Advancing the Frontiers of EV Tribology with 2D Materials – A Critical Perspective

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Abstract: Because of their higher energy efficiency and environmental friendliness, electrical vehicles (EVs) have recently positioned themselves as one of the most sustainable alternatives to traditional combustion engine vehicles. However, there remain numerous challenges (i.e., lubrication, thermal management, electrical compatibility, and corrosion, among others) that can hamper their performance, efficiency, and reliability, and hence the sustainability of EVs in the long run. Two-dimensional (2D) materials offer impressive multi-functional characteristics, including unusual thermal, electrical, and tribological properties which can beneficially impact the smooth, safe, efficient, and long-lasting operation of EVs. Therefore, in this perspective, we summarize the most recent developments related to 2D materials which can synergistically address tribological, electrical, and thermal management issues and thus enable superior performance, efficiency, and reliability in future EVs. We hope that the highlighted remarkable properties of 2D materials can generate more research efforts in this direction and eventually lead to the development of an EV-based green and sustainable transportation future for generations to come.

Keywords: 2D materials, electric vehicle, friction, lubricant, superlubricity

1. Introduction

In recent years, electric vehicles have emerged as an indispensable part of our future transportation needs and their rapid integration into the mainstream automotive market is currently underway thus indeed signifying a pivotal shift towards achieving a sustainable transportation future that is also environmentally viable.

The concept of electric mobility (or E-Mobility) spans back to the 1820s with the creation of the first electric motor designed by the Hungarian engineer Ányos István Jedlik [1]. Accordingly, the original ideas that were essential for the development of electric vehicles (EVs) are not really new. In later years, electric motors have come a long way to propel small-scale electric carriages and trams in the late 19th century, thus presenting a quieter and cleaner alternative to gasoline-powered vehicles, particularly in urban settings.

With the discovery of vast oil reserves and cheaper and higher-energy density petroleum, gasoline-powered internal combustion vehicles expanded rapidly in early 1900s; this ultimately posed great threat to the EV market which consequently declined in popularity and consumer acceptance and hence EVs totally disappeared by 1935. Overall, future hopes for EVs as mainstream transportation vehicles faded away at the expense of more robust internal combustion engines (ICEs) during the reminder of the 1900s. Nevertheless, EVs have survived over the years in some niche applications, including forklifts, golf carts, tramways, underground metros, toy automobiles, and electric wheelchairs for enhanced mobility of hospital patients, among others.

In the 1970s, concerns about oil embargoes and shortages in gasoline brought back public interest in EVs through new advances in battery technology, initially driven by industries outside the well-established automotive sector. Eventually, this sector also developed an interest in EVs. In 1996, General Motors introduced a car, “the EV1,” which can be considered one of the very first modern all-EVs. In 2008, Tesla Motors unveiled the Tesla Roadster, a high-performance electric sports car that quickly changed perceptions about electric mobility. From then on, other automakers, like Nissan and Chevrolet, started to pick up on launching their own EVs with much-improved driving ranges and desirable features. With such increasing interest in EVs, battery scientists and engineers accelerated their research efforts and these have resulted in some breakthrough developments in battery technology, enabling much longer driving ranges and reducing charging times. Ultimately, these concerted efforts made EVs one of the mainstreams of today's automotive marketplace [3]. This area continues to expand rapidly as innovations such as solid-state batteries, wireless charging, vehicle-to-grid integration, and advancements in autonomous driving are paving the way for more efficient, reliable, and much safer and greener forms of transportation (**Figure 1a**).

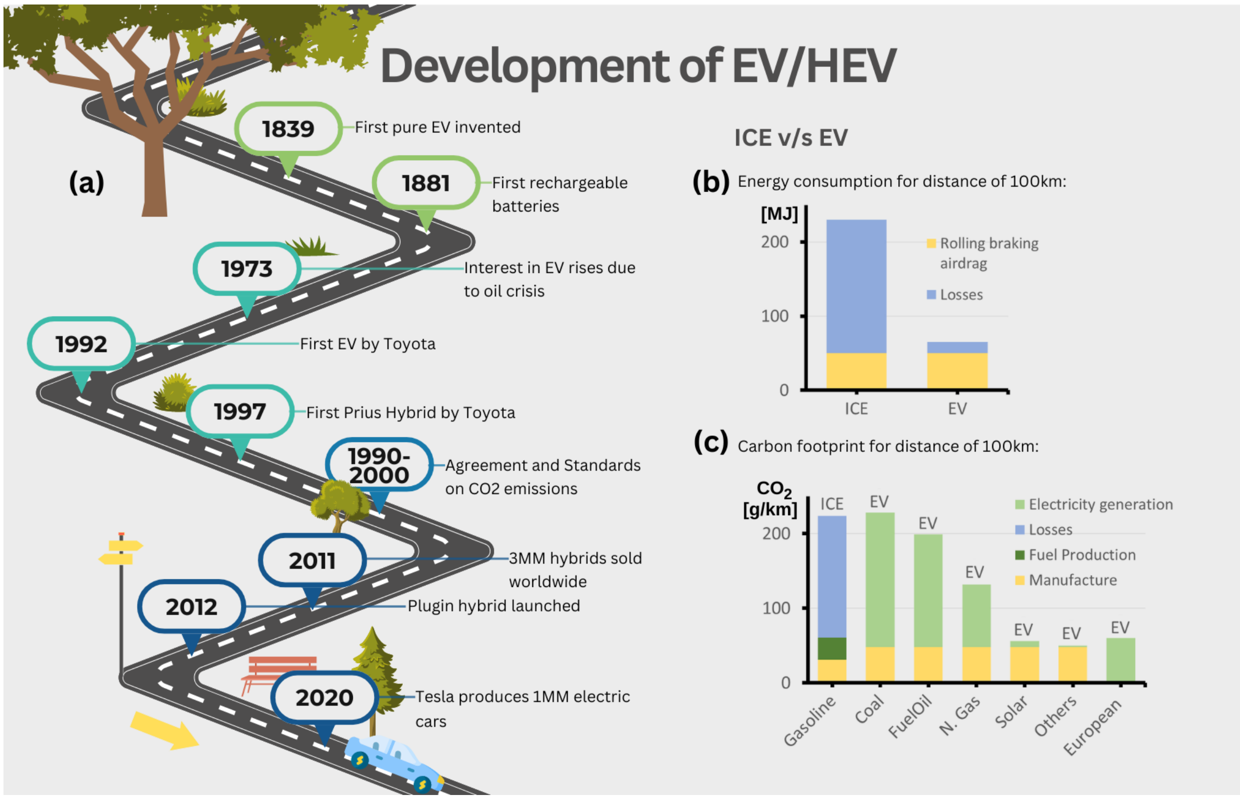

Figure 1. *(a) Historical timeline of EVs and future perspective. Comparison of the (b) energy consumption and (c) carbon footprint of an internal combustion engine and electric vehicle for a driving distance of 100 km based on the data from [2].*

Currently, many of our transportation needs are still met by ICE vehicles (ICEVs); their numbers have skyrocketed over the years and have already passed the billion mark [3]. However, these vehicles have become one of the largest sources of greenhouse gas (GHG) emissions (accounting for more than 27% of all CO_2 emissions in the USA and over 20% worldwide), hence contributing significantly to global warming and climate change [3]. Accelerated GHG emissions are already causing devastating natural disasters across the world in the forms of severe/unexpected flooding, sea level rises, powerful tornados and hurricanes, increased acidity in seawater, and severe drought due to scorching heat throughout the world, thus increasingly threatening the very delicate ecosystem and biodiversity of our planet. Considering all of these life-threatening developments, the United Nations (UN) has been holding a series of Climate Summits to mobilize world leaders to agree on immediate and dramatic cuts in GHG emissions to limit the temperature rise over the global mean below <1.5 ºC by 2030 [4]. It is projected that such a small rise could only be possible if the GHG emissions are cut by half during the remainder of this decade followed by much deeper cuts during the following decades. If all goes well, by the end of this century, the warming of our planet could be kept below 2.5ºC [5]. Otherwise, under current operating conditions, the projected global mean temperature rise will be over 4ºC, which would most likely make our planet unhabitable for many living species both on land and water, thus leading to a major environmental disaster with an apocalyptic effect on the health, safety, and economic wellbeing of all humankind. Accordingly, any efforts to slow down or even reverse this perilous scenario would be most beneficial.

There is no doubt that a rapid transition from ICEVs to EV-based transportation can certainly help in curtailing GHG emissions and their harmful effects. The good news is that this form of transportation is not new, as mentioned above, and its energy and environmental benefits have already been demonstrated [2]. As shown in **Figures 1b and 1c**, EVs' energy efficiency and carbon footprint are far more favorable than those of ICEVs, especially if the energy comes from a clean and renewable source, like wind, solar, etc. Therefore, a rapid transition to EVs makes perfect sense for a more sustainable planet and needs to be accelerated in the coming years. Car makers already produce more than 10 million EVs around the globe annually and have invested heavily in further increasing their production capacity. With all these positive developments, it looks feasible that nearly 2/3rd of all new vehicles being sold globally could be EVs by 2040 [6]. By then, hopefully, most of our electricity needs will be generated from green/clean energy resources, such as solar, wind, and nuclear, potentially making a huge positive impact in meeting the GHG targets of the UN and thus saving our planet from a climate Armageddon.

In the last decades, nanotechnology has played a significant role in different areas of engineering, including tribology. Different forms of nanomaterials as fillers to create bulk composites and coatings, as well as as additives for lubricating fluids, have been widely explored thus demonstrating their effectiveness in several tribological applications, which have been recently compiled in several literature reviews [7-11]. While there are multiple studies demonstrating efficiency of three-dimensional forms of nanomaterials [8, 9, 11], such as nanoparticles, nanorods, or nanotubes, this review focuses on 2D material perspective for future of EV lubrication. Considering the notable progress made during the last decade and the increasing need for tribological improvements in modern EVs, new research directions for nanomaterials in EV applications can be defined and executed to make such vehicles the most efficient and greenest form of transportation. This perspective article explores and highlights the most recent developments in self-lubricating 2D nanomaterials, affording superior thermal, electrical, and tribological properties to future EVs' critical power- and drivetrain components.

2. Overview of EV Systems and Fluid Requirements

Even though EVs have fewer moving parts compared to traditional ICEVs, some major components and systems are still subject to mechanical and tribological challenges for EVs, such as the electric motor and gearbox lubrication, as well as the power-electronics and the battery pack cooling [12] (see **Figure 2a**). Apart from the key friction and wear control requirements, the most desired solutions for each moving component must address new challenges involving corrosion, thermal management, static and stray electricity, and material compatibility.

