions must be considered concurrently. This perspective provides the foundation for the subsequent discussion of mechanisms, challenges, and opportunities associated with 2D-material-based EV lubrication.

1.3 Classes of 2D-Materials pertinent in EVs Lubrication

Among 2D materials, graphene and graphene nanoplatelets (GNPs) are the most extensively investigated lubricant additives due to their high mechanical strength, excellent thermal conductivity, and low shear resistance [97–99]. Numerous studies demonstrate that graphene-based additives substantially reduce friction coefficients, enhance wear resistance, and improve load-bearing capacity across a wide range of base oils, including polyalphaolefins (PAOs), synthetic esters, and water-based fluids [32–33,35,54,65,100].

Graphene oxide (GO), while structurally related, introduces oxygen-containing functional groups that enhance dispersibility in polar base oils such as synthetic esters, albeit sometimes at the expense of electrical conductivity [70,101–104]. Importantly, both GNPs and GO have been shown to influence

electrical conduction pathways and charge dissipation within thin lubricant films, particularly under electrified sliding conditions [34–35,105]. These characteristics, combined with advancing manufacturability and supply-chain maturity, position graphene-based materials as leading candidates for commercial EV e-fluid formulations [24–25,31,62,72].

MXenes (particularly $Ti_3C_2T_x$) represent one of the fastest-growing classes of two-dimensional carbides and nitrides, combining metallic conductivity with chemically active surface terminations (–O, –OH, –F) and enabling applications ranging from lubricant additives and tribological coatings to energy storage and catalysis [34,50–53,63,106–109]. Experimental investigations demonstrate that MXene-based additives can simultaneously reduce friction, enhance antiwear performance, and improve oxidation resistance under both conventional and electrified lubrication conditions [50,67,106,110–111]. However, their sensitivity to moisture and surface oxidation necessitates careful stabilization strategies, especially in ester-based e-fluids [26,111].

Hybrid systems (including graphene–MXene and MXene–MoS_2 structures) have demonstrated synergistic improvements in dispersion stability, tribofilm formation, and thermal resistance under high-speed and high-load conditions relevant to EV powertrains [50–52,60–61,112]. These findings highlight MXenes as promising candidates for high-performance EV lubrication, provided that chemical stability challenges are adequately addressed. Recent tribology-focused assessments further identify MXenes as one of the fastest-growing classes of multifunctional lubricant materials, with applications spanning lubricant additives, solid lubricants, tribological coatings, and adaptive tribological systems [108–109].

Transition-metal dichalcogenides such as MoS_2 and WS_2 possess a long history in solid lubrication and are now being revisited in nanosheet form for liquid lubrication applications [99,113–119]. Their lamellar S–Mo–S structures enable low shear strength while exhibiting sensitivity to environmental conditions, allowing tailored performance across boundary, mixed, and electrically assisted lubrication regimes [50,98,102,120].

Hexagonal boron nitride (h-BN), often referred to as white graphene, offers chemical inertness and electrical insulation, making it attractive for electrically sensitive tribological contacts operating under mixed lubrication conditions [54,72,121–127].

Beyond established graphene and MXene systems, emerging phosphorus- and boron-based layered materials are being actively investigated across chemistry and materials science communities, expanding the future design space for adaptive lubricant additives. Doctoral research and early-stage experimental studies suggest that controlled functionalization and hybridization strategies may mitigate oxidation sensitivity while preserving favorable interfacial shear behavior [128–129]. Although not yet mature for industrial lubrication, these materials illustrate the forward trajectory of 2D additive development [130]. Two-dimensional materials continue to expand beyond conventional tribology into energy, electrochemical, and multifunctional engineering applications. Advances in multiscale modelling and data-driven materials design are further accelerating the development of 2D materials for complex electrified environments relevant to next-generation EV lubrication systems [131–133].

1.4 Comparative Overview of 2D Materials and Transition to Electro-Tribology

To contextualize the diverse roles of 2D materials in EV lubrication, Table 1 provides a comparative overview of major 2D material families, highlighting their structural characteristics, dominant lubrication mechanisms, compatibility with synthetic ester-based oils, and relevance to tribo-electrical environments. Rather than serving as a purely descriptive comparison, this framework emphasizes how material structure and surface chemistry govern mechanical–electrical coupling at lubricated interfaces.

Experimental evidence comparing mineral and synthetic ester oils under coupled rheo–electrical fields demonstrates that ester-based formulations exhibit more stable viscosity–conductivity relationships, reinforcing their suitability for electrified tribological environments in EV powertrains [7,134–136]. When combined with 2D-material additives, these systems exhibit emergent electro-

tribological behaviors that extend beyond classical friction and wear paradigms. In addition to mechanical and electrical considerations, thermal management strategies in hybrid and electric vehicles can influence the operating conditions of drivetrain components, indirectly affecting lubrication performance [94].

Table 1. Lubrication performance of key 2D-materials; Adapted from Refs. [12,32–55,67,98–102,113–117,134].

2D-Mat.	Key Properties	Lubrication Mechanism	Typical Application
GNPs	Strong, conductive	Interlayer shear, charge dissipation	Min./synth. oils, EV contacts
GOs	Highly dispersible	Polarity-driven adsorption	PAO/synth. ester oils
MXene	E-conductive	Tribo-chemical film, triboelectric effects	Electrified lubrication, e-fluids
MoS_2/ WS_2	Lamellar structure	Solid-like sliding	ICE/hybrid systems
h-BN	E-insulation, thermal stability	Low-shear boundary films	Dielectric lubrication
BPs	An-isotropic bonding, reactivity	Adaptive tribofilm, superlubricity	Boundary lubrication

While Table 1 summarizes the principal characteristics of major 2D material families, their practical implementation in EV lubrication is ultimately governed by system-level factors, including electrified contacts, lubricant aging, base-oil chemistry, and drivetrain architecture. Recent studies focusing on EV bearings, greases, coatings, and hybrid lubrication systems demonstrate that tribological performance is strongly coupled to electro-thermal stresses, additive–base oil interactions, and long-term degradation behavior rather than isolated friction or wear metrics alone [39,43,47,76–80,128]. These system-oriented investigations motivate a transition from material classification toward application-driven and region-specific research strategies, which are comparatively analysed in Tables 3 and 4.

