

Mitigating electrical discharge damage in EV bearings: A critical review from inverter design to bio-based greases

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Abstract: Research on electric vehicles (EVs) has gained increasing attention due to the global transition toward cleaner and more sustainable transportation. However, ensuring the efficiency,

reliability and long-term durability of EV drivetrains remains a major challenge. In EV bearings, inverter-induced shaft voltage and bearing currents can trigger electrical discharge across the lubricating film when the local electric field exceeds the dielectric strength of the grease. These discharge events can result in surface damage and lubricant degradation, leading to premature bearing failure and affecting the motor reliability. This review critically discusses the mechanisms of electrical discharge damage in EV bearings and reviews recent mitigation strategies including motor and inverter design optimisation, bearing materials and surface engineering, and specialised lubricant formulation. This review further discusses the development of bio-based greases for EV bearing applications, including formulation requirements, bio-based oil selection, thickener system design and additive strategies. The key challenge is to balance conductivity, dielectric stability, tribofilm formation, and grease durability under coupled mechanical, thermal, and electrical stresses. Overall, this review provides a framework for developing high-performance bio-based EV bearing greases that can mitigate electrical discharge damage while supporting sustainable lubrication technologies.

Keywords: electric vehicle, bearing, bio-based grease, electrical discharge damage, mitigation strategy

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1 Introduction

The electric vehicle (EV) industry has expanded rapidly in response to the urgent need to reduce greenhouse gas (GHG) emissions and decarbonise the transportation sector [1]. GHG emissions of EVs have been reported to be 17–30 % lower than those of internal combustion engine (ICE) vehicles [2]. The transition from ICE vehicles to electrified powertrains has also created new technical demands for efficiency, durability and reliability in EV components. Because a substantial proportion of vehicle energy can be lost through frictional processes, tribological optimisation has become essential for improving the energy efficiency and component lifetime of EVs [3]. In EV traction motors, bearing reliability is particularly important because premature bearing failure can contribute significantly to motor failure [4]. Among the major bearing failure mechanisms, electrical discharge damage is especially critical because it is directly associated with inverter-induced shaft voltage and bearing currents [5].

Electrical discharge occurs when the shaft voltage across the bearing exceeds the breakdown voltage of the lubricant film, causing the release of the stored electrical energy through the lubricated contact [4, 6]. Localised discharge events can generate extremely high temperatures, potentially exceed the melting point of bearing raceway materials and produce surface defects such as pitting, frosting and fluting [1, 7]. Previous studies have shown a close relationship between the lubricant film thickness and electrical discharge behaviour, where discharge tends to occur preferentially in regions of minimum film thickness because the breakdown voltage of a thinner film is lower, making the film more prone to breakdown [8–10]. These discharge events not only damage bearing surfaces but also accelerate grease degradation, oxidation and structural breakdown, which may deteriorate noise, vibration and harshness (NVH) performance and ultimately lead to premature bearing failure [4, 11].

In response to these issues, various mitigation techniques have been explored, including motor and inverter design optimisation, bearing materials and surface coatings, and specialised lubricant formulation [5, 12–14]. Although motor and inverter design optimisation, insulated bearings, and

coatings can reduce bearing currents, these approaches do not directly control the lubricant film where charge accumulation, dielectric breakdown and tribochemical reactions occur. Therefore, extending EV bearing reliability requires an integrated electro-tribological approach that considers the coupled effects of electrical stresses, mechanical load, lubricant chemistry and surface reactions [15]. Recent studies have incorporated nanoparticles and ionic liquids (IL) into greases to modify the grease conductivity and regulate charge transport across the lubricated contact [16–19]. However, the electrical properties of the grease are strongly dependent on the additive type, morphology, concentration, and dispersion stability [1, 11, 16]. Excessive conductive additive loading may promote unwanted leakage current or discharge outside the contact region, whereas overly insulating grease may allow charge accumulation and high-energy breakdown [9, 20]. Thus, achieving an optimum balance between conductivity, resistivity, dielectric strength, and tribological performance remain a key formulation challenge.

The development of bio-based greases has gained increasing attention due to environmental concerns, reduced dependence on petroleum-derived lubricants and the growing interest in renewable or waste-derived feedstocks [21, 22]. Recent studies suggest that incorporating nanoparticles into bio-based greases can improve electro-tribological performance [2, 18, 23]. This opens avenues for designing grease formulations that combine sustainability with functional performance for EV bearing applications. However, bio-based grease formulation under electrified conditions involves a complex conductivity–stability trade-off. Bio-based oil polarity, thickener microstructure, additive dispersion, and electrical response must be considered simultaneously to ensure long-term performance under realistic EV bearing conditions [20]. Addressing these challenges requires a mechanistic framework that integrates lubricant chemistry, thickener structure and additive interactions under coupled mechanical, thermal and electrical stresses.

This review aims to provide a critical framework for the design of bio-based greases for EV bearing applications under electrified operating conditions. **Fig. 1** illustrates the overall workflow of this

review. Section 2 discusses the mechanisms of electrical discharge damage in EV bearings, including the discharge behaviour in lubricated contacts, influencing parameters, surface damage mechanisms and lubrication-related failures. Section 3 critically evaluates the current mitigation strategies, including motor and inverter design optimisation, bearing materials and surface engineering, and lubrication-based approaches. Section 4 discusses the development of bio-based greases for EV bearings, with emphasis on the formulation requirements, bio-based oil selection, thickener system design, and additive strategies. Finally, Section 5 summarises the key conclusions for the development of high-performance bio-based greases that can balance physicochemical, tribological, and electrical performance in EV bearing environments.

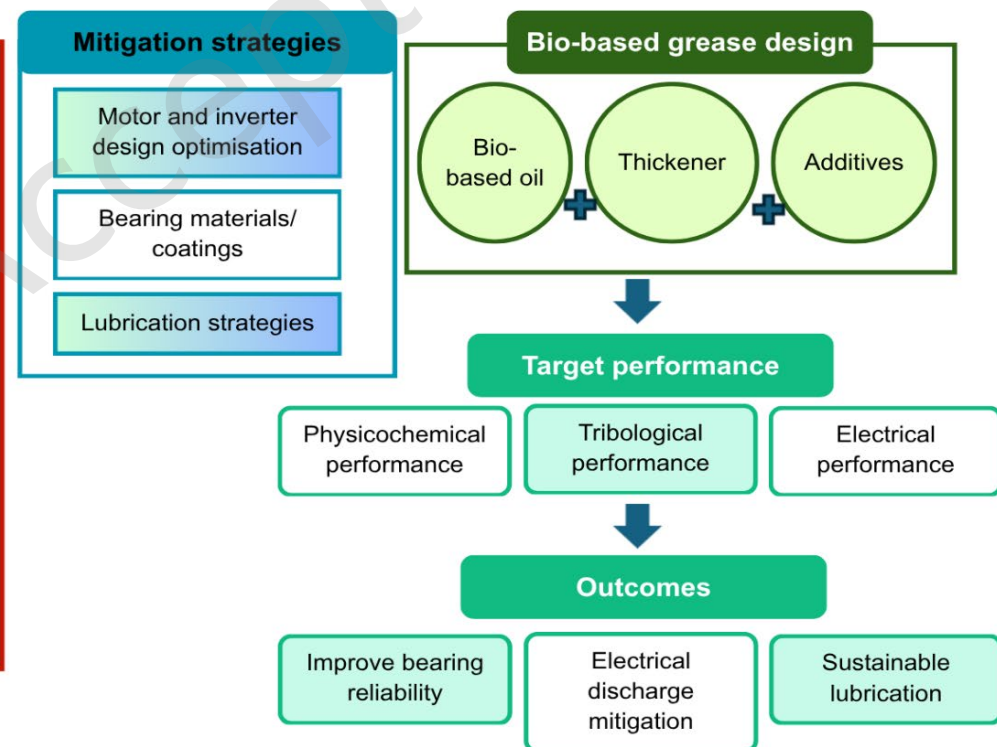
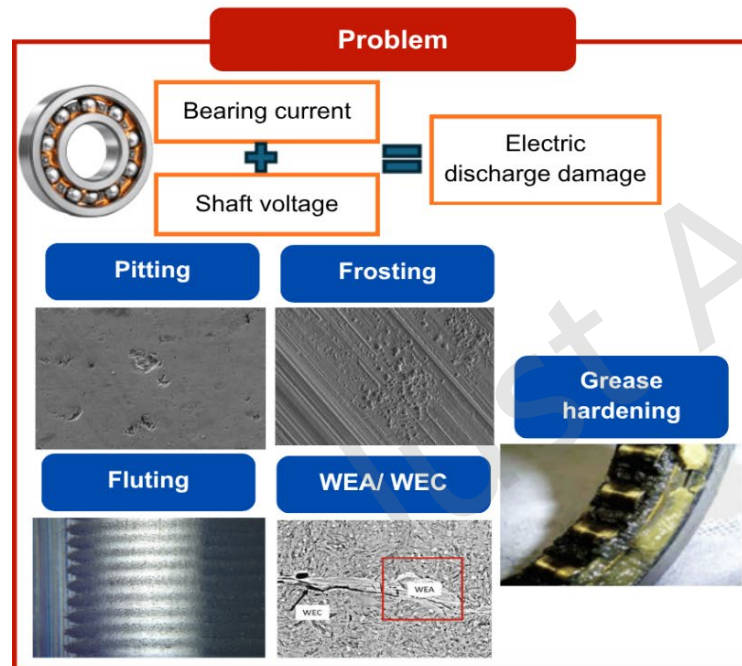
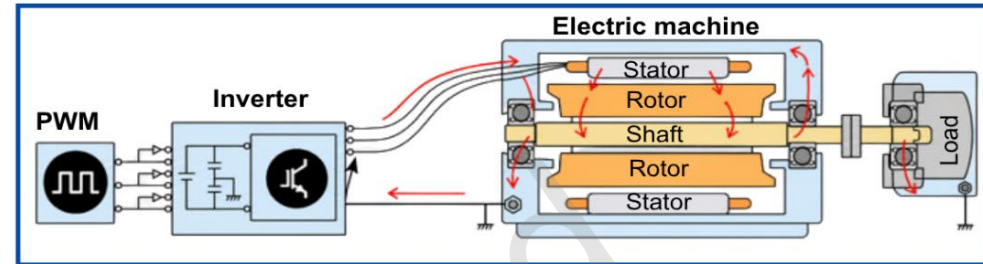
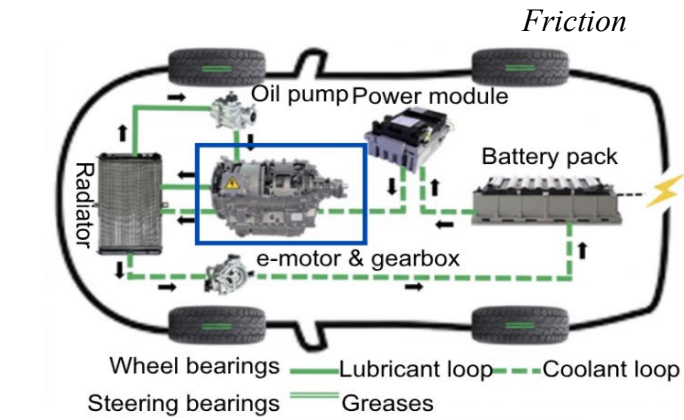


Fig. 1 Workflow of the review [24–25].