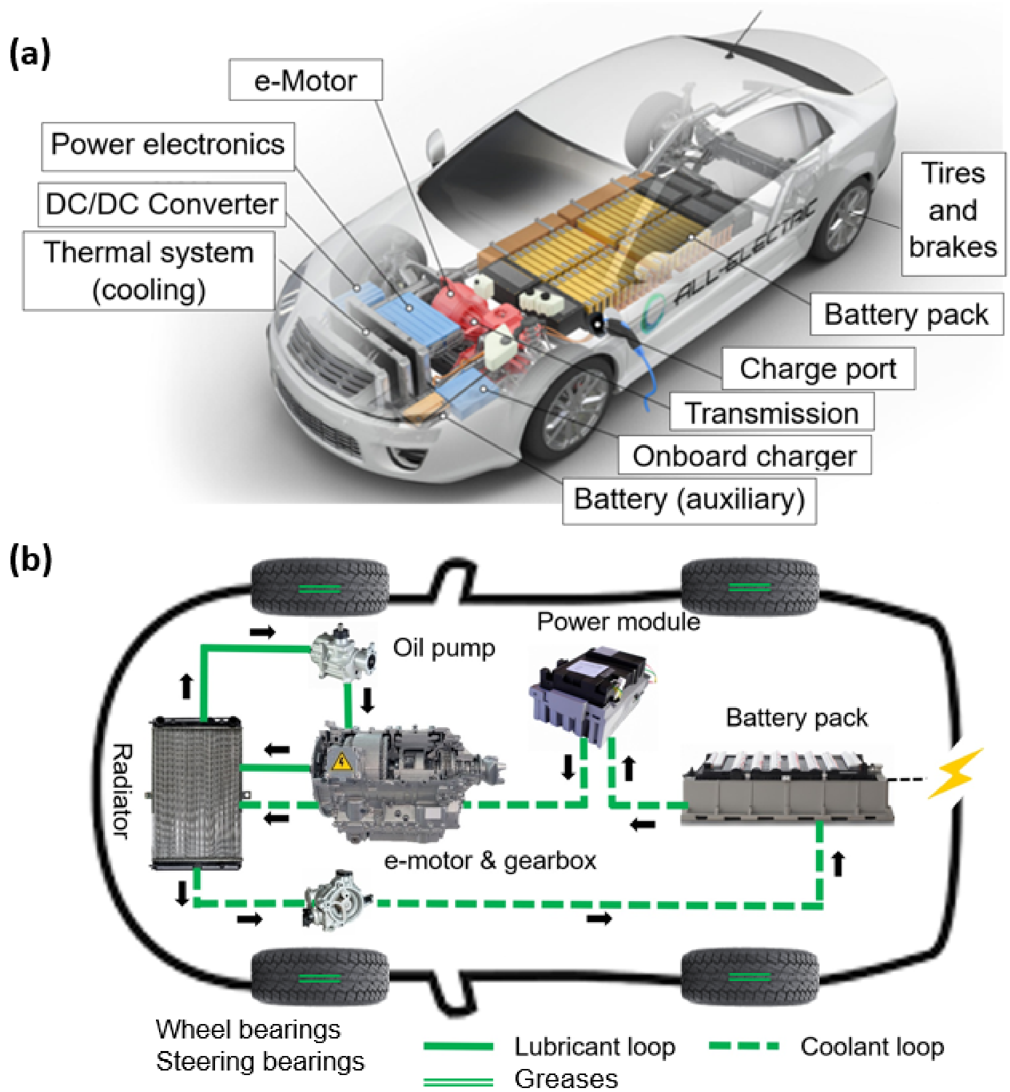

Figure 2. *(a) Key components of an All-Electric Car and (b) Illustration of lubricant and coolant circuits in an integrated electrified powertrain, battery pack, and power electronics.*

Compared to ICEVs, EVs using either batteries or hydrogen fuel cells comprise a set of powertrains (1 to 4 units depending on the EV architecture based on either a single motor, dual motor or in-wheel motor), a battery pack and/or a set of hydrogen fuel-cells, as well as a set of power electronics, which replace the engine, fuel tank and some ancillary systems [12]. These EV systems create new challenges in terms of fluids and materials used to ensure safe and efficient operation.

The powertrain is conformed by an electric motor coupled to a single-speed transmission (reducer gearbox or differential) or a multi-speed transmission (continuously variable transmission, automatic transmission, or dual-clutch transmission). The electric motors and the power electronics operation produce stray currents that go through the shaft, thus interfering with the functionality of tribological elements such as bearings and gears [13]. These currents are known as shaft or bearing currents and are known to cause detrimental effects, such as increased heat, friction and accelerated wear, which can compromise the EVs' long-range durability and energy efficiency. New lubricants (greases or lubricating oils) and tribo-materials that can withstand electrical discharge effects in the powertrain must be explored and developed. These developments must go hand in hand with other solutions based on optimizing the design of the electric machine and/or shaft-grounding brushes so that the destructive effects of stray electricity can be avoided.

The variable driving cycles in EVs can produce large heat levels across all involved systems, affecting the battery pack, power electronics, and powertrain. Consequently, lubricants with excellent lubricity and cooling properties (thermal management) [14], such as commercial automatic transmission fluids (ATFs) [15] and upcoming glycol-based lubricants [16], nano colloidal-based lubricants [17], etc., could be excellent candidates to lubricate these systems, while simultaneously dissipating the excessive heat being generated. Since the used lubricants can potentially come into contact with the e-motor wiring, both copper corrosion inhibition and good compatibility with varnishes and epoxy resins are also newly emerging requirements that were not considered by most of the traditionally used lubricant systems [18].

The incorporation and use of many high-current density batteries (battery pack) and all power electronics, including DC-DC converter or DC-AC inverter, and controller and charger, which are necessary to control the electric motor and the energy management, require cooling fluids to dissipate heat quickly and efficiently. The lifespan and performance of the batteries are determined by their operating temperature, which is suggested to lay between 20 to 40 °C [19]. Therefore, keeping the optimum temperature in an almost stable magnitude of the battery pack and power electronics is essential for battery life and performance; this is mainly achieved by a cooling circuit interconnecting the battery pack, power electronics, and powertrain, in which a coolant (thermal management fluid) recirculates into external vessels/channels, as schematically shown in **Figure 2b**. Currently, EV cooling systems are still a highly researched topic. However, phase-change materials, fins, air, or liquid coolants are the most used options to cool the batteries and power electronics [20]. Indirect and direct cooling by liquid coolants is the most appropriate technique in state-of-the-art EVs since they exhibit a high heat capacity and performance and are compact and easy-to-arrange systems. Indirect cooling is similar to that used in ICEVs and resembles the most used system in today's EVs. In this approach, the coolant circulates through a system of metal pipes surrounding the batteries and electronics. In contrast, direct cooling systems place the battery cells in contact with the coolant. This approach is more challenging and still under active research because a new type of coolant is required since the coolant is in direct contact with the battery system and this may give rise to other catastrophic problems like short circuits in batteries or power electronics [21]. Consequently, the thermal properties (specific heat capacity and thermal conductivity), material compatibility (wiring resins, metals, and other polymers), and the dielectric properties of the coolants used in EVs are all critical and their optimization is essential.

Recently, OEMs such as Shell, Castrol, ExxonMobil, and others have marketed different categories of fluids aligning with the overall EV requirements. These fluids are generally divided into transmission fluids, thermal management fluids, and greases. Transmission fluids are expected to provide lubrication in integrated e-module systems, including gearboxes, electric motors, bearings, clutches, and electrical components. Thermal management fluids are needed to ensure thermal transport and to regulate the temperature of the battery, electronics, electric motor, and windings. They must exhibit excellent electrical insulation, efficient thermal management, and good material compatibility [22, 23]. Current thermal management fluids are not expected to lubricate the driveline components; however, such a capability is highly desired in the future. It is hoped that one fluid that can provide lubrication and meet the thermal and electrical management needs of EV powertrains and drivetrains will be feasible in the future. Greases are used to lubricate the bearings of the electric motor (only in low-demanding applications EVs), wheels, and steering, supporting higher temperatures, speeds, and electric discharges [24]. The general requirements for each fluid are summarized in **Table 1**. To the best of our knowledge, although all these requirements are known to be essential in the performance of EVs, most of them are not yet specified in their respective magnitudes; this can be ascribed to the current lack of scientific knowledge, standard test methods and EVs´ systems homologation.

__Table 1.__ Summary of general requirements for different E-fluids.

Fluid parameter	Requirement	E-Fluid		
		Transmission fluid	Thermal management fluid	Grease
Compatibility with polymers	The fluid should be compatible with different polymers (elastomers, thermoplastics, varnishes, and resins) involved in the electrical systems to avoid any types of degradation.	✓	✓	✓
Anti-foaming	The fluid is highly required to have anti-foaming properties, especially at the ranges of e-motor speeds (> 10,000 RPMs).	✓		
Copper corrosion	The fluid should not corrode metallic components, especially, copper elements of the e-motors.	✓	✓	
Thermal and oxidation stability	The fluid should have excellent thermal oxidation stability to resist thermal degradation.	✓	✓	✓
Moderate to high dielectric strength	The fluid should have moderate to high dielectric strength to avoid dielectric breakdown under a high electric field.	✓	✓	✓
High electrical conductivity	The fluid should be a good electrical conductor to discharge electricity easily when breakdowns occur. This reduces the severity of sparking wear at tribological interfaces [43].	✓		✓

Low electrical conductivity	The fluid should be a good electrical insulator to avoid short circuits.		✓	
Flammability	The fluid should not be flammable under high heat and electrical discharge conditions.		✓	
Flash point	High flash and fire points are required.		✓	
Heat transfer	The fluid should have a moderate to high heat transfer coefficient to remove substantial heat generated in E-motors and batteries.	✓	✓	✓
Pour point	A low pour point is required for the operability of EVs at low temperatures.	✓	✓	✓
Viscosity index	High viscosity index is required for providing lower fluctuations in viscosity upon temperature changes.	✓	✓	✓
Viscosity	Low-viscosity fluids are required for better cooling and lower friction/viscous shear under hydrodynamic lubrication.	✓	✓	
Water resistance	The fluid should have high water resistance/hydrophobicity to avoid electrowetting.	✓	✓	✓
Wear resistance	The fluid should not lead to wear of tribological elements at high temperature and speed and electric field conditions.	✓		✓
Anti-shudder	Anti-shudder property is required for fluids used in e-transmissions comprising wet clutches.	✓		

3. 2D Materials – Their Functional Characteristics and Prospects in EVs

With the discovery of 2D materials (only an atom or molecule thick), many new and exciting properties leading to numerous unique applications have emerged in recent years [25-27]. The most famous 2D material is graphene, made of a single layer of carbon atoms arranged in a honeycomb lattice. Graphene's exceptional mechanical strength, resilience, and excellent electrical and thermal conductivities opened up the possibility of its use in various mechanical and electrical devices. Its discovery has resulted in the development of many other 2D materials whose friction and wear properties are also impressive. As a result, the library of currently available 2D materials covers a wide range of physical, chemical, and tribological characteristics and continues to grow. Furthermore, the diversity in their deposition and synthesis methods enables the practical use of 2D materials across a broad spectrum of applications, including in EVs (**Figure 3**).