As a result, EV tribology increasingly intersects with electro-tribological phenomena, including stray current effects, triboelectric charging, and electrically induced lubricant degradation [6,27,137]. Recent studies on electrified sliding contacts and triboelectric nanogenerators highlight the dual mechanical–electrical functionality of layered materials, underscoring their relevance to next-generation EV systems [7,17,138]. These findings suggest that 2D materials may not only mitigate wear but also actively influence charge transport, surface potential, and energy dissipation pathways within lubricated interfaces.

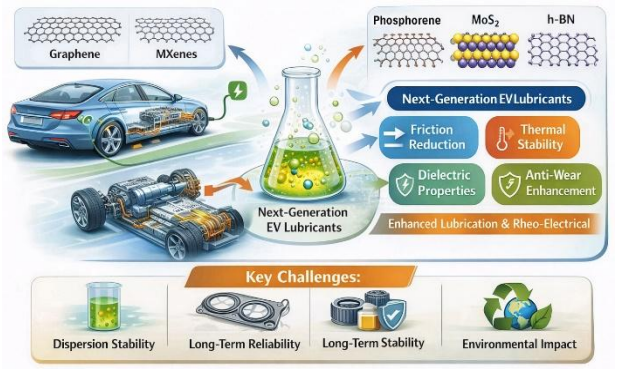


Fig. 7. Conceptual schematic of 2D-materials application and challenges in EVs lubrication.

Accordingly, the present review adopts a hierarchical perspective—spanning material physics, lubricant formulation, and system-level electrified tribology—to assess the translation of two-dimensional materials from laboratory studies to scalable EV lubrication systems.

2. LITERATURE REVIEW

2.1 2D-Materials as Lubricant Additives: General Framework

The incorporation of two-dimensional (2D) materials into liquid lubricants has emerged as a transformative strategy for mitigating friction, wear, and energy losses in modern mechanical systems. Unlike conventional molecular additives, 2D materials possess atomically thin layered structures that promote facile interlayer shear, surface conformity, and tribofilm formation under load. Early tribological studies on graphene, MoS_2, and hexagonal boron nitride (h-BN) established that these materials can outperform traditional solid lubricants when properly dispersed in oils, greases, or synthetic base fluids, particularly under boundary and mixed lubrication regimes [6,114–115].

Comparative rheo-electric studies demonstrate that synthetic ester base oils provide superior viscosity stability and electrical reliability than mineral oils under EV-relevant operating conditions, making them particularly suitable for advanced 2D-material lubricant formulations [7,17,29].

The rapid development of high-performance lubricants for EV propulsion systems has stimulated extensive research into the tribological behavior of 2D nanomaterials across diverse research cultures, synthesis practices, and industrial priorities. Scientific output from the United States, Europe, China, Japan, and South Korea reveals marked divergence in methodological rigor, materials engineering strategies, additive design philosophies, and commercial readiness. Recent firm-level analyses indicate divergent EV development trajectories, with China emphasizing rapid technological catch-up and vertical integration, while European manufacturers face path-dependency and structural lock-ins during the transition to electrified mobility [139–140]. In the European automotive sector, regional capability structures and technological relatedness have been shown to influence the pace and direction of EV adoption, occasionally reinforcing transition lock-ins [140]. In contrast, Japan's EV battery sector illustrates how strong domestic market insulation can delay technological repositioning despite early leadership [141]. These variations reflect differences in research funding priorities, nanomaterial production capabilities, environmental regulations, and industrial partnerships. Accordingly, this section critically evaluates the global literature, focusing on synthesis technologies, dispersion strategies, tribological mechanisms, and performance metrics of graphene, MXenes, h-BN, MoS_2, and phosphorene within synthetic ester and advanced lubricant matrices.

Recent studies demonstrate that the tribological performance of 2D additives is intrinsically linked to the electrochemical and rheological behavior of synthetic ester base fluids under electrified conditions [7,17,33,55,59,63]. Consequently, these additives should be regarded as functional components of electrically active lubricant films rather than conventional friction modifiers [6,35,67,142]. This coupled behavior is effectively interpreted within the framework of rheoelectricity, which links viscosity evolution, electrical conductivity, and tribological response under applied electric fields [19,29].

2.2 Graphene and Graphene-Derived Additives

Graphene and its derivatives remain the most extensively studied 2D lubricating materials worldwide. Research efforts in the United States and Europe predominantly focus on high-purity graphene nanoplatelets (GNPs), functionalized graphene, and graphene oxide (GO) to improve dispersion in synthetic esters and PAO base oils, consistently reporting reductions in friction coefficients and wear rates under boundary and mixed lubrication conditions [32–35,54,65,69]. In contrast, Asian research groups—particularly in China and South Korea—have advanced graphene-based hybrid systems incorporating h-BN, MoS_2, or phosphorene to exploit synergistic friction-reduction mechanisms [63,98–99]. These hybrid structures exhibit enhanced thermal conductivity, increased load-bearing capacity, and improved stability under prolonged sliding.