2 Mechanisms of electrical discharge damage in EV bearings

2.1 Electrical discharge mechanisms in lubricated contacts

In inverter-fed electric motors, pulse width modulation (PWM) inverters are particularly used for motor speed and torque control. However, their elevated switching frequency generates high-frequency common-mode voltages (CMV) [2, 5]. The CMV is the electrical potential difference between the three-phase winding neutral point and the reference ground [26]. The use of wide bandgap semiconductors (silicon carbide (SiC) and gallium nitride (GaN)) and higher DC-link voltages will produce high-frequency variations in CMV, which couple through motor parasitic capacitances to generate shaft voltages and introducing high-frequency bearing currents [27–28]. The shaft voltage is the potential difference induced between the rotating shaft and the grounded motor casing [29]. The bearing currents can be classified into four categories, (see **Table 1** and **Fig. 2**):

- a) Electrical discharge machining (EDM) current: The lubricating film within the bearing initially acts as an insulating layer, allowing charge accumulation on the bearing capacitance. However, when the shaft voltage across the bearing exceeds the lubricant film's breakdown voltage, sudden electrical discharge occurs and releasing the stored electrical energy as stray current arcing across the lubricated contact [4, 6]. The current at this time is called EDM bearing current, where it flows from the shaft to the inner race of the bearing, then via the rollers to the outer ring, and finally to the frame [30–31]. The discharge generates localised high temperatures on the bearing surface, causing the material to melt and resulting in surface damage [5]. This current is the most destructive type and the primary cause of electrical bearing damage that can lead to premature bearing failure; therefore, mitigation strategies are critical to enhancing motor reliability and lifespan.
- b) High-frequency circulating bearing currents: These currents are generated by the high dv/dt common-mode currents flowing to ground via the stator winding-to-frame capacitance. This common-mode current induces a high-frequency circular magnetic flux around the shaft,

inducing high-frequency shaft voltage. If the induced shaft voltage is high enough to penetrate the insulating lubricating film and destroy its insulating properties, it causes the high-frequency circulating current flow in a closed loop (flowing through shaft, bearings, and frame) [28, 32–33].

- c) Capacitive (dv/dt) bearing currents: These currents caused by the displacement current through the bearing's parasitic capacitance between the stator windings and rotor. It flows from the stator winding to the rotor, through the bearing, and to the motor frame. It increases due to the high-switching speed and the high-switching frequencies [26, 31]. This current is generally very small amplitude, and is not harmful to the bearing raceway. However, continuous exposure deteriorates the bearing lubricant through carbonization and electrical conduction [26–27].
- d) Rotor-to-ground bearing currents: These currents arise when the motor has poor grounding system that will increase the potential of the stator casing. This will cause the rotor core grounding impedance decrease and the stator casing grounding impedance increase, thereby generating current. This current will then flow through the stator casing, across the motor bearing, down to the rotor shaft, and finally exit through the driven load's bearing to ground. This current is highly dangerous as it can generate heat and electromagnetic fields on the bearing and surrounding components, causing damage both motor's bearings and shaft [27, 30–31].

Table 1 Classification of bearing current types in EV motor

Current type	Physical origin	Conduction path	Key characteristic	Reference
Electrical discharge machining (EDM) currents	Local breakdown of the lubricating film when the shaft voltage exceeds the film breakdown voltage	Shaft – inner race – rolling elements – outer ring – frame	Damped high-frequency discharge impulse	[30–31]
Circulating bearing currents	Induced by magnetic field in inverter-driven motors	Shaft – rolling elements – front bearing – motor frame – rear bearing – back to shaft	Continuous loop current	[28, 32–33]
Capacitive (dv/dt) bearing currents	Caused by displacement current through the bearing's parasitic capacitance between stator and rotor	Stator winding – rotor – bearing – motor frame	Displacement current, occurs at dv/dt events	[26–27, 31]
Rotor-to-ground bearing currents	Low-impedance rotor-to-ground path while raising stator casing impedance	Stator casing – motor bearing – rotor shaft – grounding point	Current bypassing the frame return	[27, 30–31]

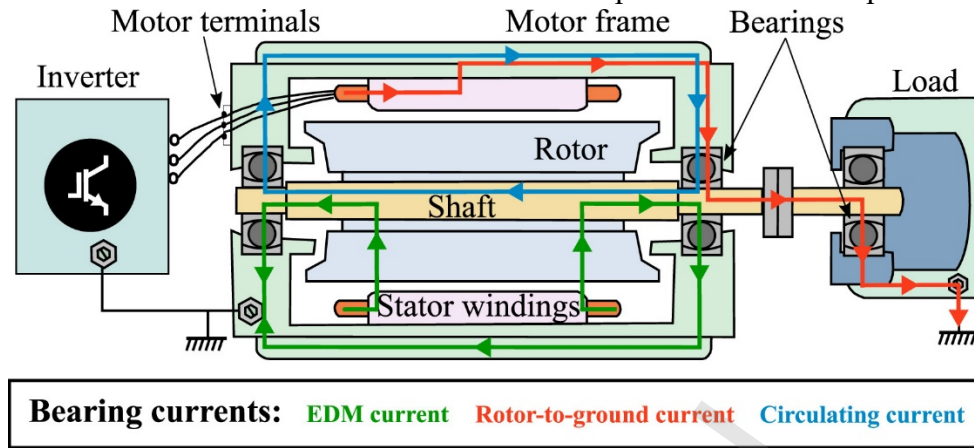


Fig. 2 Schematic representation of the bearing current. Reproduced from [24].

2.2 Parameters influencing electrical discharge behaviour

Electrical discharge behaviour in lubricated contacts is governed by a coupled thermo–electro–tribological system in which electrical, lubrication and mechanical parameters interact. Among these, the bearing voltage amplitude is decisive. Plazenet et al. [34] showed that the inverter-fed motor greases transition from capacitive to resistive modes depending on the applied voltage. At low voltages (2–5 V), the lubricant behaves capacitively, producing frequent but low-energy discharges with minimal wear. At approximately 10 V, discharge activity and energy peak (25–110 nJ per event), the lubricant shifts to a resistive mode, with fewer but sporadic high-energy discharges that cause severe localised damage. Elevated current further accelerates surface damage by raising contact temperature [30–31]. Weicker et al. [37] confirmed that DC currents induce more severe electrical damage than AC currents.

Jonjo et al. [1] reproduced the same three-state sequence at bearing level using a DC power supply step from 0 to 5 V in increment of 0.1 V, and summarised the changes in the electrical behaviour of the lubricant with applied voltage into capacitive, EDM, and resistive states, as shown in **Fig. 3**. Capacitive state occurred at low voltage amplitude where the lubricant acted as an insulator (capacitor), allowing charge accumulation without significant current flow. During this state, voltage built up smoothly and no electrical discharges occurred. The EDM region began with a further increase in the voltage amplitude where the lubricant started to “breaks” or it reached the dielectric strength of the

lubricant. During this state, small spikes in current were observed where electrical discharges began to appear, and a spark occurred. Further increase in the voltage amplitude further increased the intensity of electrical discharges, where a sudden drop in voltage and spikes in current was observed and the lubricant repeatedly broke down. The current creates huge amounts of heat on the bearing's surface and causes more severe material damage [5]. Resistive state occurred at a very high voltage amplitude where the lubricant lost its insulating capabilities due to the occurrence of the metallic contacts between the asperities of the contact surfaces [38]. During this state, no voltage built up with continuous current flows where intermittent discharge was no longer observed.

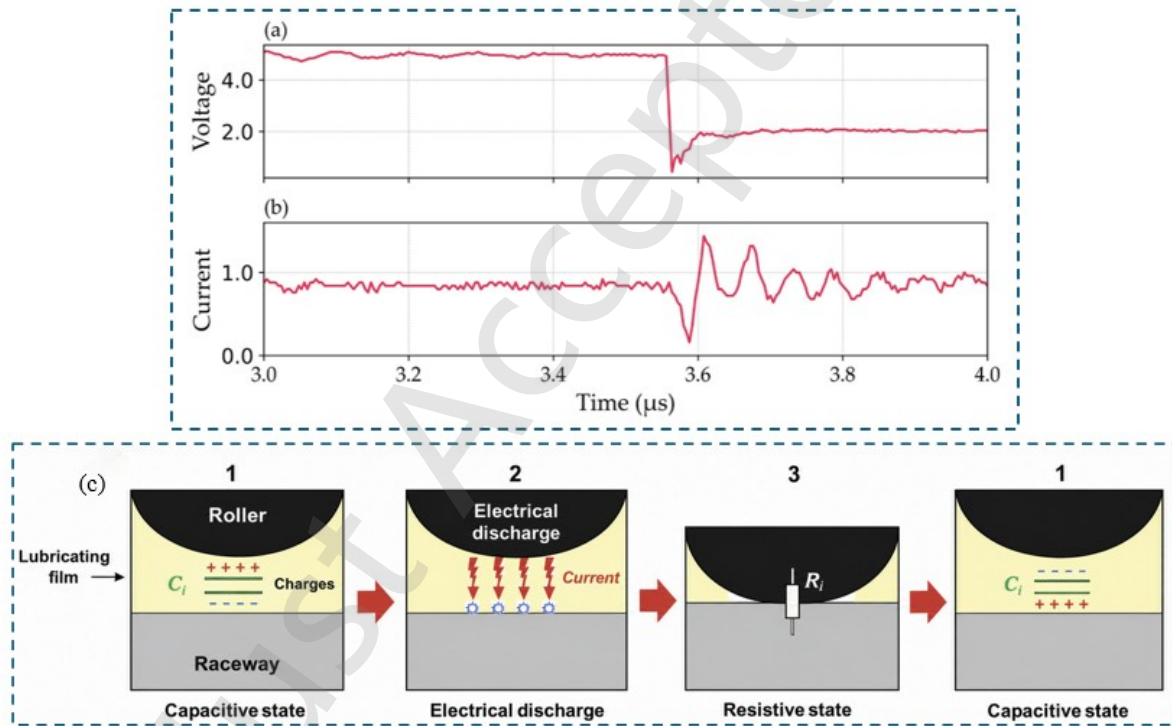


Fig. 3 Electrical discharge behaviour of grease in terms of (a) voltage with time, (b) current with time [1], and (c) corresponding behaviour. Reproduced from [5].