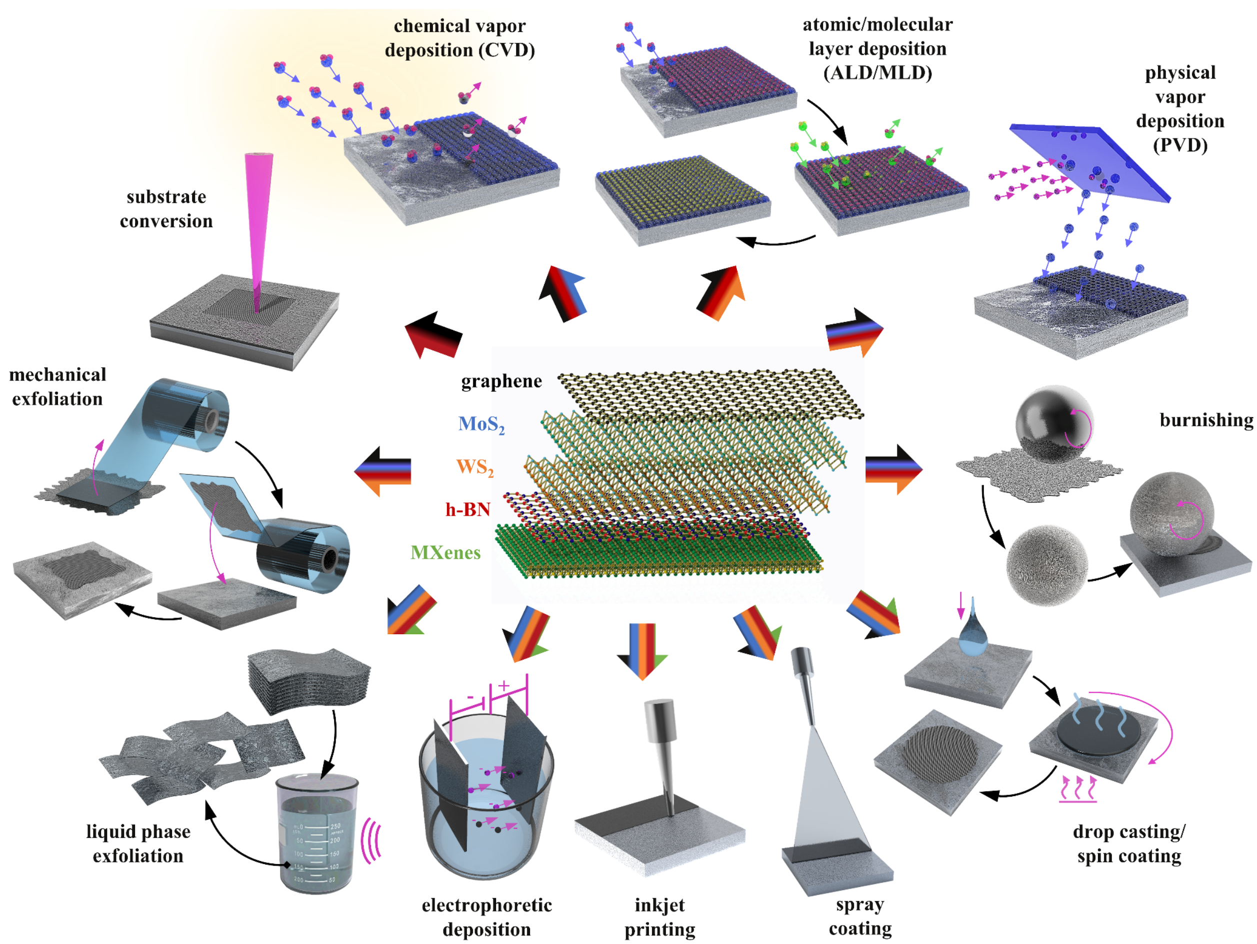

Figure 3. *Examples of 2D materials and their common synthesis and deposition methods. Reproduced with permission from [10, 28-31].*

In this regard, 2D materials offer a wide range of functional characteristics while sustaining high mechanical strength, chemical inertness, wear resistance, easy-to-shear ability (low friction), and the capability to generate lubricious tribo-films (resulting from tribo-chemical reactions to provide low friction and improved wear performance) [10, 28-31]. Due to this unique property combination, using 2D materials in EVs holds great promise in enhancing future EVs' performance, efficiency, and durability, thus making it highly prospective. The overall 2D lubrication bases on important mechanical and tribological chharacteristics of 2D materials that are revealed upon utilization of 2D materials in various material systems (**Figure 4**). In general, in EVs and in other assemblies, 2D materials can be incorporated through three different approaches. 2D materials can be used as protective solid lubricant coatings, which can bring benefits in terms of friction, wear and corrosion properties. Moreover, 2D materials can be added as lubricant additives in oils and greases, which are used for lubrication purposes in EVs. Under lubricated conditions, 2D materials can also form strongly bonded boundary films on rubbing surfaces [32, 33]; this helps to minimize noise and vibration, contributing to smoother and quieter EV operation. Furthermore, in mechanical components made of metallic or polymeric composites, 2D materials can be utilized as reinforcement phases to improve the resulting mechanical, tribological, and corrosion performance and heat management [34]. These approaches offer some interesting possibilities to further optimize the performance of specific mechanical components in future EVs.

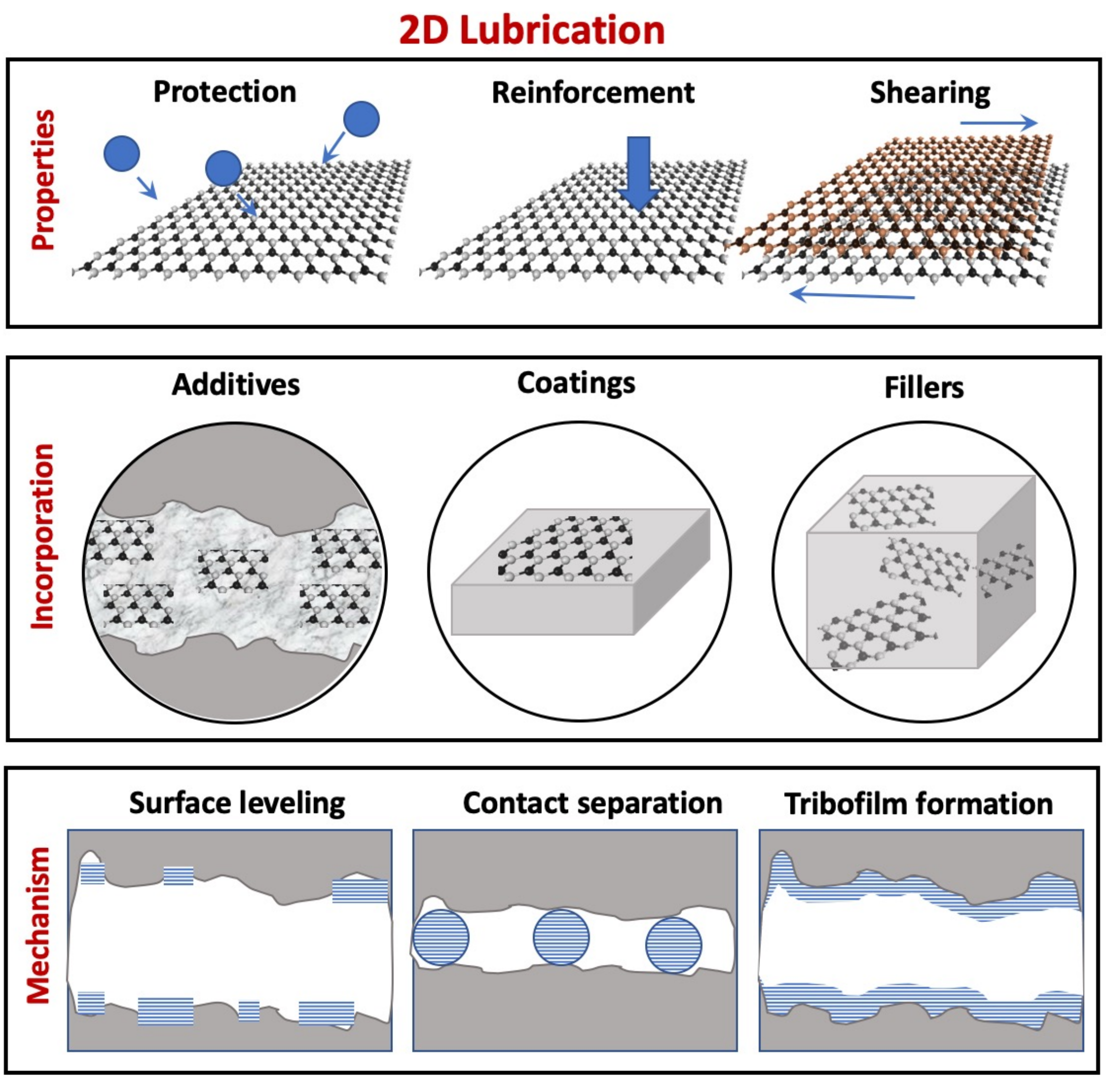

Figure 4. *Overview of the 2D lubrication concept starting from (top row) the essential properties such as surface protection, material reinforcement, and easy shearing to (middle row) approaches*

for 2D material incorporation in different systems such as additives to fluids, coatings on surfaces, or fillers to composite matrices, and to (bottom row) different mechanisms of 2D lubrication, such as surface smoothening through filling concave valeys, contact separation, and tribofilm formation.

Apart from their remarkable mechanical and tribological properties, 2D materials offer favorable thermal and electrical properties (even under extreme conditions), which are beneficial irrespective of their uses as self-lubricating additives, coatings, or fillers [25]. Some of the available 2D materials possess high thermal and electrical conductivities, which is beneficial to enhance heat dissipation while rapidly discharging electricity and, hence, preventing arcing. Most 2D materials can withstand high temperatures, thus providing extended lubricity and functionality even if the base lubricants or greases break down due to high heat or electrical discharges.