Across all regions, dispersion stability remains the primary formulation challenge. Functional groups such as carboxyl and hydroxyl moieties, as well as surface-active molecules including oleic acid and surfactants, are commonly employed to enhance compatibility with synthetic ester matrices [56]. Graphene oxide, owing to its oxygen-containing functional groups, exhibits improved dispersibility in polar base oils but may compromise long-term oxidative stability [53,55]. Comparative studies demonstrate that while GO offers effective short-term friction reduction, reduced graphene or functionalized graphene provides superior durability under extended sliding and elevated temperatures [7,17,35,51,53,105].

Hybrid systems combining graphene oxide with metallic or ceramic nanoparticles further improve load-carrying capacity and thermal robustness, albeit at the cost of increased formulation complexity—an important consideration for electrically active e-fluids [143]. Recent modelling and experimental studies also highlight that graphene morphology and aspect ratio critically influence thermo-fluidic efficiency in ester-based lubricants, underscoring the importance of shape-controlled

graphene additives for electrified powertrains [41,43]. Such conditions are particularly relevant for electric vehicle powertrains, where lubricants are simultaneously required to manage friction, wear, and electrical interactions at steel interfaces [92,144].

2.3 MXenes as Emerging Conductive Lubricant Additives

MXenes represent the fastest-growing class of 2D lubricating materials due to their metallic conductivity, tunable surface terminations, and layered morphology. These characteristics enable tribo-electrical interactions not achievable with graphene or traditional transition metal dichalcogenides (TMDs) [34,51,55,145–146]. Experimental studies confirm that $Ti_3C_2T_x$ additives can simultaneously reduce friction, suppress wear, and stabilize electrical contact resistance when formulated into mineral oils, synthetic esters, and PAO lubricants [34,50–53,67].

Chinese research groups lead MXene synthesis optimization through HF-free etching, molten-salt routes, and surface-termination control, directly improving dispersibility and chemical stability [52,55]. North American research emphasizes mechanistic understanding, demonstrating that MXene metallic conductivity and surface chemistry contribute to low-shear tribofilm formation and enhanced load-bearing capacity [51]. Recent studies have shown that nanoscale wear debris can actively participate in tribofilm formation, transforming from a degradation product into a functional lubricating layer that contributes to wear reduction [147]. Stimuli-responsive lubrication systems, such as those based on MXene-containing structures, demonstrate the potential for externally controlled friction and wear regulation, offering new opportunities for adaptive lubrication in electrified systems [88,146].

Despite these advantages, MXenes remain sensitive to oxidation and moisture, necessitating careful formulation and storage control [114]. Recent studies under coupled thermal, oxidative, and electrical stress reveal that vacancy density, edge chemistry, and surface terminations critically influence tribological performance and long-term stability [111–114]. Electro-mechanical investigations further demonstrate that MXene-containing lubricants exhibit altered charge transport and contact resistance behavior under current-carrying and electromagnetic-field-assisted sliding, directly affecting friction stability and wear evolution [37,76,79–82,148].

2.4 Transition Metal Dichalcogenides and Related Layered Solids

Transition metal dichalcogenides, particularly MoS_2 and WS_2 nanosheets, have long been recognized for their solid-lubrication capabilities. When exfoliated to nanoscale dimensions and incorporated into liquid lubricants, these materials retain lamellar shear mechanisms while benefiting from enhanced contact replenishment [87,99,113]. Hybrid WS_2/MoS_2 systems demonstrate synergistic friction reduction across wide ranges of load and sliding speed [99]. However, MoS_2 remains susceptible to oxidation and humidity-induced degradation, especially in electrified environments [70].

Recent investigations reveal that changes in crystalline phase and nanosheet morphology strongly influence surface adsorption, defect-mediated reactivity, and interfacial energy dissipation [149]. Although many of these insights originate from electrocatalytic studies, they underscore the importance of phase-aware MoS_2 design for lubricant additives operating under coupled mechanical and electrical stresses.

2.5 Hexagonal Boron Nitrides

Hexagonal boron nitride (h-BN) has gained renewed attention due to its dielectric stability and thermal robustness, making it particularly attractive for EV drivetrain environments. Its chemical inertness enables compatibility with synthetic esters and PAO oils, while recent studies demonstrate effective friction and wear reduction when used alone or in combination with graphene nanoplatelets [54,72,97]. Its electrically insulating nature further supports applications requiring high dielectric breakdown strength. Recent bearing-scale experiments further suggest that the excellent dielectric properties of h-BN may become disadvantageous under electrified rolling contacts, where nanoparticle agglomeration and charge accumulation can promote electrical discharge damage, emphasizing the importance of balancing electrical insulation with controlled charge dissipation in EV lubrication systems [150].

2.6 Phosphorene and Other Emerging 2D Lubricants

Phosphorene has experienced rapid growth in tribological research since 2023 due to its intrinsic anisotropy, low shear strength, and tunable electronic structure [70–71,97–98,101–102,120,151]. Although promising, its practical deployment is constrained by pronounced environmental instability. Encapsulation strategies, surface functionalization, and heterostructure architectures have shown success in enhancing durability [71,152]. Phase-sensitive insights originally developed for MoS_2 provide a transferable framework for understanding tribo-electrochemical behavior and stability limits in phosphorene-based additives [149].

2.7 Comparative Summary of 2D Lubricant Additives

To synthesize globally reported data, Table 2 presents a comparative overview of 2D materials, their synthesis approaches, lubrication mechanisms, performance metrics, and practical considerations for integration into synthetic ester e-fluids.

Table 2. Representative studies on 2D-material lubricant additives [50–55,70–74,98–99,113,115,145–149,150–155].