The intrinsic electrical properties of the lubricant also play a decisive role. Dielectric strength, expressed in V/m, defines the maximum field the film can withstand before losing its insulation, while breakdown voltage depends on film thickness, the voltage waveform, and local defects. Liu et al. [39] reported a direct correlation between the critical voltage and dielectric breakdown voltages, increasing discharge frequency and surface damage risk. Localised heating during discharge accelerates oxidation

and decomposition of base oil and additives, producing by-products with inferior dielectric properties. These degradation products can form partial conductive pathways within the grease matrix, progressively altering its electrical response from predominantly capacitive behaviour to resistive conduction.

Previous studies have consistently shown a strong dependence of electrical discharge activity on the lubricating film thickness. Discharges occur preferentially in regions of minimum film thickness, where reduced separation lowers breakdown voltage and increases susceptibility to discharge [8–10]. Esmaeli et al. [8] observed that discharge frequency rises as film thickness decreases, with additional influence from temperature, load, and sliding speed. Li et al. [9] showed that transitions from mixed to full-film lubrication increase film thickness, shifting the electrical state from resistive to capacitive. Guo et al. [10] confirmed that discharge damage in EV bearings concentrates in thin-film regions of the elastohydrodynamic lubrication (EHL) contact zone. In these areas, asperity contact promotes intense heating and larger discharges, while thicker films act as insulating barriers, producing more frequent but lower-energy discharges. This results in non-uniform wear pattern with the presence of numerous small pits in thin-film zones and fewer but larger pits in thicker film areas [17].

Operating conditions further modulate discharge behaviour. Jammoul et al. [40] showed a direct correlation between EDM activity and rotational speed, linked to transitions into fluid lubrication regimes where insulating films form. Discharge currents were lower under high loads because thinner films promoted conductive contact. Discharge activity increased with switching frequency up to ~20 kHz before declining, with the most severe condition occurring under unloaded, high-speed, and medium switching-frequency conditions. Similarly, Kai et al. [41] reported that higher rotational speed and voltage accelerated EDM activity, while the resulting temperature rise degraded grease and reduced its insulating capability. Collectively, these findings highlight that electrical discharge behaviour in lubricated contacts is not governed by a single parameter, but rather by a coupled thermo–

electro-tribological system. Systematic quantification of these combined effects is essential to guide effective mitigation strategies and extend bearing life in EV applications.

2.3 Damage modes and failure mechanisms in EV bearings

2.3.1 Surface damage mechanisms

In EV bearings, the predominant surface damage modes include pitting, frosting, fluting, and white etching areas (WEAs) [1, 38], as shown in **Fig. 4**. During electrical discharge events at bearing contacts, a sequence of phenomena governs the formation of electrical pitting, as illustrated in **Fig. 5** [43]. Pitting damage initiates when charge accumulates at the asperity tips, producing localised electrical discharges [11, 40]. Electrons emitted towards the substrate through regions of intermediate lubricating film thickness cause localised asperity heating, raising the temperature beyond the melting point of the bearing raceway material [7]. As discharge energy intensifies, explosive arc propagation occurs, accompanied by molten material transfer between the contacting surfaces. This process generates suspended debris within the contact zone, and repeated discharge combined with material removal leads to the development of electrical pits. The severity and size of the pits increase with higher discharge voltage and current [45]. These pits typically appear as deep, irregularly shaped, layered craters enriched with carbon and oxygen, indicating grease degradation and tribochemical surface damage [16, 39]. Over time, frequent electrical discharges produce progressively larger craters, resulting in severe electrical pitting [46]. The intensity and frequency of discharge events are strongly dependent on the lubricant film thickness, where thinner films promote higher discharge densities and consequently greater pitting density [47].

The escalation of discharge behaviour drives the progression of electrical damage from initial pitting to frosting [48]. Frosting manifests as a grey, matte, satin-like surface finish or surface discolouration across the raceways, produced by continuous electrical exposure and intensified mechanical shear that increase the pit density and uniformly roughen the surface [39, 45]. During the EDM voltage application, the thin lubricating film repeatedly breaks down and the lubricant is decomposed to form

carbonaceous residues and sodium on the raceways surface, thereby accelerating the mechanical abrasive wear mechanism and increasing the surface roughness [2]. The hardness of the breakdown surface decreases with the voltage amplitude, which is due to the competition between friction-induced hardening and current-induced softening on the bearing surface [41]. The periodic discharge behaviour associated with the voltage characteristics within the bearing makes the frosting damage evolve to fluting damage [5].

Fluting damage is characterised by the stripped, washboard-like pattern of alternating bright and dark bands on bearing raceways [12, 46]. Shutian et al. [48] extensively observed the evolution of electrical discharge damage on bearings, from pitting to widespread frosting and then to severe fluting, through real-time monitoring. They revealed that bearing voltage characteristics were dynamic and time-dependent. Over time, lubricant degradation weakened its dielectric properties and reduced the lubricant's insulating ability, which accelerated the electrical discharge behaviour. The lubricating film underwent a destruction and reconstruction cycle, resulting in an alternating morphology (bright and dark stripes) [45]. The bright stripe was caused by pitting deformation, whereas the dark stripe was caused by mechanical deformation, indicating severe electro-corrosion damage, lower oxidation, greater roughness, deeper depth, and low hardness [5, 46–47]. Weicker et al. [37] confirmed that DC current made the bearings surface more prone to fluting than frosting damage compared with AC current. This was because DC current generated highest temperature rise at the surface contact [36]. In addition, shaft voltage breakdown accelerated grease ageing, decomposition, and oxidation [51]. Safdarzadeh et al. [52] confirmed the formation of decomposed products (iron oxide and iron carbide), resulting in three-body abrasion [53]. The increase in iron particles in the form of wear debris and differences in surface roughness resulted in abnormal vibration and noise [5, 37, 42, 54].

White etching areas (WEAs) and white etching cracks (WECs) induce premature bearing failures, which generally reduce the L_{10} life (bearing life) by 5–20 % [8]. WEAs are subsurface microstructural alterations that can lead to cracking or flaking of bearing raceways and appear white under an optical

microscope after etching [38, 50]. WEAs are primarily composed of nanocrystalline body-centred cubic (BCC) ferrite with a grain size of 10–300 nm and often have higher hardness than the matrix by 30–50 % [30, 50]. Nikolic et al. [56] confirmed that WEAs consisted of small grains with sizes smaller than 30 nm in the bearing steel and that the WEAs were controlled by severe plastic deformation and recrystallisation of martensite into nanocrystalline ferrite. The microstructural alterations started with the clustering of carbides and form coarse carbides due to severe plastic strain and lubricant decomposition. The coarse carbides then began to deform and finally dissolved into the matrix [57]. The cracks growth started in areas of altered microstructure and passed through or along the white structure, known as WECs [58].

WEAs/WECs are triggered by electrical current, operating conditions, lubricant formulation, and hydrogen [30, 54–55], where hydrogen is the main driver [57]. Possible sources of hydrogen are lubricant decomposition, additives, or operating environments [55]. The decomposition of lubricant under sliding contact conditions occurs due to water contamination, surface cracks, and the general corrosion phenomenon [61]. Bai et al. [62] concluded that electrical current accelerated lubricant degradation with more than a 50-fold increase in free radical formation as well as promoting the increment of diffusible hydrogen content by 500 %. This phenomenon quickened the microstructural alterations (WEAs formation). Sanchez et al. [35] found that the additive elements could also accelerate the formation of WECs. They observed that carbon, zinc, phosphorus, and sulfur in the lubricant produced rougher, thinner tribofilms that may increase frictional forces, thereby facilitating the diffusion of hydrogen into the steel. Davis et al. [57] concluded that bearing materials had a greater effect on the generation of WEAs/WECs compared with lubricant under high-frequency dynamic loading. The tests were conducted using different steel materials (55SiMo8, 100Cr6, and 8 %Cr) and they found that 8 % of Cr showed different sub-surface alterations with a 33 % reduction in the average roundness of large carbides. They revealed the material effects dominated over lubricant effects. These

findings indicate that lubrication effects are an accelerating factor, though they are not a single dominant cause for WECs.

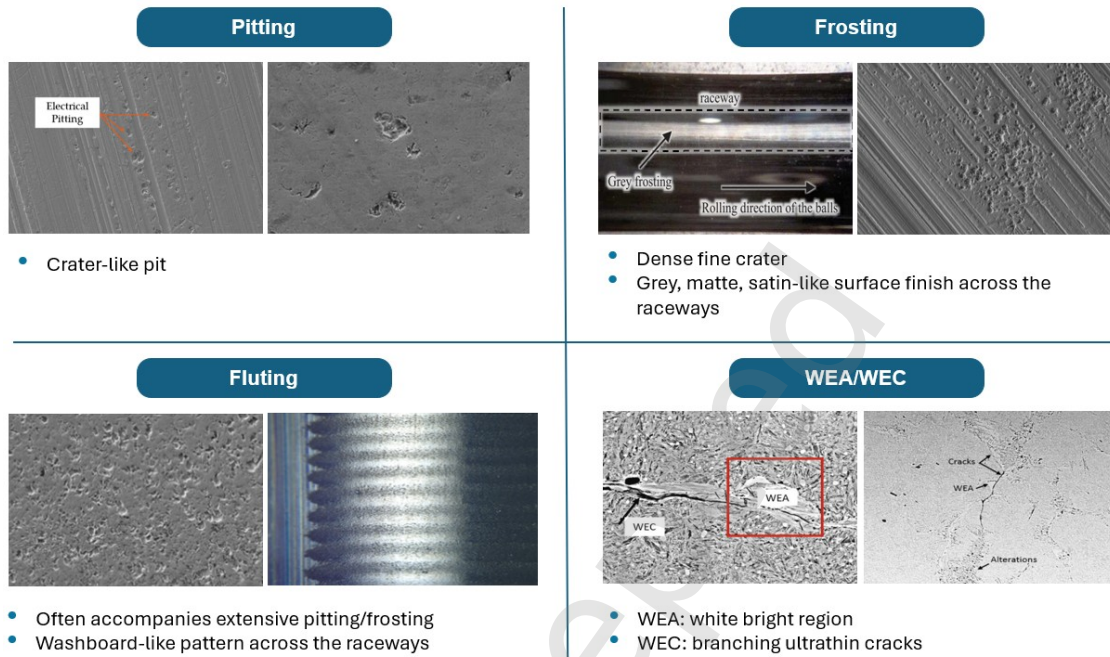


Fig. 4 Visual and key features of predominant surface damage for EV bearings [11, 32, 39, 42, 44, 51, 54].