Moreover, 2D materials are known for their excellent chemical stabilities and high oxidation resistance, which is also a key property for all three targeted applications. Due to the involved mechanical and electrical stress in EVs, tribo-corrosion, which may induce accelerated wear conditions, plays a significant role. In this context, 2D materials have gained substantial interest as corrosion inhibitors since they possess unique properties that can significantly enhance their protective performance against (tribo)-corrosion in various environments [35]. Films made of 2D materials can also act as an impermeable barrier for corrosive species, thus protecting the underlying substrate materials and preventing their degradation. Moreover, their tunable electronic properties and surface chemistry by functionalization help to manipulate and further tailor charge transfer properties, thus modifying interfacial properties and hindering the onset of corrosion. This is of particular interest for EVs since variable driving conditions (intensive torque-speed peaks for the e-motor) and regenerative braking tend to generate high levels of heat, which increases the oxidation of the lubricants being used. Compared to other recurrent additives, the high resistance of 2D materials ensures the longevity of the lubricants and maintains their performance over an extended period, reducing the need for frequent lubricant changes. The unique properties of 2D materials as backup lubricants (when applied even at minimal quantities) also offer the potential for downsizing and weight reduction in EVs.

Figure 5 summarizes the main electrical and thermal characteristics of some 2D materials. Each 2D material exhibits a wide range of properties with potential applications in electronics, optics, catalysis, sensing, mechanics, and potentially in EVs, as will be elaborated further in the following.

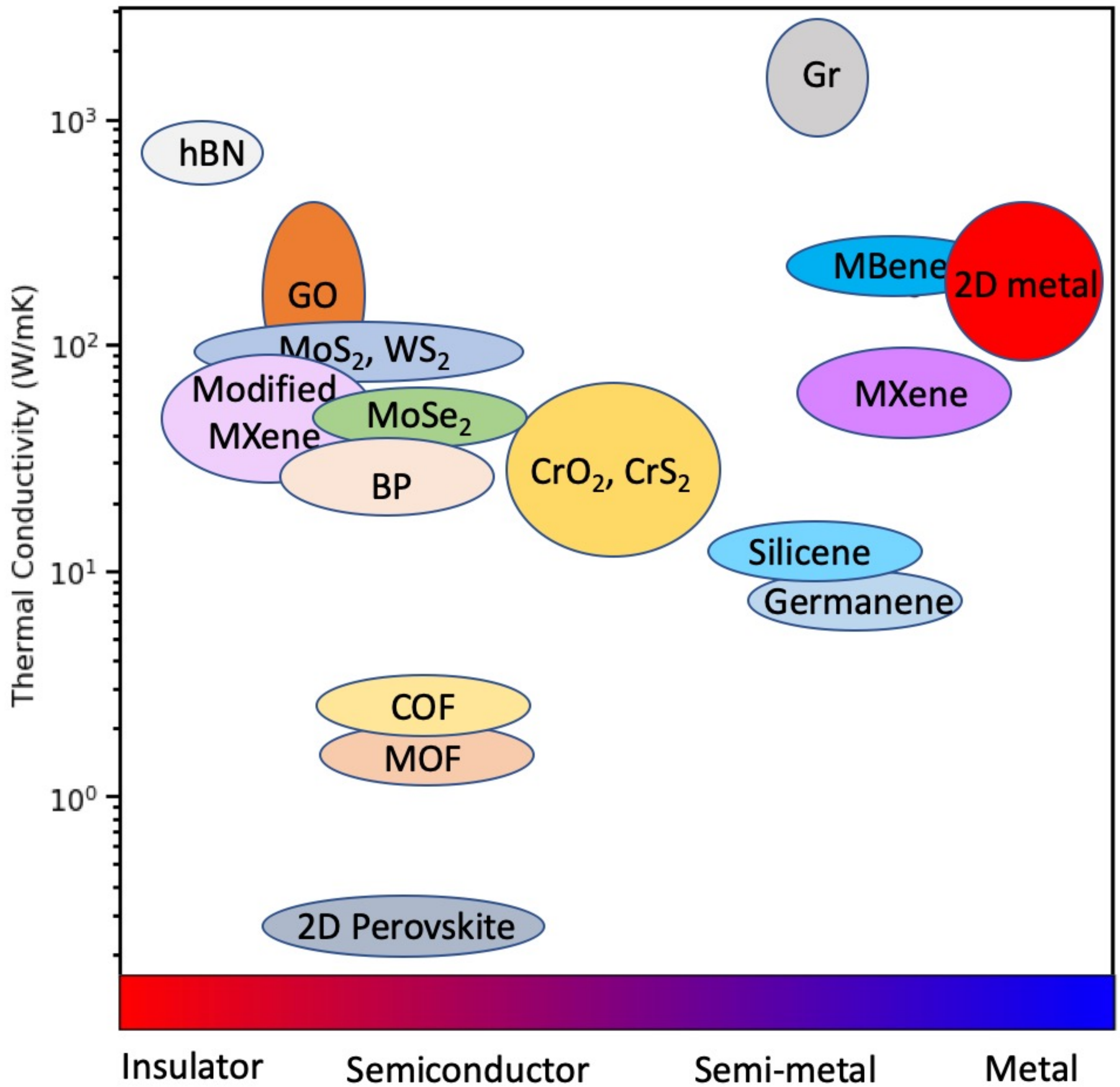

Figure 5. *Summary of common 2D materials as well as their electrical and thermal characteristics [36-53].*

3.1 Fundamental aspects at the nano-scale

When targeting the application of 2D materials for EV components, additional restrictions can be imposed by the long-term stability of the materials and their properties. Previous reports indicated that the electrical and tribological properties of 2D materials are not independent of each other [54, 55], and the electric field might affect the friction and wear of 2D films [56-58]. From a fundamental perspective, Greenwood *et al.* [59] demonstrated at the nano-scale level that an efficient charge transfer across graphene-tip single asperity contacts in atomic force microscopy (AFM) experiments is needed for the stability of the frictional response of the entire system. In the case of insulating tips, the presence of an electric field led to a large electrostatic attraction with trapped charges, thus increasing friction (**Figure 6**). The doping of graphene in graphene-semiconductor contacts provided additional means to manipulate and tailor the proposed system.

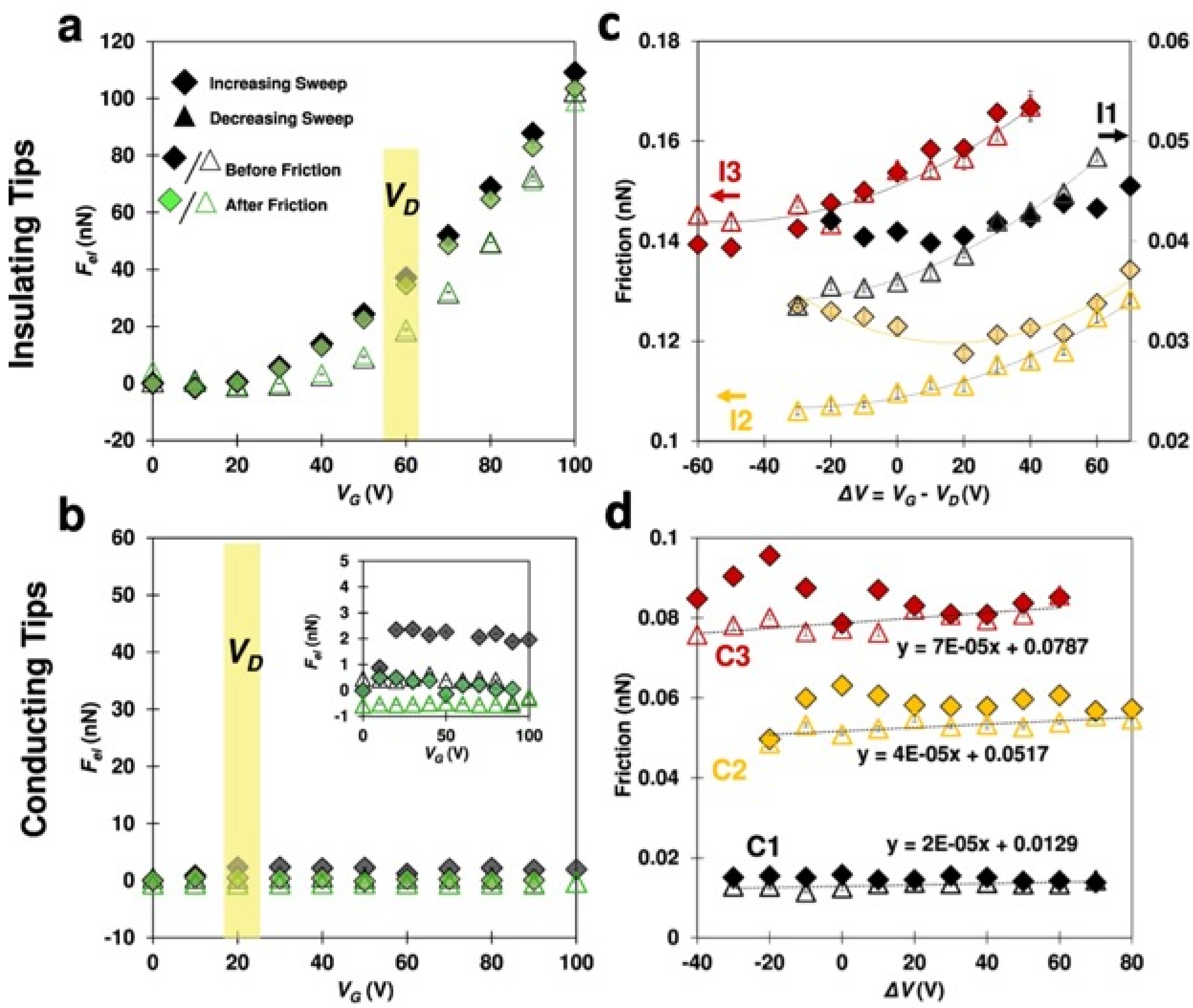

Figure 6. *(a, b) Representative electrostatic attraction before and after friction measurements as a function of the back-gate potential for insulating and conducting tips. (c, d) Corresponding friction as a function of the difference between backgate potential and the sample's Dirac point. Reproduced with permission from [59].*

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In AFM studies, Zeng *et al.* [60] demonstrated that the friction between MoS_2 nano-sheets and the respective probe is sensitive to an external normal electric field. At the same time, applying a bias reduced the wear of MoS_2, though only till certain threshold bias values. This reduction was attributed to the formation of a transfer film between the AFM probe and the sample. When the applied bias exceeded the threshold value, the oxidation of MoS_2 nano-sheets resulted in both friction and wear increase.