2D-mat.	Action[1]	Base Oil	Scalability
GNPs	High	Esters/ Synthetics	Commercial
GOs	Medium	Nano-fluids	Lab scale
MXene	High	Engine oil, emulsions	Experimental
MoS_2	Medium	Engine oil	Widely available
MoS_2/ MXene	Medium	Engine oil, esters	Lab scale
WS_2/ MoS_2	Extreme		Commercial
h-BNs	Medium	Hi-speed motor oils	Widely available
BPs	Extreme	Ester/ Silicone	Low
GNP/ MXene	Medium	Epoxy/ mixes	Experimental
BP/ MoS_2	High	Lab tests	Experimental
[1] Performance in friction/wear reduction			

Table 2 demonstrates that the highest-performing materials vary depending on the lubrication regime and thermal/electrical constraints of the application. Graphene-based systems show the most balanced performance across friction, wear, and dispersion stability, and they offer the most industrial readiness. MXenes show exceptional anti-wear behavior and high load capacity due to their conductive surfaces and strong mechanical integrity; however, their oxidation sensitivity and shelf-life limitations continue to hinder widespread adoption. MoS_2 remains unmatched in high-temperature resilience and severe boundary lubrication, while h-BN excels in thermally demanding and electrically sensitive environments typical of EV drive systems. Phosphorene, although still emerging, demonstrates unique anisotropic slip and excellent synergy in hybrid configurations.

Table 3. Comparative Assessment of Production Cost, Scalability, Environmental Factors, and Typical Additive Concentration Ranges for 2D-Material Lubricant Additives [50–55,70–74,98–99,150–158].

2D-mat.	Cost/ Scalability	Environmental/ Stability Factors	Range (wt.%)
GNPs	Medium–High/Good	Low toxicity/High	0.01–0.1[2]
GOs	Medium/ Very good	Corrosive/ Reactive	0.01–0.1
MXenes	High/Moderate	Oxidation-sensitive/Needs care	0.005–0.05
MoS_2	Low–Medium/ Excellent	Low toxicity/ Thermally stable	0.1–1.0[3] 0.05–0.2[4]
h-BNs	Medium/High	Chemically inert/Benign	0.1–1.0
BPs	Very High/Low	Air-sensitive/ Reactive	0.005–0.02
Hybrids[1]	High/Moderate	Variable/ Improved	0.01–0.1
[1] e.g., MoS_2/MXene, Graphene/MXene [2] 50–500 ppm in dielectric fluids [3] in engine oils [4] in esters			

Table 3 demonstrates that production cost, scalability, environmental behavior, and required additive concentration vary substantially across 2D-material families, directly influencing their suitability for ester-based e-fluids. Graphene-derivatives exhibit favorable scalability and moderate environmental impact, requiring only

50–500 ppm in dielectric fluids to achieve tribological improvements, making them commercially attractive. MXenes, while offering superior friction reduction, remain limited by high production cost, susceptibility to oxidation, and lower scalability, though their unusually low optimal loading (0.005–0.05 wt.%) offsets some cost concerns. MoS_2 and h-BN maintain excellent cost–performance balance with broader industrial maturity and accessibility. In contrast, phosphorene's exceptional lubricity is overshadowed by extreme synthesis cost and instability under ambient conditions, confining its usage to ultralow loadings and laboratory-scale studies. Hybrid materials bridge performance gaps but require complex synthesis, elevating production costs. Overall, Table 3 highlights that the most industrially viable additives for next-generation synthetic ester e-fluids remain graphene derivatives, h-BN, and MoS_2, while MXene and phosphorene demand further process innovations for cost-effective deployment.

2.8 Implications for Electrified and EV Lubrication Systems

From a rheo-electrical perspective, electrified lubrication systems must be treated as coupled mechanical–electrical continua in which viscosity evolution, charge transport, and dielectric breakdown are interdependent [19]. The literature consistently shows that no single 2D material satisfies all tribological, rheo-electrical, thermal, and environmental requirements for next-generation EV lubricants. This limitation is especially critical in current-carrying contacts, where electrically assisted sliding promotes localized discharges and accelerates lubricant degradation if charge dissipation pathways are not properly engineered [37,148].

Accordingly, hybrid strategies combining graphene, MXenes, and functional additives are increasingly proposed to exploit complementary mechanisms [6,35,67]. Sustainability and life-cycle considerations further shape additive selection, as nanostructured lubricants must balance tribological efficiency with environmental impact and end-of-life constraints [159]. These trends reinforce the shift toward system-level lubricant design, in which electro-mechanical coupling and rheo-electric behavior are co-optimized rather than treated as secondary effects [6,19,36,142].

2.9 Summary of Literature Trends

Overall, the literature indicates that no single 2D material satisfies all tribological, electrical, thermal, and environmental requirements for EV lubrication systems. Instead, additive selection depends on balancing lubrication performance, scalability, environmental compatibility, and application-specific operating conditions, as summarized in Tables 2 and 3. These findings provide the basis for the research gaps discussed in Section 3.

3. RESEARCH GAPS

Despite substantial advances in the development and application of 2D-materials as lubricant additives and functional tribological elements, several critical research gaps remain unresolved, particularly in electrified powertrains, e-fluids, and EV-relevant operating environments. Recent critical perspectives emphasize that although friction and wear reduction are frequently reported, system-level integration challenges, long-term reliability, electro-tribological stability, and multifunctional performance requirements remain insufficiently addressed [6]. With the rapid expansion of studies published between 2023 and 2026, these gaps have become more clearly defined but remain largely unclosed. EV- and drivetrain-focused syntheses further stress that tribological performance metrics alone are inadequate without concurrent consideration of rheo-electrical behavior, base-oil chemistry, and system-level sustainability constraints [8,19,29,78,159].