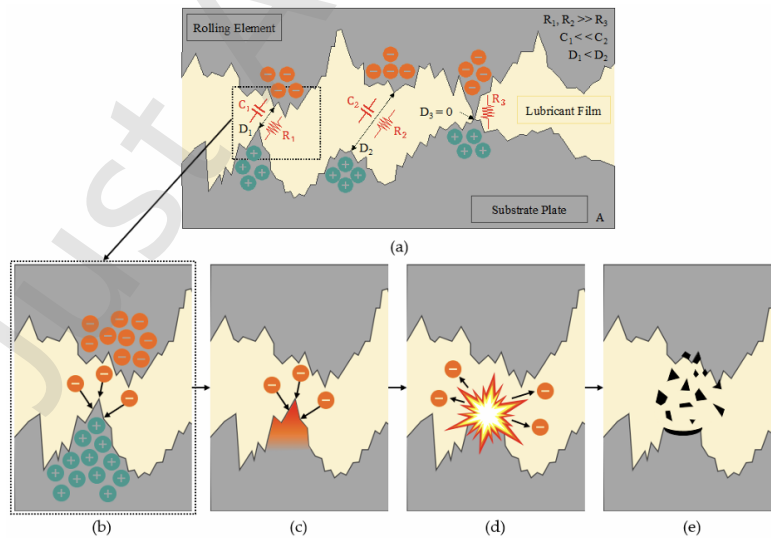


Fig. 5 Schematic illustration of electrical pitting formation mechanisms: (a) charge accumulation at the asperity tips, (b) electron emission towards the substrate through regions of intermediate film thickness, (c) localised asperity heating, (d) arc propagation with molten material transfer, and (e) formation of suspended debris and electrical pits [43].

2.3.2 Lubrication-related failures

Lubrication-related failures in EV bearings arise from three coupled pathways: (i) electrical film breakdown and EDM-induced surface damage, (ii) discharge-induced chemical degradation, and (iii) thermal-oxidative grease ageing and starvation. These processes weaken dielectric strength, shift grease behaviour from capacitive to resistive conduction [58, 64], accelerate thickener collapse and base oil depletion, ultimately leading to lubrication failure [65]. Each of these pathways is addressed by the lubrication-based mitigation strategies in Section 3.3, where every additive strategy is explicitly linked to the specific failure mode it targets.

3 Electrical discharge damage mitigation strategies

3.1 Motor and inverter design optimisation

Electrical source control mitigates electrical discharge damage by suppressing the generation, propagation, or accumulation of parasitic electrical potentials before current passes through the bearing. This approach targets the inverter, precisely controlling CMV and switching transients (dv/dt) at the output to address their root causes. CMV generated by PWM inverters are widely recognised as the dominant contributor to shaft and bearing voltages, with high-frequency CMV directly inducing bearing damage [24, 66]. The rise of CMV causes the high-frequency leakage current to flow to the ground through the motor stray capacitor, winding insulation, and radiated electromagnetic interface in a motor drive systems fed by three-phase PWM converters [66]. Consequently, advanced PWM optimisation strategies have been developed to mitigate inverter-induced electrical stresses. For example, optimised zero-CM PWM completely removed CMV in paralleled inverters while reducing circulating currents by ~34 % [67]. Nevertheless, the transition towards wide-bandgap semiconductor devices, particularly silicon carbide (SiC)-based inverters, has increased the severity of shaft voltages and bearing currents due to their substantially higher switching frequencies and steeper dv/dt characteristics. For this purpose, advanced modulation techniques such as active zero-state PWM (AZSPWM) have been developed, which can reduce bearing voltage amplitudes by ~50 % [68].

In parallel with inverter-side mitigation, shaft grounding can establish a low-impedance electrical channel between the rotor shaft and grounded motor frame, diverting discharge current away from the bearing contacts. Current grounding technologies comprise microfiber grounding rings, graphite brushes, conductive seals, and grounding bearings, where each is defined by unique contact mechanisms, frequency responses, durability profiles, and maintenance needs [69]. Several reviews conclude that grounding strategies are essential components of integrated EDM mitigation strategies, particularly as switching technologies move towards SiC or GaN devices with higher dv/dt and CMV potential [58, 71]. Graphite brushes, traditionally employed for shaft grounding, often suffer from limited space, vibrational instability, and increased wear at high rotational speeds in EV motors, and thus require regular maintenance and introduce contamination problems, which reduces their long-term effectiveness [70, 72].

Shaft grounding using microfiber rings represents a highly effective mechanical mitigation strategy against electrical discharge machining, providing a low-impedance parallel return path. Shaft grounding shunts stray currents away from the bearing raceways and maintains shaft voltages below the critical dielectric breakdown threshold of the lubricating film [65, 74–75]. Moreover, they offer low production costs, space-saving and versatile installation options, as well as relatively low friction losses for high-speed EV applications [69]. The implementation of conductive ring dedicated hybrid transmission (DHT) establishes a low-resistance pathway, which reduces the voltage value. This approach eliminates electrical discharge within the bearing, thereby preventing bearing electrical damage [5]. Conductive brushes have also been shown to be effective for current reduction, offering a common solution for mitigating bearing currents [4]. Although conductive brushes can effectively release bearing voltage, their effectiveness is limited by the intrinsic maintenance requirements and regular replacement [68]. This contrast highlights a broader engineering trade-off between electrical conductivity, durability, and maintenance requirements of contact-based grounding technologies.

Conversely, alternative grounding methodologies such as insulated bearings offer a robust, non-contact solution by increasing the dielectric strength between the inner and outer races, thereby preventing current flow through the bearing elements [24, 66]. Although this approach effectively reduces direct current passage through the bearing assembly, reported EDM current reductions are typically limited to ~40–60 %, indicating only partial mitigation effectiveness. More critically, insulated bearings do not eliminate circulating shaft currents or rotor-to-ground current pathways, potentially redirecting electrical stress toward adjacent drivetrain components, including driven-load bearings. However, their long-term efficacy depends on maintaining secure ring-shaft connections and consistently low-impedance grounding pathways. Without these, their protective capabilities diminish significantly [28, 75].

Accordingly, passive filtering technologies such as common-mode chokes, dv/dt filters, and sine-wave filters have become integral components of EV inverter systems to attenuate high-frequency electrical disturbances. Conventional common-mode chokes generally reduce common-mode current amplitudes by ~30–50 %; however, their capability to eliminate CMV entirely remains limited, resulting in only moderate suppression of the EDM phenomenon [27]. Nevertheless, properly designed common-mode filters and common-mode chokes can be tuned such that most of the CMV appears across the filter, thereby minimising neutral-point and bearing voltages and eliminating EDM spikes. Despite these benefits, passive filters introduce additional parasitic losses, increase system complexity, and reduce the overall inverter efficiency [69, 76]. The practical implementation of such comprehensive filtering solutions also faces limitations related to weight, volume, and thermal management within the constrained environments of EVs [74]. Consequently, recent research has been conducted on integrated inductor–capacitor (LC) and inductor–capacitor–inductor (LCL) filtering structures capable of simultaneously attenuating differential-mode and common-mode noise while minimising weight and volume. These integrated filters reduced weight and volume by 11.9 and 42.8%, respectively, compared with conventional discrete filters [74].

Active filtering technologies have demonstrated superior capability for mitigating CMV and bearing currents, particularly under dynamic operating conditions characterised by rapidly changing switching frequencies and load transients [30]. Studies have shown that GaN-based wide-bandgap inverters, when paired with an active damped sine-wave filter, provide a “nearly ideal” electrical environment for motor bearings, effectively neutralising the source of electrical discharge damage in bandgap inverter applications [75]. Zhang et al. [76] proposed an active common-mode filtering system that combined input and output filters to reduce electromagnetic interference (EMI) and protect bearings. Its key innovation is an edge-compensation output filter, which targets only the steep voltage transitions instead of the full waveform. This design reduces dv/dt , suppresses common-mode currents in bearings, and avoids the high losses and bulky inductors of earlier methods, providing a compact and efficient solution for inverter-fed motor drives. Tian et al. [77] presented a highly-efficient cascaded active EMI filter (AEF) architecture tailored for wide-bandgap (WBG) device-based integrated motor drives (IMD). The feedforward feedback cascade structure provides a practical, compact, and high-performance EMI suppression solution for WBG-based IMD. The integration of advanced filtering techniques, particularly those leveraging wide-bandgap devices, offers a promising pathway to simultaneously enhance motor drive efficiency and mitigate bearing electrical discharge, though further investigation into their long-term reliability and cost-effectiveness in diverse EV operational scenarios is warranted.

Stand-alone grounding strategies may be insufficient under increasingly aggressive switching environments associated with modern EVs. Emerging evidence increasingly supports the adoption of multi-layered mitigation architectures that combine optimised PWM strategies, filtering systems, and shaft-grounding technologies to achieve synergistic suppression of bearing currents. For instance, combining multi-layered PWM with filter topologies achieved a remarkable 91 % reduction in bearing currents compared with conventional space vector PWM, particularly in the low-speed region [78]. Similarly, coupling AZSPWM with CM filters reduced bearing current magnitudes to approximately

one-fourth of baseline levels in high-voltage, high-frequency EVs [68]. Such integrated approaches are particularly advantageous because residual CMV components arising from parasitic resonances or incomplete filter attenuation can still be safely diverted through dedicated shaft-grounding pathways, thereby preventing dielectric breakdown of the lubricating film. This layered mitigation philosophy reflects a broader transition from isolated countermeasures towards holistic electromagnetic compatibility-oriented drivetrain designs.