3.2 2D materials as lubricant additives

Nanomaterials have been considered promising candidates for improving the tribological characteristics of oils and greases [61]. Mixing 10-20 nm nanoparticles (NPs) of alumina, titania, diamond, etc., in the polyalphaolefin (PAO) allowed to significantly decrease friction (by up to 50%) and wear (by several orders of magnitude) of the lubricated surfaces, but also to enhance the thermal conductivity of the fluids (up to 50% [62]), which are essential characteristics for efficient energy dissipation. Consequently, the friction and wear reduction benefits were demonstrated for the sliding systems lubricated with NP-containing greases due to protective tribofilm formation. While prior reports widely focused on using NPs as nanomaterial candidates, certain benefits are accessible only with 2D materials.

3.2.1 Low-viscosity oil additives

Del Rio *et al.* [63] generated hybrid Mn_3O_4-graphene nanocomposites (Mn_3O_4-G) to be used as additives in paraffinic base oil for transmission fluids in EVs. The friction and wear performance of the hybrid nanocomposites was tested using a ball-on-three-plates test rig depending on the adjusted concentration (0.025 – 0.1 wt.-%) under an applied contact pressure of up to 1.1 GPa. The best performance was found for a concentration of 0.075 wt.-%, which induced a slight reduction in the resulting COF as well as a 50 % reduction in the worn area. In a follow-up study [64], the same group evaluated the performance of oleic acid-coated TiO_2 nanoparticles in low-viscosity PAO 8 with the overall purpose of being used in EVs for friction and wear optimization. PAO 8 containing 0.35 wt.-% of the coated nanoparticles induced a 30 % friction reduction and 73 % reduction in the resulting worn area when tested under pure sliding conditions.

Aguilar-Rosas *et al.* [17] studied the effect of the superficial area of graphene (ranging between 300 and 750 m^2/g) when adding 0.5 wt.-% of graphene to low-viscosity PAO 4 using a newly implemented four-ball tester for electrified contacts (**Figure 7**). Irrespective of the superficial area of the graphene used, it was demonstrated that the graphene addition in low concentration helped to improve the thermal stability of PAO 4 and reduced the electrical breakdown voltage by 35 %. Apart from that, the addition of graphene induced a non-Newtonian viscosity behavior (shear thinning), while the measured viscosity increase correlated with the increase in graphene's superficial area. Under electrified conditions, the graphene addition did not significantly alter the frictional performance while inducing a modest reduction in wear and a notable reduction in the temperature change.

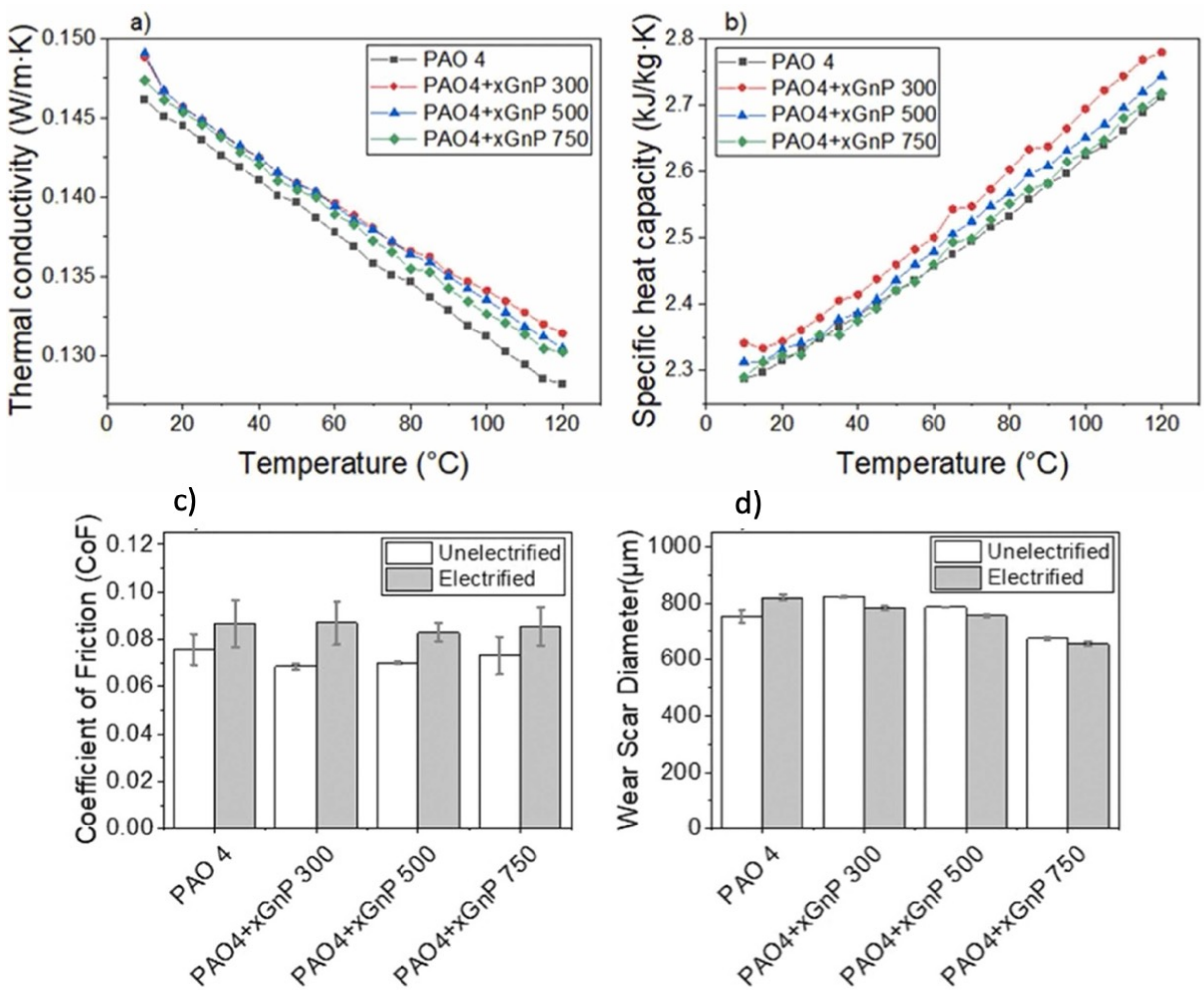

***Figure** 7. (a, b) Thermal conductivity and specific heat capacity of the neat PAO4 and PAO-4 – based nanofluids with graphene addition. (c, d) Corresponding friction and wear of steel surface lubricated with these fluids. Adapted with permission from [17].*

3.2.2 Coolant agents/additives

The reliable operation of EVs highly depends on using batteries sustaining high energy densities, minimal self-discharge, and an extended lifespan. However, elevated temperatures due to high amounts of generated heat, especially upon charging and discharging by high-demand EV use, can trigger uncontrolled thermal surges, resulting in safety concerns such as short circuits and explosions. To maintain the best battery performance and lifespan, the thermal management of the entire battery and power-electronic system is essential [65, 66].

The air cooling approach, traditionally used in gasoline cars and relying on fan-produced air circulation, is simple and relatively inexpensive but ineffective for EVs. Instead, batteries in EVs are often cooled by using liquid battery-cooling systems that circulate coolant fluids through passages, both inside a plate and around the cells in the battery. Proper thermal dissipation is considered the major requirement for selecting the coolant, but the battery cooling function requires constant circulation. The sustainability of the moving pump components in contact with the coolant represents the challenges regarding the resulting tribological efficiency. For instance, the coolant tends to degrade with time and eventually breaks down, thus potentially clogging the passages if not changed. At the same time, the moving parts of the pumps can fail due to friction and wear as well as corrosion issues on their surfaces due to the extended exposure to the coolants. As a result, new approaches are needed to improve the thermal management's effectiveness while simultaneously lubricating the cooling pump components and preventing their failure.

In this context, the addition of suspended 2D material flakes in the fluid can significantly increase the thermal conductivity of the liquid. Though most research has been performed using nanoparticles, including Cu, Al_2O_3, TiO_2, SiO_2, etc., as additives to water and water-glycol-based coolants, there are preliminary results underlining the promising potential of graphene- [67, 68] and MXene-based [69] nanofluids. Specifically, it has been shown that the addition of 0.001-0.005 vol.-% of graphene to the mixture of ethylene glycol and water allowed to reduce the operating battery temperature by 12 – 29 %, which was attributed to the high thermal conductivity and large surface area of graphene [70]. However, considering that the fluid may be in contact with electronics and the battery cells, particularly in direct cooling systems, special attention must be given to the dielectric properties of the fluid when adding conductive nanoparticles. The gain in thermal properties can be the loss of dielectric strength, which can be dangerous for the batteries and electronics.

Notably, MXenes, [71, 72] graphene, [73, 74] and silicene [75] have also been considered to improve the functionality of phase-changing materials (PCMs) used in battery thermal management systems to absorb excess heat during charging and discharging. In this context, MXenes appear promising due to their inherent high thermal conductivity and excellent high-temperature stability compared to traditional PCMs, such as paraffin waxes, salt hydrates, and alcohols [71].

3.2.2 Grease additives

Yan *et al.* [76] investigated the possibility of tailoring lithium grease's friction and wear performance using boron nitride (BN) and MoS_2. In this regard, they considered the performance of greases containing only BN and MoS_2 as well as both nanoparticles in variable ratios (1:2 and 1:3) while keeping an overall concentration of 2 wt.-% for all cases (pure and hybrid additives). Tribological testing was realized using a ball-on-disk set-up under rotational sliding with an adjusted contact pressure of 600 MPa. The best performance was shown for adding pure BN (2 wt.-%), which induced a 50 % friction reduction and a 4-fold wear reduction. Very similar results were verified for the BN-MoS_2 hybrid (1:2 ratio).

Despite the promising results for use of 2D materials as additives to liquid and semi-solid lubricants observed in controlled lab environments, scaling up these applications involves overcoming several hurdles. These include the lack of industrial-scale testing necessary to commit to producing new formulations, commitment to ensuring consistent quality and performance of 2D materials in mass production, developing cost-effective manufacturing processes, and meeting stringent industry standards and environmental regulations.

3.3 2D materials as protective coatings and solid lubricants

While fluids are often used as the most appealing lubrication and thermal management approach, there are situations of lubricant deprivation that can lead to failures of the sliding surfaces. Additional protection of the surfaces is beneficial to avoid the dramatic consequences of lubricant failure; this is possible by implementing additional protection of the surfaces by using 2D materials as protective coatings. The selection of potential 2D material candidates in these cases is guided by other application requirements, such as thermal properties and stability under applied electric fields. In a recent study, Farfan-Cabrera et al. [77] explored the tribological behavior of lubricated H-DLC and H-free DLC coatings under the influence of DC electric current discharges in pin-on-disc tests. They found that H-DLC performed very well under both unelectrified and electrified sliding. It showed little or no change in CoF and wear due to electrification compared to H-free DLC. In contrast, electrification caused a very significant detrimental effect on CoF and wear of H-free DLC. It was ascribed to the pre-existence of some graphitic phases accelerating the graphitization process of the whole coating during electrified sliding.