3.1 Limited Understanding of Degradation Pathways under Coupled Stressors

A primary challenge concerns the dispersion stability of graphene, MXenes, MoS_2, h-BN, and phosphorene in ester-based dielectric matrices. Although multiple studies report functionalization strategies for graphene derivatives [32,54,65] and surface-terminated MXenes [34,50-53], systematic investigations of long-term colloidal stability under high electric fields, thermal cycling, and shear-induced aggregation remain scarce. In particular, the susceptibility of MXenes to oxidation and hydrolysis in ester media is poorly quantified, despite consistent indications that such degradation strongly affects lubrication performance [26,63]. At the nanoscale, mechanochemical processes driven by shear and

contact stress can modify surface chemistry and material structure, thereby influencing friction and wear behavior under operating conditions relevant to EV lubrication [87].

This gap reflects an incomplete understanding of degradation mechanisms in 2D-material-enhanced lubricants subjected to simultaneous thermal, oxidative, electrical, and mechanical stresses. While individual effects—such as phosphorene oxidation [70–71,152], MXene surface-termination evolution and vacancy-driven water chemisorption [111,114], and graphene additive instability [32–33,35,143]—have been examined independently, their coupled interactions under electrified sliding conditions remain largely unexplored.

Although recent grease-focused studies demonstrate that thickener chemistry, additive depletion, and catalytic degradation significantly influence performance under combined stressors, comparable systematic investigations of 2D nanomaterials dispersed in EV e-fluids remain scarce [26]. This limitation is particularly critical for synthetic ester base oils, where rheo-electrical stability, oxidation resistance, and electrical conductivity evolution are strongly coupled to additive chemistry [7,17,27,160]. Despite growing interest in EV fluids, current 2D-material tribology research remains largely decoupled from base-oil-driven degradation phenomena under realistic EV duty cycles [7,17,37,160]. Rheo-electrical analyses further indicate that ester polarity, contaminant sensitivity, and electrically induced viscosity drift can amplify degradation pathways in nano-enabled e-fluids, yet these effects are still weakly integrated into existing degradation models [7,19,148]. Although synthetic esters are widely considered promising for EV lubrication, their tribological behavior under combined electrical, thermal, and mechanical stresses remains inadequately characterized, particularly in comparison with conventional lubricant systems [7,17,160].

3.2 Electrified Tribology, Charge Transport, and Field-Induced Effects

A second major gap lies in the absence of standardized tribological testing protocols for evaluating 2D additives under EV-relevant conditions. Most studies rely on conventional tribometers operating under loads, speeds, and temperatures that do not reflect the high rotational speeds (20,000–30,000 rpm), high-frequency switching, and electrically biased environments characteristic of e-drivetrains [23,51,72]. Despite increasing experimental activity, the lack of EV-specific testing protocols remains a critical bottleneck for assessing coupled electrical–tribological degradation mechanisms [20]. As outlined in recent EV-focused tribology textbooks, coupled electrical, thermal, and mechanical stresses introduce degradation pathways that are insufficiently addressed by conventional lubricant design strategies [21].

Published studies also employ widely varying additive concentrations, dispersants, base oils, and surface preparations, severely limiting cross-comparability. Only a limited number of investigations propose consistent concentration windows for graphene or MXenes in ester oils [32,50,54], and none offers unified evaluation frameworks validated across laboratories or automotive OEMs.

This lack of standardization is compounded by the absence of rheo-electrical benchmarking methodologies capable of correlating viscosity evolution, charge transport, and dielectric breakdown under load. Recent studies demonstrate that electric fields can induce non-linear viscosity–conductivity coupling in ester-based lubricants, fundamentally altering lubrication regimes [7,19]. Without integrating such metrics, existing electrified tribology datasets remain incomplete.

Although the influence of electric fields on tribological performance has gained attention, the electro-tribological behavior of 2D materials remains insufficiently characterized at EV-relevant voltage and current densities. Conductive MXene-containing lubricants exhibit altered friction behavior and charge dissipation pathways [34,67,111], yet the risks of dielectric breakdown, electrical short-circuiting, uncontrolled charge accumulation, and electrically induced surface damage remain poorly quantified across different classes of 2D lubricant additives [150]. In parallel, triboelectric and electro-mechanical energy-harvesting studies reveal strong field coupling that may be beneficial or detrimental depending on the lubrication context [35,37,137,161]. For nanofluid-based

lubrication systems, unresolved challenges persist regarding long-term dispersion stability, particle–surface interactions, and their impact on friction and wear under EV-relevant operating conditions [79]. Consequently, systematic links between rheo-electrical behavior, additive dispersion, tribofilm formation, and electrically driven degradation in ester-based nano-lubricants remain largely absent.

3.3 Insufficient Structure–Function Relationships across 2D–Material Families

A third gap concerns the limited mechanistic understanding of interactions among 2D layers, ester molecules, and metal or ceramic surfaces under electro-tribological coupling. Although tribofilm formation has been widely reported for the major 2D material families [54–55,67,111,113,151], systematic comparisons under identical electro-tribological conditions remain scarce. Insights from non-tribological fields, such as biosensing and imaging, demonstrate that nanoscale defect chemistry, surface functionalization, and interfacial charge transfer critically govern functional performance in 2D–materials—relationships that remain insufficiently mapped in electrified lubrication systems [56]. This fragmentation limits rational material selection and predictive lubricant formulation [6,115].