In addition, electrostatic shields between the winding and the rotor, or around the slots, reduced shaft-to-frame voltage and EDM, with design guidelines indicating strong attenuation and a minor effect on torque and losses [79]. A coated barium titanate (BTO) layer applied to the rotor increased stator-rotor capacitance, reducing the shaft voltage by 18 %. The combination of BTO layer with stator tooth wedge techniques further reduced the shaft voltage by up to 37 %. This approach was specifically proposed to mitigate EDM bearing currents without affecting the magnetic design [80]. Similarly, modifying motor design at the conceptual stage by incorporating oblique slots or optimising winding configurations could inherently reduce winding-to-rotor capacitance, thereby reducing the bearing voltage ratio and mitigating bearing currents without compromising overall machine performance [71, 84].

A novel zig-zag stator slot-opening geometry has been shown to minimise winding-to-rotor capacitance through an enhanced analytical model and finite-element validation. This approach outperformed oblique and conventional slot topologies by yielding the lowest bearing voltage ratio, thereby minimising EDM currents. In addition, this approach preserved the torque close to baseline levels with reduced ripples, although it introduced manufacturing complexities that hindered automated production [82]. The complex step of winding the coil around the teeth for zig-zag slots remains a significant manufacturing challenge, which often necessitates manual intervention or specialised robotic systems, which can substantially increase production costs and limit scalability. Due to these limitations, Lee et al. [83] proposed a novel salient stator pole-shoe structure to suppress

shaft voltage and bearing currents in permanent magnet synchronous motors, as validated by electrostatic finite element analysis. This design effectively reduced capacitive coupling between the stator windings and rotor while improving manufacturability through minimal geometric modifications. **Table 2** shows a comparative overview of various mitigation strategies via motor and inverter optimisation.

Studies in the literature consistently demonstrate that optimising motor and inverter design is highly effective to mitigate electrical discharge damage by targeting the electrical excitation source responsible for shaft voltage generation. Among the reviewed approaches, PWM modulation optimisation and multi-level inverter topologies are particularly attractive because they reduce CMV directly at the inverter stage without requiring extensive mechanical modifications. Passive filtering techniques, such as common-mode chokes and dv/dt filters, effectively suppress high-frequency current propagation, although their ability to eliminate EDM currents remains limited due to residual CMV. Meanwhile, advanced motor-side approaches including electrostatic shielding and parasitic capacitance reduction address the root electrostatic coupling mechanisms; however, they introduce manufacturing and packaging challenges. Hence, there is no single strategy that can fully eliminate EDM currents in modern high-frequency EV drivetrains, especially with the growing adoption of wide-bandgap inverters. Consequently, recent research trends favour hybrid mitigation frameworks integrating inverter modulation optimisation, filtering systems, grounding technologies, and bearing insulation to achieve comprehensive long-term suppression of shaft voltage and electrical discharge damage.

Table 2 Comparison between different approaches for motor and inverter optimisation [24, 30, 72, 85, 88–90]

Approach	Primary mechanism	Advantages	Limitations
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PWM optimisation	Reduces CMV and dv/dt during inverter switching	Reduces shaft voltage, bearing current and EDM activity without major hardware changes	Cannot completely eliminate CMV May increase control complexity
Random PWM/spread-spectrum PWM	Distributes switching harmonics over wider frequencies	Reduces repetitive EDM pulses and EMI peaks	CMV still exists More difficult control implementation
Multilevel inverters	Produces smaller voltage steps during switching	Significantly reduces dv/dt, CMV, and bearing currents	Higher cost, size, and circuit complexity
Shaft grounding	Provides low-impedance path for stray current dissipation	Effectively reduces shaft voltage and EDM currents; relatively low cost	Wear, contamination and reduced effectiveness at very high speeds
Insulated bearings	Electrically isolates bearing current path	Prevents current flow through bearings and reduces EDM damage	May shift current to other components if grounding is inadequate
CM chokes	Blocks high-frequency CM currents	Simple and effective for reducing circulating currents and EMI	Does not fully remove shaft voltage

dv/dt filters	Smooths voltage rise rate from inverter output	Reduces transient voltage spikes and capacitive current	Adds size, cost and power losses
Sine-wave filters	Converts PWM output into near-sinusoidal waveform	Significantly reduces CMV, EMI, and bearing currents	Bulky and expensive for compact EV systems
Active common-mode filters	Uses active filtering and edge-compensation techniques to suppress CM voltage and current	Reduces dv/dt, EMI and bearing common-mode currents with lower losses and smaller inductors Compact and efficient design	Requires additional active circuitry and advanced control implementation
Active EMI filters	Injects compensating signals to cancel EMI and high-frequency noise	Improves EMI suppression and reduces high-frequency electrical stresses	Increased system complexity, cost, and controller requirements
Motor geometry optimisation	Reduces parasitic capacitance in motor structure	Suppresses bearing voltage ratio	Additional manufacturing complexity and cost
Electrostatic shielding	Blocks capacitive coupling between stator and rotor	Reduces shaft voltage build-up	Additional manufacturing complexity

3.2 Bearing materials and surface engineering

Bearing materials and surface engineering offer another route for mitigating electrical discharge damage. This section is organised into two subsections that distinguish the technologies that interrupt the external bearing-current path via outer-ring insulating coatings from those applied within the rolling contact that alter the electrical and tribological behaviour of the contact itself.

3.2.1 Outer-ring insulating coating

Insulating bearings interrupt the current path through enhanced electrical resistance, which drastically elevates the impedance between the bearing components and ground, thereby preventing electrical discharges [4]. The insulation approaches typically involve the application of an insulating layer onto the outer or inner ring or the use of hybrid/full-ceramic bearings [64]. Hybrid/full-ceramic bearings exhibit improved performance and greater strength at high temperatures. Experimental studies on electrical discharge damage demonstrate that hybrid/full-ceramic bearings effectively reduce shaft current-induced damage compared with steel bearings, with full-ceramic bearings showing the best performance [87]. Hybrid ceramic bearings are best suited for high-speed and light-load applications, whereas full-ceramic bearings are suitable for extreme environments such as corrosive, high-temperature, or electrically insulating conditions [88–89]. However, although these approaches offer strong insulating properties, they are limited by their high cost. Consequently, researchers are pursuing alternative approaches, including specialised coatings and advanced dielectric greases, which provide improved electrical resistance, excellent tribological performance, and cost-effectiveness.

Ceramic insulating coatings, particularly Si_3N_4 , SiC , ZrO_2 , and Al_2O_3 , have long been recognised for their electrical insulating properties, corrosion resistance, and thermal stability. Applying a ceramic coating on the outer ring is the most common approach used by bearing manufacturers, as it effectively isolates bearing currents [89–90]. For DC applications, a ceramic ring coating of nominally 100 μm thickness acts as a pure insulator with a resistance of 50 $\text{M}\Omega$ or more, while the bearing dimensions and tolerances remain identical to those of an uncoated bearing [12]. Since the impedance of such a

coating comprises a frequency-independent ohmic resistance in parallel with a frequency-dependent capacitive component, raising the impedance at high frequencies requires either a thicker coating, a smaller coated area, or a material with a lower dielectric constant [90].

Al₂O₃ coatings have been found to effectively reduce bearing current amplitude and prevent electrical discharge damage. In general, Al₂O₃ coatings are prepared using plasma spraying technology owing to its advantages such as low preparation costs, high efficiency, and good coating quality. However, optimising the coating thickness and porosity is critical to block discharge pathways in bearings [91]. This is because plasma-sprayed Al₂O₃ coatings suffer from γ -Al₂O₃ phase formation, which absorbs moisture in humid environments, which reduces the resistivity of the coatings. α -Al₂O₃ phase coatings are desirable for EV bearings. The coatings must provide higher dielectric strength, higher resistivity, better wear resistance, and better chemical stability [91]. Wang et al. [92] demonstrated that multi-dopant (TiO₂, Y₂O₃, and Cr₂O₃) plasma-sprayed Al₂O₃ coatings could significantly increase the α -Al₂O₃ phase content, reduce porosity, and improve dielectric strength. Hybrid sol-gel Al₂O₃ layers have been explored to suppress circulating currents. Vishvakarma et al. [93] achieved crack-free Al₂O₃ coatings of 40 μ m with high electrical resistance (120 M Ω), indicating its high potential for insulating bearings.

At the system level, insulating-coated bearings can substantially reduce bearing currents in electric motors; however, they cannot completely eliminate them. Since the additional capacitance only changes the bearing voltage ratio, EDM discharges are not fully eliminated where metal-to-metal contact persists, and improper arrangement of insulated bearings can create dangerous conditions for adjacent non-insulated bearings by rerouting the shaft-current paths. Full-bearing tests on EV 6309-series bearings with an insulation coating (6309-J20AA-C3) confirmed this behaviour: under injected currents of up to 3 A (0–1000 V pulse generator), the coating reduced the circulating current from 3 A to 1.8 A and prevented pitting, yet did not fully suppress the current [33]. Consistent with this, a coating on the outer ring cannot interrupt circulating bearing currents or rotor-to-ground currents, which follow

paths that bypass the ring-housing interface, and may redirect electrical stress toward adjacent drivetrain components. Resin-based insulating coatings have demonstrated potential to insulate EV bearings and are more cost-effective than ceramic coatings. Fan and Shiota [94] showed that polysiloxane-containing polyimide (si-PI) coatings with hexagonal boron nitride (hBN) fillers effectively suppressed crack propagation, reduced wear, and exhibited strong electrical insulation. Optimising the filler content is critical to maximise the benefits of this highly insulating material for protecting bearings from electrical discharges [95].