Liu *et al.* [78] proposed to incorporating graphene films to improve the thermal management efficiency of water-based cooling systems. The graphene film, attached to an aluminum heat sink integrated with cooling water, was assembled on the surface of the Li-ion battery. This approach helped stabilize the temperature of the cooling water at 17.6 °C. Moreover, the experimental results demonstrated a temperature reduction of 11 and 9 °C for Li-ion battery modules under discharge rates of 2C and 1C, respectively.

At the same time, graphene has been proposed as an oxidation barrier coating for liquid and two-phase cooling systems [79]. During boiling tests, the inlet temperature and volumetric flow rate of ultra-pure water used as working fluid were kept at 59.5 ± 0.5 °C and 222 ml/min, respectively. The graphene film exhibited robust adhesion to the underlying copper substrate, maintaining its integrity even when subjected to repeated forces during the bubble ebullition cycle under long-term vigorous boiling conditions (up to 9 h). The six plotted curves (**Figure 8**) depict closely resembling heat transfer traits of the two substrates across the majority of test points, showing that the graphene coating did not alter the thermal performance of the surfaces in either operational regime. At the same time, the presence of graphene significantly suppressed corrosion of the underlying copper surfaces even under long-term exposure to the working fluid. In this case, however, ensuring a uniform, homogeneous and defect-free coverage with graphene is critical since prior studies indicated that tears in the protective 2D film act as nucleation points for corrosion initiation and propagation [35].

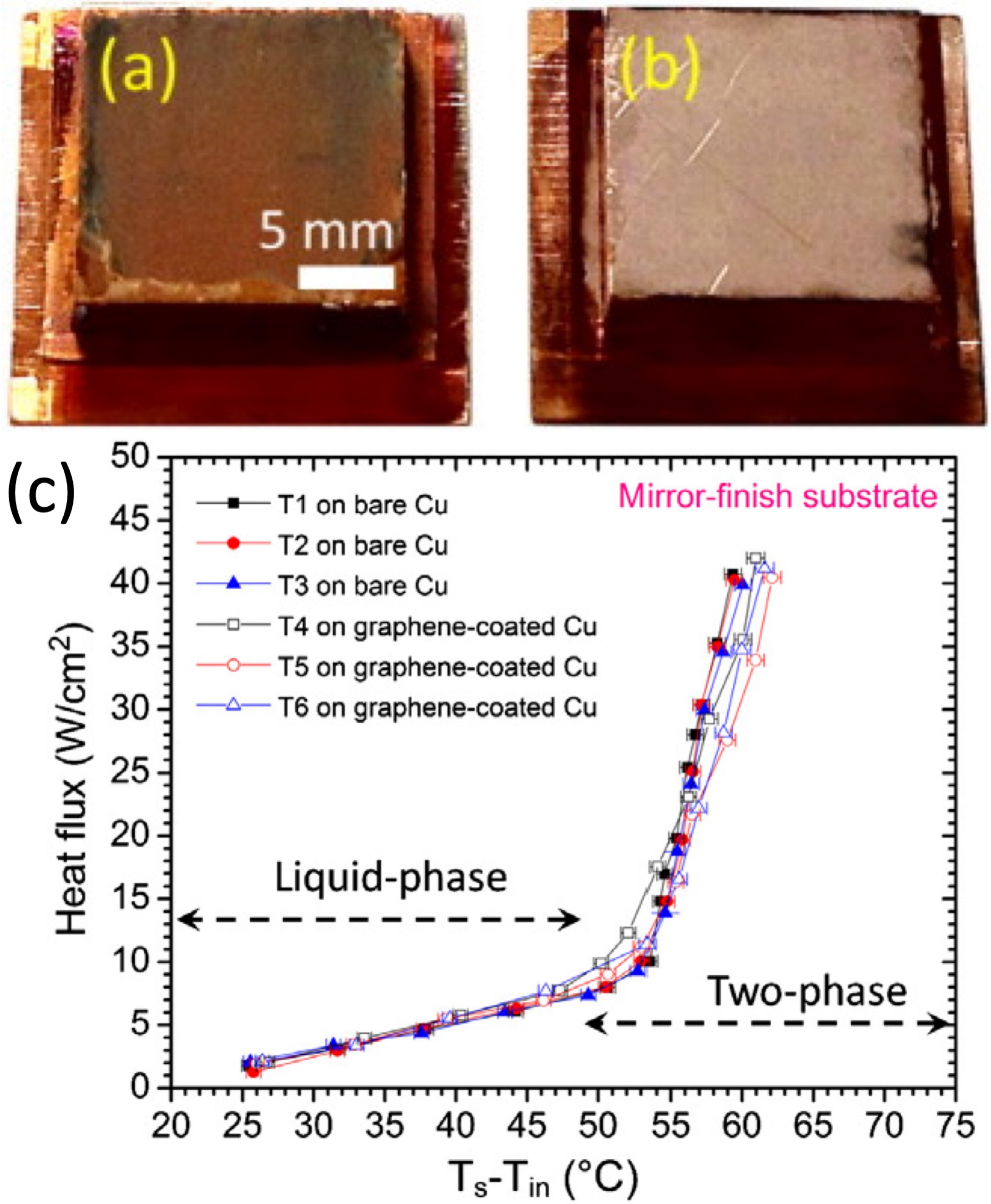

Figure 8. *Digital photograph of (a) bare and (b) graphene-coated mirror-finished copper substrate after thermal testing. (c) Flow boiling curves for mirror-finished bare copper and graphene-coated copper surface with a mass velocity G ≅ 38 kg/m2 s and an inlet fluid temperature* T_{in} *= 59.5 ± 0.5 °C, respectively. Adapted with permission from [79].*

Though the primary focus for addressing the challenges associated with friction and wear involves lubricating fluids, there is still a need for efficient solutions that work under dry conditions. An example of such a system is power plugs. As the batteries require fast charging for the convenience and robustness of the EVs, this problem becomes broader than just increasing the battery efficiency. The challenges often originate from the failure of connectors used during the charging cycles. In this case, using 2D materials as coating provides an effective solution for improving the characteristics of the connectors. Specifically, it was demonstrated that using graphene flakes on gold surfaces significantly decreased the friction of Au/TiN contacts and stabilized electrical contact resistance at low values over the a prolonged time (**Figure 9)** [80].

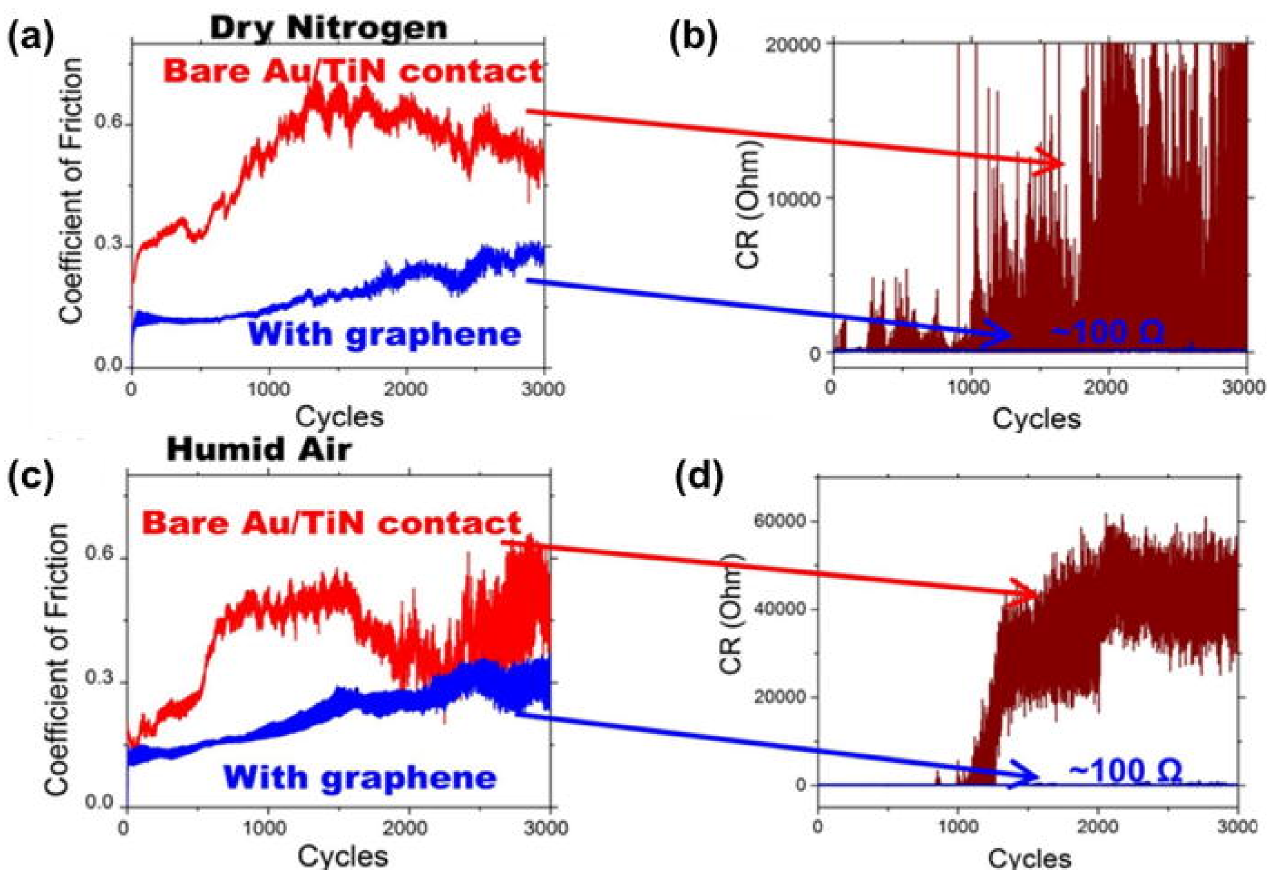

***Figure 9**. (a, c) Temporal evolution of the COF with the corresponding (b, d) signal of the contact resistance for bare gold/TiN and graphene-coated contacts in (a, b) dry nitrogen and (c, d) humid air. Graphene does not only suppress friction and wear but also maintains low contact resistance of the sliding interfaces. Reproduced with permission from [80].*

Since 2D materials are already used in various mechanical systems (we should give some examples here, let us think about them), expanding their uses to electrical components would already be at a high technology readiness level. And it does not only refer to mechanical systems such as bearing and steering components but also to periodic contacts seen in electrical connectors in charging systems.