Atomic-scale mechanisms, particularly under oscillating electrical potentials, remain poorly explored. Phosphorene, despite rapid growth in fundamental research [67,70–74,98–99,102,115,151], lacks dedicated mechanistic tribology studies under lubrication, leaving substantial uncertainty regarding its degradation pathways and stability in ester-rich environments. Moreover, emerging 2D materials—including antimonene, bismuthene, selenides, and hybrid layered systems—introduce additional complexity, as their tribological behavior is closely linked to oxidation state, defect density, and interfacial chemistry [121,152,157]. Phase- and morphology-sensitive studies demonstrate that subtle crystallographic variations can significantly alter interfacial charge transfer and degradation kinetics, reinforcing the need for phase-aware tribological frameworks [149,162].

3.4 Scalability, Sustainability, and Environmental Compatibility

A fourth gap lies in the limited integration of scalability and life-cycle considerations with tribological performance. Beyond performance metrics, challenges related to reproducibility, process standardization, and scalable manufacturing remain critical barriers for the practical deployment of 2D-material-based lubricants [163]. Although scalable synthesis routes for MXenes, MoS_2, and phosphorene have been reported [26,63,70,98–99], few studies quantify carbon footprint, waste-chemistry profiles, or regulatory alignment at lubricant-relevant production scales. Regional comparisons reveal substantial differences in manufacturing maturity, yet consolidated assessments linking synthesis energy demand to tribological benefit remain scarce [5,15]. While superlubricity has been demonstrated for several 2D–materials under laboratory conditions (Fig. 6), critical gaps remain in translating these effects to engineering-scale EV components, particularly regarding load-bearing capability, contact geometry, and long-term durability [146]. Although bio-based and sustainable lubricant additives offer clear environmental advantages, systematic studies addressing performance trade-offs, durability, and compatibility with electrified EV components are still limited [89,91,93,95].

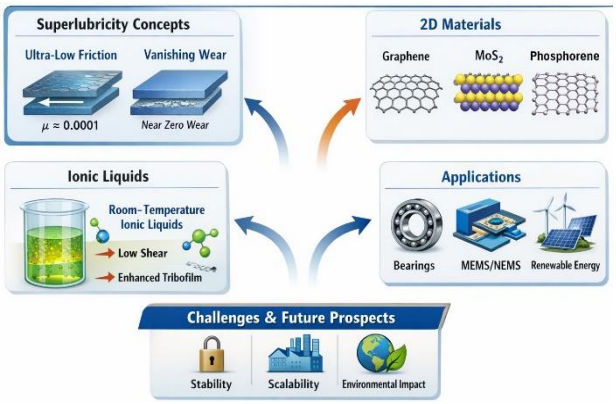


Fig. 8. Coupled tribo–electro–thermal challenges in 2D–material-based EV lubrication, adapted from Refs. [19,73,164].

Environmental compatibility remains insufficiently addressed. Many studies neglect compatibility with biodegradable base oils and low-viscosity synthetic esters required for

next-generation EV fluids [4–5,27]. Moreover, synthesis routes for MXenes and phosphorene frequently involve energy-intensive or chemically aggressive processes, raising concerns regarding sustainability and regulatory compliance [116,136]. Although decarbonization-focused research emphasizes life-cycle considerations in energy systems [136], such perspectives remain weakly integrated into tribological studies of 2D additives.

3.5 Reliability, Standardization, and Application-Oriented Validation

A final critical gap concerns the translation of 2D-material tribology from laboratory studies to commercial e-fluid formulations. Most studies rely on simplified short-duration tribometer tests that neglect additive-package compatibility, corrosion inhibitors, transient duty cycles, moisture ingress, and mixed lubrication conditions representative of EV operation [4,6,26,37,67,113]. Survey-level analyses consistently identify the absence of unified testing protocols and system-integrated frameworks as a major barrier to industrial adoption [30]. Consequently, a major research gap lies in the lack of system-level investigations that integrate tribological, electrical, and thermal considerations to evaluate 2D-material-based lubricants under realistic EV operating environments [92,94,144,165].

Although cross-scale validation—from nanoscale mechanisms to component-level performance—is widely recognized as essential [6], no existing study integrates tribology, dielectric behavior, thermal management, and aging into a unified performance model. This limitation is particularly critical for EV applications, where these properties must be optimized simultaneously. Drivetrain-scale investigations further confirm that reliability under electrified lubrication cannot be inferred from short-duration tribometer tests alone, especially in the presence of electric fields and nano-enabled charge transport mechanisms [19,37,48,150]. These challenges motivate the structured gap synthesis presented in Tables 4 and 5.

Table 4. Key research gaps in 2D-material-based lubrication synthesized from representative literature. [19,34,55,67,91,113,111,121,136–137,148,152].

Research area	Research Gap
Coupled degradation	Lack of data on simultaneous thermal–oxidative–electrical stresses accelerate failure
Electrified tribology	Absence of frameworks linking friction, charge transport, and rheology under electric fields
Structure–function	Insufficient studies correlating crystal structure and surface chemistry across 2D–materials
Sustainability	Lack of lifecycle and environmental assessments for large–scale manufacturing
Long–term reliability	Limited long-term validation under combined mechano-electrical stresses in EV lubricants
Ester–oil interaction	Poor understanding of how synthetic ester chemistry affects electrified additive stability
Rheo-electrical coupling	Absence of standardized methods to link viscosity to conductivity in ester e-fluids

Table 5. Major research gaps in 2D-material-enhanced ester e-fluids, adapted from Refs. [7,19,34,48,55,63,67,98–99,149,151–152,162,166].