3.2.2 Rolling-contact functional coating

Unlike outer-ring insulating coatings that interrupt the external current path, rolling-contact functional coatings are applied directly within the rolling contact and operate through mechanisms that include controlled electrical conduction, current-induced graphitisation, tribochemical oxide formation, and sacrificial tribofilm generation. The current research trends for coating in EV applications are focused on diamond-like carbon (DLC) coatings. DLC coatings have been widely used in the automotive field due to their excellent tribological performance, high chemical inertness, corrosion resistance, and hardness. Farfan-Cabrera et al. [13] demonstrated that hydrogenated DLC coatings were resilient, maintaining tribological performance under DC discharges. However, hydrogen-free DLC is not suitable for coating the bearing surface, as it undergoes catastrophic wear and graphitisation when exposed to electrical discharges. The pre-existence of some graphitic phases or microdroplets further accelerates graphitisation of the whole coating. Jang et al. [96] showed that H-DLC coating with high electrical resistance and dielectric breakdown strength could effectively prevent leakage current, thereby reduce electrical wear. The primary failure mechanism under boundary lubrication was dielectric breakdown whereas it was surface degradation under mixed lubrication. High-resistance H-DLC from deposition techniques of physical vapor deposition-based filtered cathodic vacuum arc deposited H-DLC (designated as ARC-DLC) is highly recommended for high-speed, variable-voltage mixed lubricated interfaces. Under boundary conditions, its superior electrical resistance suppresses

leakage current and increases dielectric breakdown strength to 14 V (nearly 3x higher than standard steel). Under mixed lubrication, ARC-DLC limits asperity current density, suppressing localized Joule-heating-induced graphitization and structural softening by two orders of magnitude.

Furthermore, Behtash et al. [97] demonstrated that amorphous carbon (a-C) DLC could adapt under current loads up to 1500 mA by forming protective graphene layers. Tetrahedral amorphous carbon (ta-C) coatings degraded rapidly at currents as low as 300 mA, producing micropitting and oxidation of the substrate. Their low resistance, coupled with cathodic arc microdroplet defects, creates conductive pathways that focus electric discharges, accelerating destructive sp^3 -to- sp^2 phase transformations and causing rapid delamination at currents as low as 100 mA. The current density itself played a significant role in controlling the current-carrying capacity and friction of a-C DLC. Higher current density reduced friction due to the enlargement of graphene nanosheets formed on the sliding surface [98]. These studies highlight that material chemistry (hydrogen content and bonding structure) and electrical parameters (current intensity and density) play a decisive role in the resilience of DLC coatings under electrified conditions. Ongoing research is needed to clarify the mechanisms governing the behaviour of DLC coatings under electric currents for their adoption in EV applications.

Other hard coatings, such as chromium nitride (CrN) coatings, have also been explored, as they are highly effective at mitigating electrical damage in EV bearing applications. CrN coatings exhibited excellent tribological performance under DC current loading (0–1.5 A), both dry and lubricated. CrN coatings on AISI 316L steel reduced wear by 79.1 % under dry sliding and by 98.7 % under PAO6-lubricated sliding relative to the uncoated substrate. Tribochemical oxidation of the coating surface during current-carrying friction formed a chromium oxide (Cr_2O_3) layer, which contributed to the protective response. The substantially stronger protection under lubricated conditions reflects the combined action of the oxide layer and the lubricating film, which together reduced direct asperity contact and moderated the electrical boundary conditions at the interface [99].

Table 3 summarises the fundamental properties, electrical strategies, failure mechanisms, and wear-protection performance of rolling-contact coatings under electrified conditions. These coatings function by tolerating electrical stress at the contact through mechanisms such as insulation, controlled conduction, current-induced graphitisation, and oxide or tribofilm formation. Current literature suggests that conductive CrN coatings are suitable for high-load, boundary-lubricated interfaces, while high-resistance H-DLC coatings are recommended for high-speed, variable-voltage, mixed-lubricated interfaces. In contrast, hydrogen-free ta-C coatings should be avoided in electrified bearing assemblies due to their sensitivity to current-induced degradation.

Hydrogenated DLC and CrN demonstrate resilience under electrified sliding, whereas hydrogen-free ta-C coatings fail rapidly, underscoring the importance of mechanistic insight into degradation pathways such as dielectric breakdown, graphitisation, or electrochemical reactions. These contrasting behaviours emphasise that stable electro-tribological performance requires systematic validation under full-bearing conditions. Surface-engineering approaches therefore remain a promising, but environment-dependent, route to mitigate electrical discharge damage in EV bearings.

Table 3 Comparative electrical and tribological characteristics of rolling-contact coatings under electrified conditions

Coating type	Electrical strategy	Resistivity/ resistance	Breakdown behaviour	Key failure modes	Electrified wear performance
CrN [99]	Active conduction	Resistivity: 4.15 $\mu\Omega\cdot\text{cm}$	No breakdown (Conducts current without arcing)	Accelerated oxidation to lose Cr_2O_3 phase	Dry wear rate: 1.9×10^{-4} (79.1 % reduction versus steel substrate) PAO6 wear rate: 9.7×10^{-6} (98.7 % reduction versus steel substrate)
H-DLC	Passive insulation (Suppresses leakage)	Resistance: $3.0 \times 10^8 \Omega$	Boundary ($\lambda =$ 0.04): 14 V Mixed ($\lambda = 1.4$): 20 V [96]	Joule-heating, graphitization, dehydrogenation, delamination [100, 104]	Boundary: $\sim 0.50 \times 10^{-3} \mu\text{m}^3/\text{N}\cdot\mu\text{m}$ Mixed: $0.024 \times 10^{-3} \mu\text{m}^3/\text{N}\cdot\mu\text{m}$ [96]
Sputtered a-C [97]	Low-resistance sp^2 conduction	Not mentioned	Remains stable and intact up to 1500–1800 mA	High currents ($>900 \text{ mA}$) raise temp $>100^\circ\text{C}$,	Low and stable wear (wear rate $2.81 \times 10^{-4} \text{ mm}^3\text{A}^{-1}\text{N}^{-1}$)

<i>Friction</i>				https://mc03.manuscriptcentral.com/friction	
				impairing graphene	Forms protective graphene sheets on
				moisture adsorption	track
Pulsed arc ta-	Unstable insulator	Resistivity:	Catastrophic	Rapid sp ³ -to-sp ²	Catastrophic wear
C [97]	(high sp ³)	$\sim 1.4 \times 10^{-1}$	breakdown at	graphitization, macro-	(wear rate 1.69×10^{-3} , 6× higher
		Ωcm [100]	100–300 mA	droplet short-circuiting	than a-C).
				[13, 101]	Severe pitting and peeling

3.3 Lubrication strategies

Lubrication strategies are increasingly recognized as complementary approaches to mitigating electrical discharge damage in EV bearings, particularly under high-frequency fields. The strategies in this section target three coupled failure pathways, each associated with a distinct degradation mechanism.

(i) Electrical film breakdown and EDM-induced surface damage.

EDM currents cause the bearing degradation progress via surface damage and grease degradation. The discharges phenomena generate localised heating, Joule heating, and surface pitting, which will alter the microstructure of the lubricating grease and accelerating oxidation [41, 46, 63].

(ii) Discharge-induced chemical degradation.

Repeated discharge activity leads to significant degradation of the dielectric properties of the grease [63]. The chemical ageing reduced the dielectric strength and deteriorated the insulating ability of the grease, leading to ineffective lubrication and reduced load-carrying capacity [58, 64]. These degradation products progressively shift the grease from predominantly capacitive behaviour to resistive conduction, a state in which grease no longer supports voltage accumulation but instead facilitates charge leakage.

(iii) Thermal-oxidative grease ageing and starvation.

Electrical fields and sustained high-temperature exposure accelerate lubricant degradation through thermal oxidation and evaporation. Localised Joule heating from current flow across contacts reduces film thickness and promotes surface pitting [101]. The grease life follows the Arrhenius-type thermal-oxidative behaviour, with degradation strongly dependent on chemical composition [60–61]. Thermal ageing disrupts the thickener microstructure, impairing oil bleeding and increasing leakage rates [104]. Elevated temperatures thin the lubricant film, lowering the breakdown voltage and reducing the discharge threshold under high-speed conditions [41]. Concurrently, base oil evaporation depletes the

grease, leading to hardening and viscosity increase. This hardening diminishes oil-supply capacity, thereby causing lubrication failure once the base oil is exhausted [65].

Each of these pathways is addressed below, where every additive strategy is explicitly linked to the specific failure mode it targets. Two design routes are available: either conductivity is raised so that charge is gradually conducted to ground before breakdown occurs, or dielectric strength is increased so the lubricant withstands higher voltages without failure [105–108]. Each additive group targets a distinct failure mode: (i) conductive carbon networks suppress EDM pitting, and surface roughening; (ii) metallic nanoparticles mitigate arc-induced pitting and rising contact resistance; (iii) oxide nanoparticles reduce wear and roughness; (iv) ionic liquids and their composites address charge accumulation and dielectric breakdown; and (v) insulating additives delay breakdown by raising the film's withstand voltage. The central design constraint across all strategies is the operational window within which the additive remains effective, since type, morphology, concentration, and dispersion stability strongly govern grease conductivity and reliability.

Carbon-based nanoparticles. To mitigate electrical pitting, fluting, and surface roughening, carbon nanoparticles (CNP), graphite, and multi-walled carbon nanotubes (MWCNT) form percolation networks that facilitate electron transport across the grease film. In lithium grease, CNP reduced pit density from 9.4 % to 2.5 % at 1 A at a loading of 1 wt%, with the best balance between conductivity and surface protection achieved at 0.5 wt%. At higher currents (≥ 2 A), Joule heating and agglomeration accelerated wear and promoted oxidation [109]. In bearing tests, MWCNT at 0.4 wt% reduced raceway roughness from 2.08 μm to 0.61 μm , a 70.67 % reduction, markedly outperforming insulating oxide particles, which act primarily as wear-mitigation agents [1]. In palm-oil glycerol grease, MWCNT lowered the breakdown voltage range from 1.0–2.2 V to 0.5–0.75 V at 3 wt%, reduced the coefficient of friction (COF) by 60 % (to 0.06), and at 2 wt% delivered the best vibration damping and oxidative stability [2]. Processing routes are equally decisive where ultrasonication of functionalised MWCNT

for 1 h produced the lowest, most stable coefficient of friction (0.15–0.20) and the smallest wear scars, whereas longer sonication fragmented the tubes into abrasive particles [110].

Metallic nanoparticles. To suppress arc-induced pitting and rising contact resistance, metallic nanoparticles provide strong arc suppression and oxide-film formation. Silver nanoparticles in polyurea grease inhibited electrical pitting more effectively than any other colloid tested, outperforming Fe_3O_4 nanoparticles under identical equivalent-weight loading [111]. Copper nanosheets reduced the coefficient of friction by 53.51 % at 10 wt% and substantially reduced the wear rate, outperforming copper wires and particles because their two-dimensional sheet structure increases the contact area and current-carrying capacity. However, when the nanoparticles content exceeds 10 wt%, excessive copper damages the lubricating film [112].