3.4 2D materials as fillers in composites

Using 2D material-based composites in EVs holds significant promise; however the central focus in this context is directed towards incorporating these composites into the construction of EV components, such as chassis, body panels, and battery casings, that enables substantial weight reduction without compromising structural integrity [81-84]. In this regard, 2D materials are used as fillers or reinforcement phases of composites [85-89]. Over the past few years, there has been a notable increase in bearing failures in EVs, which was attributed to the electrical environments in which bearings work. Specifically, the presence of shaft voltages and bearing currents has accelerated the failure at the bearing contacts through morphological changes, such as frosting, pitting and welding during fast discharging, and lubrication failure due to the voltage-accelerated lubricant degradation [90]. A potential strategy to tackle these problems caused by the electrical environment is to shield the electric field [91] and/or improve the conductivity of the contacting interfaces, thus eliminating the respective charge build-up [92]. Later, using 2D materials, such as graphene, enhances the dissipation of the induced charges, thus potentially preventing failures of the electrical contacts [93]. At the same time, graphene and several other 2D materials demonstrate high thermal conductivity, thus assisting in efficient heat dissipation and thermal management, making them suitable for maintaining optimal operating temperatures and preventing overheating of electric drivetrains, bearing systems, and battery components [94, 95].

In terms of tribological performance, adding 2D material fillers helps suppress material wear or erosion and reduces friction [26]. Compared to their usage as additives or coatings, a notable advantage of using 2D materials as fillers in composites relates to their distribution throughout the entire bulk composites. While coatings and additives are only effective when present in the tribological interface, composites reinforced by 2D materials are also effective when worn off over time since new lubricious 2D material can be released from the bulk of the composite. Bashandeh *et al.* conducted tests comparing graphene-enhanced polymer coatings to both polytetrafluoroethylene (PTFE) and pristine polymer coatings, subjecting them to temperatures as high as 300°C [96]. Notably, at the highest temperature, the graphene composite coating exhibited superior performance compared to both reference coatings.

Lv *et al.* [97] demonstrated a similar friction and wear reduction when adding BP nano-sheets to PTFE and polyetheretherketone (PEEK)/PTFE composites. Adding only 5 wt.-% of BP resulted in a 3-fold friction reduction (down to 0.04) and an order of magnitude wear reduction when tested in macroscale ball-on-disk experiments against silicon nitride balls. The analysis of the wear tracks suggested that the observed experimental trends can be explained by transforming the initial BP coating into a lubricious film consisting of phosphorus oxide and phosphoric acid.

Combinations of 2D materials are also used as friction and wear-reducing components in composite materials and coatings operating across different temperature regimes and environmental conditions. For example, the incorporation of MoS_2 mixed with graphite powders into plasma electrolytic oxidation-formed aluminum oxide coatings allowed to accomplish sustainability of the tribological protection upon transitioning from a humid to dry environment due to the adaptive behavior of 2D materials [98, 99]. Moreover, this chameleon coating exhibited remarkably low coefficient of friction values (~0.02) during testing at elevated temperatures [100].

Overall, the existing studies demonstrate great improvement in the tribological characteristics of composite structures with introduction of 2D materials suggesting clear pathway for their integration in functional components of EVs. Composites with 2D materials can improve the wear resistance and heat dissipation capacity in brake components, that experience much higher stresses due to high load/torque conditions in EVs than in traditional combustion engine transportation.

3.5 2D materials based prototypes for tribological applications

There are different global companies taking the 2D materials science and engineering to reliable technological applications and products currently, which come from a long-term development for meeting very specific targets in a reliable way. Considering that vehicles are composed of thousands of components that operate systematically for achieving the highest performance, some of those 2D materials based products (>TRL 3) are already being proved and implemented in modern ICEVs and Hybrid vehicles with their performance to some extent. For example, in 2013, a consortium conformed by European companies, surface coating technology providers and engine manufacturers developed and proved functionalised diamond nanoparticles and their dispersion in a metal matrix, novel electroplating processes, plasma electrolytic oxidation, metal doped diamond-like carbon coatings (DLC) and appropriate materials for pistons and piston rings from internal combustion engines. They demonstrated that doping diamond-like carbon coatings with silicon and wolfram was able to obtain coatings that can tolerate higher temperatures, reduced friction and wear of the engine, also allowing significant reduction of the cylinder operating temperature. The implementation of this product was expected to create a significant market potential for the consortium, targeting an initial potential market of € 650 million [101]. Other example, is the product launched this year by Graphene-XT (a EU-backed company) that is a graphene-based lubricating oil for high-performance ICEVs and motorcycles. Through extensive field tests, the researchers confirmed that adding graphene makes the oil more stable and helps to reduce friction, heat and wear between engine parts, as previously found in laboratory [102].

Within the advent of the EV vehicles, those already commercialized products can be reassessed to demonstrate their reliable operation and efficiency under the particular conditions of EVs. This is one of the biggest challenges for companies since it involves great expenses and efforts in re-engineering and new product validation combined with scarce standards and technology for the technical evaluations.

4 Future research perspective

According to this comprehensive review, we have identified the main critical EV systems, in which nanomaterials can positively affect the performance of EVs. For instance, as EV components operate under high torque and operating speeds, generating excssive heat and accelerating processes of pitting, scuffing, and fatigue failures, the added nanomaterials must increase the thermal conductivity and specific heat capacity with the overall goal to improve the respective thermal management in the powertrain. Moreover, they help to reduce friction and wear of tribological interfaces under both unelectrified and electrified conditions. To tackle problems with excessive electrical charges accumulating within transmission systems, the utilized nanomaterials must provide an appropriate electrical conductivity to reduce the damage caused by electrical discharging across tribological interfaces. At the same time, the nanomaterials must be compatible with wiring resins and polymers involved in seals, structural components and sensors inside the motor and transmission to avoid accelerated material degradation (**Figure 10**).

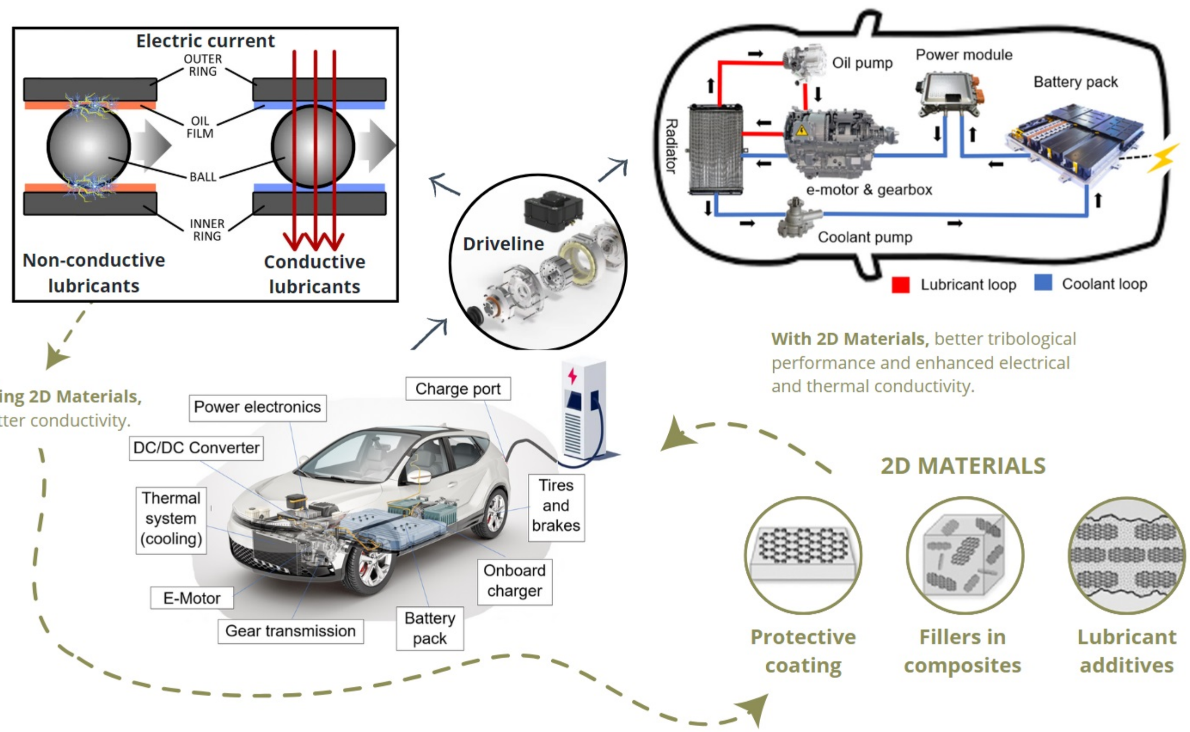

***Figure 10**. Depending on the specific requirements of the key components in an All-Electric Car, forming lubricant and coolant circuits in an integrated electrified powertrain, battery pack and power-electronics, lubricants should be electrically conductive or non-conductive. 2D materials can be used as additives in lubricants and coolants or they can be applied as coatings and composite fillers directly at the contact experiencing tribological issues.*

Bearings, supporting the rotating components of the EV motor, experience high operating speeds and elevated temperatures during operation. Consequently, insulating coatings can be applied to rolling bearings and gears to reduce and/or avoid electrical discharges at the interface. The coolants used in the battery pack and power-electronics can be exposed to electrified components, thus asking to keep or increase the dielectric strength of the coolant and promote a suitable shear-viscosity behavior even at low temperatures. In case of electrical connectors and contacts, the stable control of the flow of electricity between the battery and the electric motor while preventing short circuits or arcing between adjacent terminals is essential. This can be ensured by using coatings applied to the connectors to protect them from degradation during continuous operation and additives to keep or decrease the insulating characteristics of liquid lubricants surrounding the contacts.

Finally, as the battery adds significant weight to EVs, during acceleration and deceleration tires and brakes experience very high torque during acceleration and deceleration, leading to high friction, wear, and temperature increase, thus intensifying the need for nanomaterials helping to increase the mechanical strength of the used polymers (resins, rubber, among others) as wellas reduce friction and wear of tribological interfaces while being stable under thermal cycling.