Research Gap	Description
Ester stability	Lack of long-term oxidation, sedimentation, and electrochemical stability data for 2D-dispersions
Standardization	Absence of harmonized testing protocols specifically for electrified drivetrain environments
Electro–mechanisms	Missing atomic-level insight into how electric fields drive tribofilm formation and degradation
Sustainability/LCA analyses	Insufficient lifecycle assessments (LCA) linking synthesis costs and energy to performance
Commercialization	Poor integration with real-world additive packages and lack of holistic thermal/dielectric models

Table 4 reveals that the most critical gaps are not isolated to individual material families, but instead emerge from the interaction between degradation mechanisms, electrification effects, and the absence of unified evaluation

frameworks. These gaps are particularly pronounced in ester-based e-fluids, where rheo-electrical coupling and long-term stability under electric fields remain insufficiently understood. To contextualize these challenges within practical lubricant formulation constraints, Table 5 refines the analysis by focusing specifically on ester e-fluid systems.

Table 5 further narrows the analysis to ester-based e-fluids, highlighting that long-term electrochemical stability, rheo-electrical characterization, standardized testing protocols, and integration with commercial additive packages remain the principal barriers to practical implementation. These findings reinforce the need for future lubricant designs that simultaneously optimize tribological, electrical, thermal, and environmental performance.

3.6 Summary of Research Gaps

Overall, Section 3 highlights the critical barriers to adopting 2D materials in EV-relevant lubrication systems extend well beyond friction reduction. Instead, they arise from unresolved challenges related to degradation under coupled stressors, rheo-electrical behavior, scalability, sustainability, and application-oriented validation. By synthesizing these gaps in Tables 4 and 5, this section establishes a structured foundation for the subsequent analysis of methodological limitations and research needs.

4. OPPORTUNITIES AND OUTLOOK

The rapid acceleration of electrified mobility has created significant opportunities for integrating 2D–nanomaterials into advanced e-fluids that must simultaneously lubricate, cool, and electrically insulate next-generation drivetrains. Unlike traditional internal combustion engine lubricants, EV–specific fluids operate under distinct regimes characterized by high rotational speeds, elevated voltages, localized electric fields, and increased thermal fluxes within compact, integrated motor–gearbox systems. These operating conditions demand lubricants with enhanced thermal conductivity, controlled electrical behavior, and ultra–low friction performance that can be tuned at the nanoscale—characteristics that 2D materials such as graphene, MXenes, TMDs, MoS_2, h-BN, and phosphorene are inherently suited to address [6–7,17,32,50,63,70,113]. From a rheo-electrical perspective, these requirements must be treated as coupled phenomena, in which viscosity evolution, charge transport, and dielectric stability jointly govern lubrication performance under electric fields [19]. As research progresses, new opportunities emerge for tailoring surface functionalities, defect densities, and lamellar architectures to meet the multiphysics demands of EV propulsion systems. The regional differences in EV industrial strategies underscore the need for lubricant and materials innovations that remain robust across diverse technological and regulatory pathways [139–141].

One of the most promising opportunities lies in the development of multifunctional additive systems, in which 2D materials act not merely as friction modifiers but as active interfacial components capable of load sharing, tribofilm self-repair, and electric-field modulation [4–5,15,147]. Recent EV-focused, system-level analyses emphasize that such multifunctional lubrication strategies must be evaluated using drivetrain-level efficiency, durability, and sustainability metrics rather than isolated tribometer measurements [8,78]. The polar nature of synthetic esters promotes improved dispersion and stronger interfacial interactions with surface-modified 2D nanoparticles, thereby reducing agglomeration and enhancing tribofilm formation under boundary and mixed lubrication regimes [53–54]. Recent studies further demonstrate that MXene- and graphene-based additives can form conductive or semi-conductive boundary films, enabling controlled charge dissipation under electrified sliding conditions [34,50,143,161]. This behavior is particularly relevant for electric motors and power-electronics bearings, where uncontrolled electrical discharges accelerate lubricant degradation and surface damage. Beyond friction and wear reduction, 2D materials offer opportunities for multifunctional lubrication, including electrical conductivity modulation, thermal management assistance, and interfacial stability under electrified operating conditions [9,29]. Future progress in superlubricity for EV applications is likely to depend on realistic strategies emphasizing robustness, scalability, and durability rather than idealized friction minima observed under laboratory conditions [164].

Comparative rheo-electrical measurements conducted under applied electric fields indicate that synthetic ester oils exhibit more predictable viscosity–conductivity relationships than mineral oils, a characteristic critical for maintaining stable lubrication in electrically active contacts. In parallel, hybrid additive concepts—combining 2D materials with organic friction modifiers, antioxidants, or surface-active esters—offer a viable pathway for mitigating dispersion instability and oxidation sensitivity, which have been consistently identified as key formulation challenges [17,27,59,160]. Synthetic ester base oils present a promising platform for EV lubrication due to their tunable polarity and compatibility with advanced additives, while simultaneously requiring careful control of rheo-electrical stability under electric fields [7,17,160]. Such hybrid systems demonstrate strong potential as multifunctional nanoplatforms capable of simultaneously reducing friction, enhancing heat dissipation, and stabilizing electrical pathways in increasingly compact EV drivetrains.

From a sustainability and system-level perspective, the integration of 2D materials aligns closely with emerging trends toward low-viscosity synthetic esters and bio-based base oils. Structure–function insights derived from vegetable-oil-based lubricants suggest that polarity, molecular flexibility, and oxidative stability can be synergistically enhanced through the selective incorporation of 2D nanomaterials [27]. This strategy creates opportunities to reduce reliance on high treat rates of conventional sulfur- and phosphorus-containing additives, thereby lowering environmental impact while maintaining or improving tribological performance. Moreover, recent perspectives emphasize that 2D materials may enable secondary functionalities, including triboelectric energy harvesting and moisture-responsive behavior, opening new avenues for condition monitoring and smart lubrication concepts in EV systems [6,135,161]. The convergence of sustainability goals with EV performance requirements creates an opportunity to develop environmentally benign lubricant formulations that do not compromise electrical, thermal, or tribological functionality [89,91,95].