Oxide nanoparticles. To mitigate wear and roughness generation rather than high-current discharge, oxide nanoparticles such as Al_2O_3 form protective tribofilms on the rubbing surfaces. In the same bearing tests, Al_2O_3 at 0.4 wt% reduced raceway roughness from 2.08 μm to 1.30 μm , a 37.5 % reduction and roughly half the improvement achieved by MWCNT at the same concentration. This difference reflects the dielectric nature of bulk alumina and its uneven dispersion, which constrain charge transfer. Their contribution to bulk conductivity is limited, so oxides are best employed where wear protection rather than charge dissipation is the dominant requirement [1].

Ionic liquids and composites. To address charge accumulation and dielectric breakdown, ionic liquids exploit intrinsic ionic conduction, avoiding the dispersion and percolation constraints of solid fillers. Alkyl imidazolium IL greases achieve conductivities above 1000 $\mu\text{S}\cdot\text{cm}^{-1}$ together with dropping points above 220°C and good corrosion resistance [113]. In an ester-based IL grease tested on an EHD ball-on-disc rig, raising the IL content increased the film dielectric strength and raised the breakdown threshold from 1.4 V to 3.9 V at intermediate loadings, but excess IL diluted the base-oil viscosity and reduced the dielectric strength. The discharge evolution in EHD contacts lubricated with IL-based conductive greases, showing that dielectric breakdown initiates at side lobes, migrates to the

central film, and eventually relocates outside the contact zone as voltage increases [39]. Although ILs offer promising benefits, they have drawbacks in terms of corrosive potential and reduced efficiency at high temperatures. Hence, studies are being carried out to optimise ILs formulations for durability, environmental compatibility, and resistance to high temperatures [114]. Hybrid composites combine mechanisms: in an IL–PANI/WS₂ grease, WS₂ acts as a conductive network that dissipates localised electrical energy while the conjugate π bonds in PANI intercalated between the WS₂ layers improve electron transport, producing a synergistic tribofilm with superior antiwear for steel–steel contacts [106]. Dai et al. [11] extended this composite strategy by designing a hydrogen-bonded eutectic polyurea grease complexed with titanium carbide MXene (Ti₃C₂Tx)-based. At 0.5 wt% loading, the system reduced wear volume by 91 %, decreased contact resistance, and suppressed electrical erosion in EV bearings, though higher concentrations intensified mechanical wear.

Insulating additives. To delay dielectric breakdown, insulating additives raise the breakdown voltage and resistivity of the film by introducing electron traps. Inorganic modification montmorillonite (IOMMT) doped into lithium grease at 1.5 wt% delivered the best combination of insulating and tribological performance, increasing the AC breakdown voltage by 21 % (6.54 kV versus the base grease) and increased volume resistivity by ~65 %, while also reducing COF and wear width through tribofilm formation. The layered silicate structure and strong polarity of IOMMT particles facilitated adsorption films and oxidation-derived protective layers, giving superior anti-wear performance compared with organic modification montmorillonite (OMMT), montmorillonite (MMT), and SiO₂ [115].

The additive strategies reviewed above are combined in **Table 4**, which maps each grease additive to the failure mode it targets and records the reported optimal concentration, the main benefit, the effective current or voltage threshold, the failure mode beyond the threshold, and the failure mechanism. The degradation mechanisms underlying these operational windows are elaborated in the text below the table.

Table 4 Comparison of grease conductivity studies

Additive type	Additive	Optimal concentration	Effective electrical threshold	Main benefit	Failure mode beyond threshold	Failure mechanism	Ref.
Carbon-based	Carbon nanoparticles (Li/Ca/Al greases)	0.25 wt%	DC up to 1 A; bulk impedance ↓ 52–57 %	~45 % wear reduction; stabilized friction	Friction instability	Electrothermal stress and viscosity shifts	Kabir et al. [116]
Carbon-based	Carbon nanoparticles (Li grease)	0.5 wt%	DC up to 1 A	Pitting density ↓ from 9.4 % to 2.5 %	Agglomeration & oxidation	Excessive Joule heating	Tajedini et al. [109]
Carbon-based	Nanographite (PAO + diester grease)	0.2 wt%	AC 5 V, 50 Hz	Reduced COF in fluid regime	Film thinning & localized thermal damage	Dielectric breakdown from capacitive-to-resistive transition	Li et al. [9]

Carbon-based	MWCNT (Li grease, functionalised)	2 wt% (1 h ultrasonication)	<i>Friction</i> AC via potentiostat	Lowest COF (0.15–0.20); smallest wear scar (704 µm); conductivity 1.24×10^{-8} S/m	Agglomeration	https://mc03.manuscriptcentral.com/friction Structural degradation	Daswarman et al. [110]
			DC sweep 0–5 V, discharge eliminated >4 .5 V	70.67 % roughness reduction	Agglomeration	Protective tribofilm breakdown	Jonjo et al. [1]
			DC up to 10 V (100 N load); EDM threshold 0.6 – 1.0 V	Breakdown voltage ↓ from 1.0–2.2 V to 0.5–0.75 V; COF ↓ 60 %;	Excessive oil separation & grease bleeding	Thermal degradation of thickener structural bonds	Abozeid et al. [2]

				vibration ↓			
				~30 %			
Metallic	Silver nanoparticles (Polyurea grease)	~0.19 wt%	DC 31 V, 0.5 A	Strong reduction in pitting area; superior conductivity and thermal dissipation	Surface melting	Localized high current density exceeding the nanoparticle thermal dissipation capacity; thermal film breakdown	Janik et al. [111]
Metallic	Cu nanosheets (Li grease)	10 wt%	Electrical contact resistance (69.94 mΩ)	COF ↓ 53.51 %; wear ↓ 93.96 %; resistance ↓ 92.23 %	Oxidation & agglomeration	Lubricant film breakdown	Zhu et al. [112]

			<i>Friction</i>		https://mc03.manuscriptcentral.com/friction		
Oxide	Al ₂ O ₃	0.4 wt%	DC sweep 0–	37.5 %	Agglomeration &	Third body abrasion	Jonjo et al.
	nanoparticles		5 V,	roughness	severe wear	and discharge	[1]
	(Li grease)		discharge	reduction		breakdown	
			eliminated >4				
			.5 V				
Layered solid	MoS ₂ (micro versus nano, Li grease)	0.25 wt%	DC up to 3 A; 25–80°C	93 % wear ↓ at 40°C (micro); 85 % at 80°C (nano)	Thermal oxidation	Disruption of 2D layered structure forming hard particles	Tajedini et al. [47]
Polymer/composite	Titanium carbide MXene (Ti ₃ C ₂ Tx)-based (Polyurea grease)	0.5 wt%	AC 14 V	91 % wear ↓; strong tribofilm	Agglomeration	Thickener collapse and severe film starvation	Dai et al. [11]

Polymer/ composit e	Ionic liquid conductive grease (ester based IL)	20 wt%	<i>Friction</i> Breakdown threshold raised from 1.4 V to 3.9 V	Higher dielectric strength, improved conductivity, reduced film recession	Arcing damage	https://mc03.manuscriptcentral.com/friction Base oil viscosity dilution, dielectric breakdown and film collapse	Liu et al. [39]
Insulatin g	Nano-montm orillonite (PTFE-thicke ned grease)	1.5 wt%	AC breakdown up to 6.5 kV	Excellent insulation; improved wear resistance	Agglomeration & severe wear	Dielectric breakdown and third body abrasion	Cao et al. [115]

The mechanisms behind the limiting conditions in Table 4 fall into three categories: (i) Dispersion loss: above their optimum concentrations, carbon nanoparticles agglomerate, with detached or oxidised debris acting as third-body abrasives; oxide nanoparticles such as Al_2O_3 cluster due to their dielectric nature and high surface energy [1, 3, 109], excess IL–PANI in composite greases increases abrasive wear [106], and prolonged ultrasonication fragments functionalised MWCNT into hard abrasive particles [110]. (ii) Network and film destabilisation: mechanical shear and thermal oxidation disrupt CNT percolation networks [2], excess IL dilutes the base-oil viscosity and thins the film [39], silver-nanoparticle greases exhibit a rheological trade-off as the carrier fluid lowers the grease flow point [43], and copper nanosheets oxidise and damage the film beyond the optimum loading [112]. (iii) Electro-thermal degradation: at currents ≥ 2 A, Joule heating promotes nanoparticle agglomeration and electrochemical surface oxidation, reversing the protective effect observed at 1 A [109], at high field strengths, discharge relocates from the contact side lobes to the central film and eventually to arcing outside the contact [39]. Conversely, nanographite can reduce oil-film resistance to the point where discharge initiates outside the contact, causing mechanical wear of the sliding surface [9].

These studies indicate that lubrication mitigation strategies are governed by not only by its chemistry but also by the electrical, thermal, and shear environment in which it operates. Conductive additives dissipate charge but risk electro-thermal degradation when overloaded, whereas insulating additives delay breakdown but cannot prevent voltage accumulation beyond thresholds. The key challenge is not simply to increase or decrease the grease conductivity, but to identify the optimum operational window that suppresses discharge-driven wear and maintain stable lubrication. The current literature still lacks a mechanistic understanding of how lubricant chemistry, thickener structure, and additives interact under EV bearing conditions. This is imperative to provide a mechanistic framework for developing high-performance bio-based greases tailored to EV environments.

4 Development of bio-based greases for EV bearings

The growing environmental concerns have led researchers to extensively study bio-based lubricants as alternative candidates to petroleum-based lubricants due to their biodegradability and renewability [6]. Using bio-based lubricants in various applications has become one of the routes to reduce the carbon footprint globally [22]. The global demand for bio-based lubricants is 370 kilotonnes, where the industrial sector is the primary consumer. The global bio-based lubricant market is forecasted to be USD 4.01 billion by 2030 with a compound annual growth rate (CAGR) of 6.7 % [117]. Despite this growth, biodegradable greases presently account for merely 1% of the global grease market, indicating that high-performance bio-based grease formulations remain underdeveloped [118].

Sustainability alone is insufficient for EV bearing applications. Grease formulations must fulfil the key performance criteria for EV environments. This requires an integrated formulation strategy in which the bio-based oil, thickener network, and additives are designed to achieve a balanced physicochemical, tribological, and electrical performance. The development of bio-based EV greases will contribute to the global transition towards clean energy and may reduce fossil fuel dependency, which supports the United Nations Sustainable Development Goals 12 (Responsible Consumption and Production) and 13 (Climate Action). Moreover, the aim of high-performance EV greases is to improve the EV bearing reliability, which will further support Sustainable Development Goals 7 (Affordable and Clean Energy) and 9 (Industry, Innovation, and Infrastructure) by contributing to cleaner electrified mobility and sustainable industrial innovation.