Table 2. *Sumary of requirements and challenges for using nanomaterials for EV systems.*

EV system	Component / Fluid	Main requirements	Challenge	Potential 2D materials	Reason / references
Motor / transmission	Lubricant	Moderate to high electrical conductivity.	The added nanomaterials must provide suitable electrical conductivity to the lubricant in order to reduce the damage caused by electrical discharges at the tribological interfaces.	Graphene, graphene-based materials, MXenes	Excessive electrical charges accumulate within transmission system.
		Excellent tribological properties under unelectrified and electrified conditions.	The added nanomaterials must help to reduce friction and wear of tribological interfaces under both unelectrified and electrified conditions.		EV components operate under high torque and operating speeds, accelerating the processes of pitting, scuffing, and fatigue failures.
		High thermal conductivity and specific heat.	The added nanomaterials must increase thermal conductivity and specific heat capacity for improving thermal management in the powertrain.		High operating speeds lead to elevated temperature within EV components.
		Good compatibility with polymers, elastomers and resins.	The added nanomaterials must be compatible (to avoid material degradation)		The lubricants are often used in contact with polymeric surfaces.

			with wiring resins and polymers involved in seals, structural components and sensors inside the motor and transmission.		
		Copper corrosion inhibition	The added nanomaterials must help to inhibit copper corrosion from windings.		Exposure to electrical components is possible during operation.
		High thermal stability.	The added nanomaterials must resist higher temperatures than common organic additives like ZDDPs.		The lubricant experiences a wide range of temperatures during operation.
		Low viscosity and appropriate rheological behavior.	The nanomaterials added must promote a suitable shear-viscosity behavior.		Low viscosity oils must be considered for lowering shear losses.
	Rolling bearings and gears	High wear resistance and low friction under unelectrified and electrified conditions.	Insulating coatings must be applied to rolling bearings and gears to reduce or avoid electrical discharges at the interface.	TMDs, BN, MXenes	Bearings, supporting the rotating components of the EV motor, experience high operating speeds and elevated temperatures during operation.
Battery pack and power-electronics	Coolant	High dielectric strength under different temperatures.	The nanomaterials must help to keep or increase dielectric strength of the coolant at	MXenes, graphene, silicene	The coolant can be exposed to electrified components.

			different temperatures.		
		Good compatibility with polymers, elastomers and resins.	The added nanomaterials must be compatible (to avoid material degradation) with wiring resins and polymers involved in seals, structural components and sensors inside the motor and transmission.		Battery cooling systems contain polymer-based components.
		Ultra-low viscosity	Low viscosity fluids must be considered for lowering shear and pumping losses. The nanomaterials added must promote a suitable shear-viscosity behavior even at low temperatures.		The proper functioning of the systems requires constant pumping of the coolant which can potentially clog the passages.
		High thermal conductivity and specific heat.	The added nanomaterials must increase thermal conductivity and specific heat capacity for improving thermal management in the battery pack.		The use of lithium-ion batteries, which power most EVs, generates high amounts of heat, especially upon fast charging and discharging.
		High boiling point	The added nanomaterials must resist high temperatures.		During exposure to high temperatures, the coolant tends to degrade with time

					and eventually breaks down.
		Low freezing point	The added nanomaterials must help to keep a low freezing point.		The coolant should sustain its characteristics under various temperature conditions.
Electrical connectors and contacts	Coating	High electrical conductivity	Conductive coatings must be applied to sustain stable electrical conductivity.	Graphene, graphene-based nanomaterials, MXenes	Stable control of the flow of electricity between the battery and the electric motor is essential for stable and reliable operation
		High wear resistance and low friction	Coatings must be applied to the connectors to protect them from degradation during continuous operation.		Under various application conditions, the connectors can experience friction, wear, and corrosion, which can lead to an increased electrical resistance of the contacts.
		Corrosion inhibition	The coatings must work as a protective barrier preventing adsorption of moisture and contamination.		Corrosion of metal components in connectors negatively affects the reliability of the electrical systems.
	Lubricant	Low electrical conductivity	The added nanomaterials must help to keep or decrease the insulating characteristics of liquid lubricants.	BN, TMDs, MXenes	Preventing short circuits or arcing between adjacent terminals is needed.
		Excellent tribological properties	The added nanomaterials must help to reduce friction and wear of tribological interfaces.		Adhesion and corrosion in the contacts can cause component failure.

		High thermal conductivity	The added nanomaterials must increase thermal conductivity of base lubricants.		These components generate significant heat during operation.
Tires and brakes	Composites in tires	High load caring capacity	The added nanomaterials should increase mechanical strength of resins.	Graphene, MXenes.	Battery adds significant weight to the EVs.
		High wear resistance	The added nanomaterials added must help to reduce friction and wear of tribological interfaces.		During operation, tires experience high friction and wear events.
	Composites in brakes	High wear resistance	The added nanomaterials added must help to reduce friction and wear of tribological interfaces.	Graphene, BN, TMDs, MXenes	EVs experience very high torque during acceleration and deceleration.
		High thermal stability	The added nanomaterials must be stable under thermal cycling .		Brakes can experience high temperature increase during operation.
		Excellent corrosion resistance	The added nanomaterials added must help to prevent the corrosion-induced degradation.		EVs can operate under different environment conditions potentially exposing components to moisture and dust accumullation

Based on the performed concise analysis, it became evident that EVs' thermal, electrical, and tribological challenges are wide and intertwined in many ways rendering a single or straightforward solution impossible. In such a complex and harsh operating environment, we anticipate that the design and development of new materials offering multi-functionality, such as superior thermal, electrical, and tribological properties, should be favorably considered for future EV applications. In this regard, prior fundamental research on 2D materials has demonstrated their outstanding electrical, thermal and tribological performance resulting from their intriguing structure-property relationship. Specifically, their highly protective nature against corrosion and wear, while at the same time providing much-reduced friction to further enhance efficiency, makes them an excellent fit to improve and design the next EV generation. While the fundamental base for using 2D materials in EVs has already been laid, more application-related research under realistic EV working conditions is necessary to further understand and optimize the use of 2D materials in this upcoming field. In this context, more specialized laboratory equipment, as well as component- and system-level test rigs, need to be developed to adequately mimic the coupled electrical and tribological stresses of EVs.

From a materials point of view, the class of 2D materials and their modifications and functionalizations are continuously growing due to novel and improved synthesis approaches. While unified by their lamellar 2D structure, the family of 2D materials offers a notable chemical diversity, enabling the proper material selection depending on the application-related needs and requirements. In this regard, graphene, TMDC, and their derivatives resemble the most prominent members of the 2D family, combining many attractive thermal, electrical, and tribological features. Hence, their true potential should be demonstrated immediately under conditions that are very typical of high-performance EVs. Apart from the graphene- and TMDC-family, the newly emerging class of MXenes (early transition metal carbides, nitrides, and carbonitrides) should be given special attention due to their outstanding wear performance and excellent electrical conductivity, thus rendering them promising candidates to be applied in EVs. Here, modeling and simulation approaches can help accelerate the discoveries and optimizations of new material combinations with targeted characteristics relevant to specific EV components. In recent years, simulation methods have played a key role in understanding the properties of 2D materials and projecting their performance in various environments and testing conditions [118]. With the recent advancements in machine learning and big data analysis, computer modeling approaches will help the scientific community establish a theoretical understanding of the behavior of 2D materials and offer the advantage of reduced computational costs and shorter timelines compared to conventional experimental testing.

In addition to the availability of different structures and chemistries, what makes 2D materials attractive is that they can be applied for protective purposes (friction, wear, and corrosion) under EV conditions in different ways. 2D materials can be used as additives in EV oils and greases, as protective solid lubricant coatings in dry-running components, or as fillers in composite parts of the EV assembly. While their use as lubricant additives is probably the most mature and straightforward stage, special attention must be paid to the compatibility of the used 2D material with the respective lubricant. Here, the primary function of 2D materials is to keep friction and wear under control at high loads and torque, as well as start-stop conditions, when liquid lubricant alone fails to protect surfaces and reduce friction. In this regard, only the compositions with long-term dispersion stability and no pronounced sedimentation and/or agglomeration of the 2D materials under electrified conditions can beneficially improve the resulting tribological performance and energy efficiency in EVs. Notably, research efforts are dedicated to the chemical functionalization of 2D materials to precisely manipulate their surface chemistry. It will be extremely desirable to functionalize 2D materials at molecular levels so that they literally become a part of the liquid carrier oils without physical separation or agglomeration; this would supply both lubricants to the contact interfaces simultaneously to ensure the most effective and long-lasting protection against wear and other types of degradations. We hypothesize that this is an interesting approach to manipulate and design 2D materials with excellent lubricant compatibility, thus notably boosting their success as lubricant additives under EV conditions.

Concerning the use of 2D materials as solid lubricant coatings and fillers in composites under EV conditions, these approaches are largely underexplored both from a fundamental point and from an applied perspective. However, considering the existing state-of-the-art regarding 2D material efficiency as solid lubricants and fillers under normal tribological conditions without electrification, the immense potential of these application strategies under EV conditions becomes evident. Related to the use of solid lubricant coatings, the coating-substrate adhesion and interface are essential to guarantee their successful application towards improved low friction and low wear conditions. In terms of composites, the filler-matrix interface is crucial to enable the respective stress transfer and to improve the electrical conductivity. Regarding both aspects (coating-substrate and filler-matrix interfaces), chemical functionalization can be a game changer to smoothen and improve interfacial characteristics.

From an economic point of view, 2D materials used to be cost-prohibitive, but because of the recent advances in synthesis and bulk manufacturing processes, their cost has come down considerably and continues to decrease. It should be noted that 2D materials, due to their layered structure, usually require a very minimal amount to work efficiently. With the use of such materials in various EV fluids, it could be possible to achieve fill-for-life type performance improvements. Specifically, combined liquid-solid lubrication provided by these fluids can keep future EVs going without any significant tribological breakdowns or failures.

From a sustainability point of view, since 2D materials exhibit exceptional electrical and thermal properties, their use to improve heat management and promote energy efficiency of electrical systems will be crucial for reducing power consumption and greenhouse gas emissions. At the same time, the unique characteristics of 2D materials and their combinations enable innovative design of more efficient battery storages and advanced sensors, leading to safer and longer-lasting functional components and reducing the need for frequent repairs and replacements. Here, designing the strategies for recycling and reusing 2D materials could potentially accelerate their sustainable application.

Finally, according to the findings in this review, the improvement of tribological EV systems to get the highest overall EV performance through 2D materials can be significantly attained in the coming years if the major challenges are solved. For now, we can assume the great impact these solutions for contemporary EVs (land vehicles) could bring to our lives regarding service quality or driving performance in the coming years. However, thinking of the next EV generation (aerial passenger vehicles or drones and electric flights) coming in the following decades, any malfunction or loss of performance in the powertrain tribological components and EV fluids can represent not only a problem of friction or wear, causing more heat or decreasing durability and efficiency, but a significant safety concern for passengers. Hence, the progress and optimization of EV powertrain technology must be a topic of ongoing research.

Credit author statement

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