Advances in large-scale liquid exfoliation, high-shear processing, continuous-flow MXene etching, and stabilized phosphorene synthesis have further reduced barriers to reproducibility and industrial uptake [63,97]. These developments are particularly relevant for e-fluids, where consistency, purity, oxidation stability, and environmental compliance are mandatory. Regions such as China, South Korea, and the European Union have already demonstrated strong industrial momentum in scaling MXenes and graphene for tribological applications [50–51,55,67]. These trends are consistent with recent tribology outlooks that identify 2D materials as enabling technologies only when integrated within system-level efficiency, emissions, and life-cycle assessment frameworks [36,156,158]. As manufacturing processes mature, cost–performance ratios are expected to align more closely with commercial lubricant constraints, supported by evolving sustainability regulations and circular-material initiatives.

From a formulation and durability standpoint, hybrid additive strategies combining 2D materials with antioxidants, surface-active esters, or antiwear agents represent a practical route to overcoming dispersion instability, oxidation sensitivity, and moisture susceptibility—challenges repeatedly reported in both laboratory-scale and applied studies [26–27,59,110–111]. Recent investigations into MXene oxidation behavior, graphene-based hybrid nanocomposites, and metal-oxide/graphene systems underscore the importance of tailoring surface chemistry and additive synergy to ensure long-term stability under coupled thermo-electrical stresses [111,114,143]. These durability-driven design strategies are particularly relevant for EV drivetrains, where lubricant-mediated reductions in vibration, noise, and parasitic losses directly influence system efficiency and component lifetime [48].

To maintain continuity between the identified research gaps and future directions, the opportunities summarized in Table 6 are directly mapped to the unresolved challenges discussed in Section 3. In particular, gaps related to coupled thermal–oxidative–electrical degradation, electrified tribology, and insufficient structure–function relationships are addressed through

multifunctional and electrically adaptive 2D-material-based additive strategies. Similarly, sustainability, scalability, and long-term reliability concerns motivate opportunities centered on synthetic ester compatibility, bio-based lubricants, and smart lubrication concepts incorporating sensing and triboelectric functionalities. This traceability underscores that the proposed outlook is gap-driven rather than exploratory, reinforcing the strategic relevance of 2D materials for next-generation electrified lubrication systems.

Table 6. Key Opportunities for 2D Materials in EV Lubrication Systems [17–27,34,50,63,78,90,111,143–144,148,156–158,161].

Opportunity Domain	Target Application	Key 2D-mat.
Electrified contacts	EV bearings, motor shafts, power electronics	GNPs, MXenes, MoS_2, h-BNs
Additive systems	E-fluids, integrated drive units	MoS_2/MXene, GNP/h-BN
Sustainable design	biodegradable e-fluids, ultra-low viscosity oils	GNPs, MXenes, h-BNs
Smart lubrication	Predictive condition monitoring	MXenes, GNPs, BPs

Table 6 highlights that the most promising opportunities for 2D materials emerge at the intersection of electrified tribology, multifunctional additive design, and sustainability-driven formulation strategies. Opportunities targeting electrified contacts and rheo-electrical control directly address the degradation and charge-transport gaps identified in Section 3.2 and Table 4, while sustainability-oriented pathways respond to scalability and life-cycle challenges summarized in Tables 3 and 5. The placement of Table 6 therefore serves to translate the descriptive material comparisons in Tables 1–3 and the gap-oriented synthesis in Tables 4 and 5 into actionable research and formulation pathways.

In summary, future EV e-fluid engineering will increasingly depend on multifunctional 2D-material additives capable of simultaneously improving tribological, thermal, and electrical performance. Achieving this objective will require scalable synthesis, compatibility with ester-based lubricants, and system-level validation under realistic electrified operating conditions. Viewed through a gap-driven perspective, these opportunities define a clear pathway toward next-generation multifunctional lubrication systems for electrified mobility [4–5,15,50,54,92,94,144,165].

5. CONCLUSION

This review highlights that the rapid evolution of electrified transportation is driving lubrication science toward a new generation of dielectric, thermally robust, and environmentally responsible e-fluids capable of supporting high-speed, high-load, and electrically active tribological interfaces. Comparative evidence across the literature shows that graphene-based materials, MXenes, h-BN, MoS_2, and emerging phosphorene systems each offer distinct tribological benefits when properly dispersed, stabilized, and chemically integrated into advanced lubricant matrices. Collectively, these findings establish 2D materials as leading candidates for multifunctional lubricant additives in next-generation EV lubrication systems.

At the same time, the practical integration of 2D materials into commercial e-fluids remains constrained by cost, production scalability, dispersion stability, long-term oxidation resistance, and compatibility with metallic and polymeric components within electric powertrains. Although substantial progress has been achieved through surface functionalization, hybrid material design, and sustainable synthesis routes, real-world lubricant performance remains highly sensitive to additive concentration, operating environment, and interactions between 2D material surfaces and ester-based lubricant formulations. The literature consistently highlights the need for rational additive selection, careful balancing of rheological and dielectric properties, and tribo-chemical characterization tailored specifically to EV drivetrain architectures.

Overall, the technical evidence points to a field in rapid transition, shifting from predominantly mechanistic studies toward increasingly application-driven research aligned with industrial requirements. Advances in scalable MXene synthesis, graphene derivative functionalization, and ester compatibility

optimization have accelerated the translation of laboratory insights into practical formulations. Nevertheless, the research frontier remains inherently multidisciplinary, requiring close integration of tribology, materials chemistry, electrochemistry, lubricant formulation, and system-level EV design to fully realize the industrial potential of 2D-material-enhanced EV lubrication systems.

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