4.1 Formulation design requirements for EV bearing greases

Grease is a semi-solid composed of base oil (70–95 wt%), thickener (3–30 wt%), and additives (0–10 wt%) [119]. The performance criteria for EV greases differ substantially from those of grease used in ICE vehicles. **Fig. 6** summarises the general requirements of EV greases. EV greases must perform well in EV environments, which involve electric discharges, high-speed rotations, and frequent speed changes, to avoid issues such as electrical discharge damage, material degradation, and bearing failures.

Hence, EV greases require excellent electrical properties (conductivity and dielectric strength), tribological characteristics, thermo-oxidative stability, material compatibility with advanced polymers, and long-term reliability under electrified conditions. These requirements are crucial for EV greases to control the film formation, charge accumulation, dielectric breakdown, current leakage, tribofilm development, and degradation under electrical stresses. To address these challenges, researchers actively innovate the base oils, thickener networks, and additives [113–115].

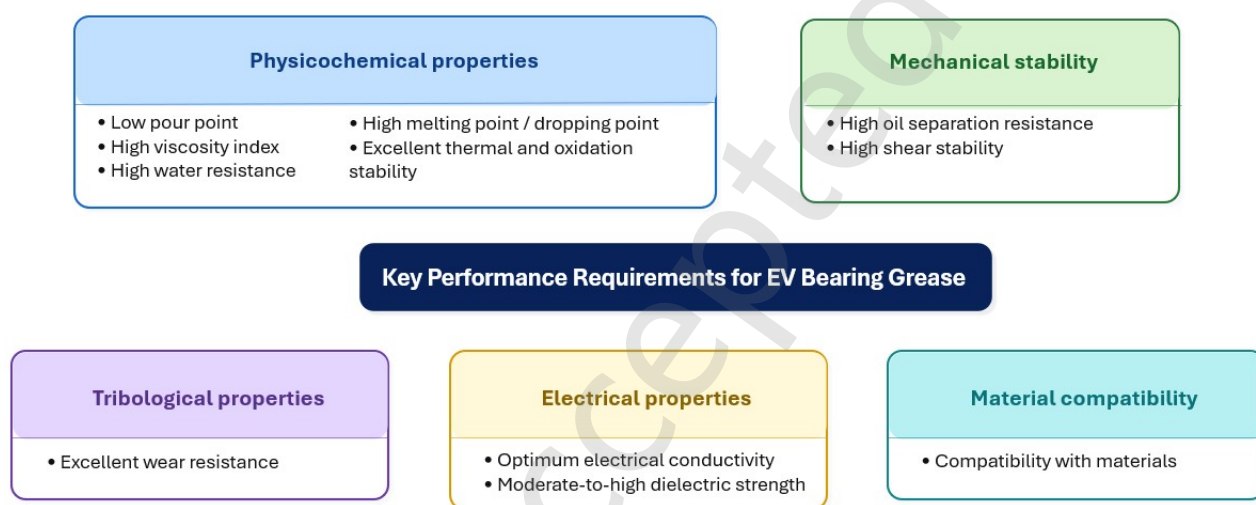


Fig. 6 General requirements of EV greases [25, 114].

4.2 Selection of bio-based oils

The American Petroleum Institute (API) categorises base oils into five primary classes (I–V) according to their chemical composition and physical characteristics, including saturated concentration, sulphur content, and viscosity index (VI). In the lubricant industry, the API grouping is frequently used to characterise the quality level of base oils and to direct their application in various formulations. Groups I–III refer to mineral base oils, Group IV consists of fully synthetic oils (polyalphaolefins), and Group V comprises all other base oils not categorised in Groups I–IV, including esters, polyalkylene glycols (PAGs), and other synthetic oils [121]. Groups III, IV, and V are suitable for low-viscosity base oils and are considered as high-quality base oils due to their high VIs, high saturated hydrocarbon contents, and low impurity levels [122]. **Table 5** shows an overview of the primary groups of base oils classified by the API and their suitability for use in EV greases.

The selection of base oils for EV greases is essential to ensure high thermal stability, oxidative resistance, excellent tribological performance, and compatibility with electric components. Among the API base oil groups, the oils in Groups IV and V are most suitable for use in EV bearing greases. Group IV (PAO) oils offer consistent performance and electrical stability, while Group V (esters and other bio-based oils) oils offer biodegradability and polarity advantages. However, Group V oils have varied performance depending on their chemical structure, they are susceptible to absorbing water, particularly in high-humidity environments, and they have a high tendency to crystallise under extreme cold conditions [117–118]. Incorporating modification techniques, such as polarity tuning and additive addition, into the grease can address these issues and fulfil certain criteria.

Bio-based lubricants are usually produced from plant oils, animal fats, and other bio-based feedstocks [125]. Several types of vegetable oils have been explored for their potential as bio-based lubricants, including edible oils (palm, soybean, sunflower, canola, rice bran, and coconut) and non-edible oils (castor, jatropha, karanja, jojoba, rubber seed, and linseed/flaxseed) [126]. Vegetable oils offer various advantages, including excellent lubricity, strong affinity for metal surfaces, high flash points, high VIs, reduced volatility, and greater dispersibility. However, they have inherent intrinsic disadvantages such as poor oxidative stability, low-temperature flow issues, and hydrolytic stability [22, 119]. These limitations make the direct application of unmodified vegetable oils unsuitable for use as base oils for EV applications unless they are chemically modified or enhanced with additives. Chemical modification transforms natural triglycerides into more stable and versatile lubricants by targeting functional groups with double bonds, alkoxy, and acyl. Reactions such as transesterification/esterification, epoxidation, hydrogenation, ring-opening reactions, estolide formation, or polymerisation can tune the inherent properties of raw vegetable oils [124, 126–128]. Bio-based synthetic esters offer greater control of low-temperature properties, thermo-oxidative stability and lubricity, rendering them suitable for use as lubricants or additives. The common types of bio-based synthetic esters include monoesters, diesters, and polyol esters [130]. Researchers often

tailored these synthetic esters to suit application requirements, where their properties depend on their molecular structure. The correlation between molecular structure and the properties of the esters is shown in **Fig. 7**.

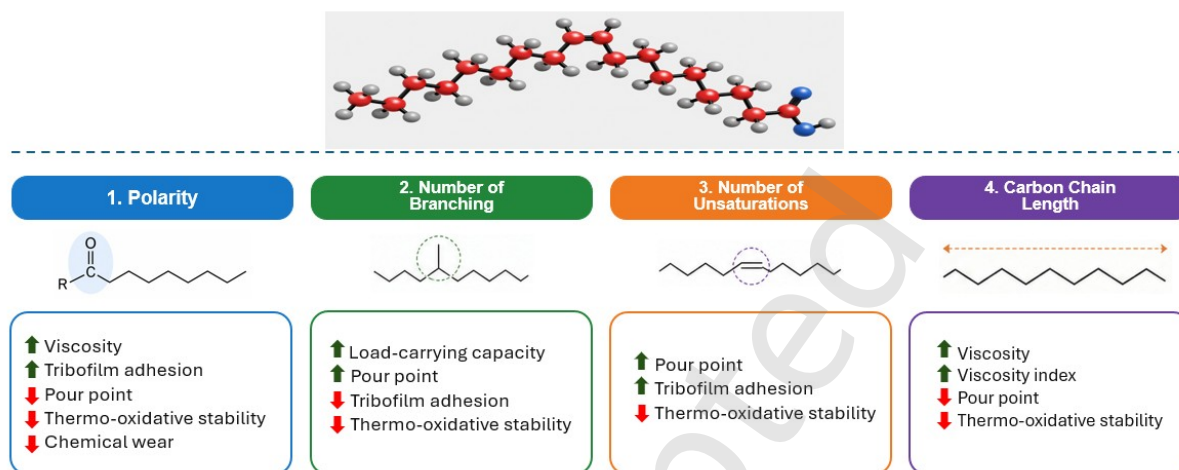


Fig. 7 Correlation between the molecular structure and properties of esters [131].

Table 5 Base oil groups classified by the API and their suitability for use as base oils in EV greases [114, 116].

API Group	Characteristics	Key properties	Biodegradability [132]	Electrical properties [117, 124]	Suitability for EV greases
Group I	Solvent-refined oils with high sulphur content and low saturates	Moderate VI, lower oxidation stability, higher volatility compared with that of higher groups	Low	Low dielectric strength	Low suitability; not ideal for EV applications and bio-based formulations

<i>Friction</i>		https://mc03.manuscriptcentral.com/friction			
Group	Hydroprocessed	Moderate VI,	Low	Moderate	Moderate
II	oils with lower sulphur content and higher saturates	better oxidation stability, and lower volatility than those of Group I		dielectric strength	suitability; still lacks high thermal stability needed for EVs and not ideal for bio-based formulations
Group III	Highly refined oils with very low sulphur content and high saturates	High VI, good oxidation stability, low volatility, low sulphur, good additive acceptance compared with those of Groups I and II	Low	Moderate dielectric strength	Moderate-to-high suitability for EV applications; not ideal for bio-based formulations
Group IV	Synthetic polyalphaolefins (PAO)	High VI, excellent thermo-oxidative stability, hydrolytic stability, shear stability, low pour	Moderate for low-viscosity grade	High dielectric strength	High technical suitability for EV applications; not ideal for

		point, low			bio-based
		corrosivity,			formulations
		compatibility with			
		common			
		materials, additive			
		response, low			
		electrical			
		conductivity			
Group	All other base	High VI, high	Moderate for	High	PAG: High
V	oils not covered	polarity, good	low-viscosity	dielectric	suitability but
	by Groups I–IV,	lubricity, good	grade of PAG	strength	less ideal for
	including esters	thermal properties,	High for		bio-based
	from	good additive	synthetic ester		formulations
	petrochemical or	solubility, often	from bio-oils		Esters: High
	renewable	biodegradable			suitability and
	feedstocks such	depending on			ideal for bio-
	as diesters,	feedstock			based
	polyol esters,				formulations
	and complex				
	esters				

4.2.1 Physicochemical properties of bio-based oils

4.2.1.1 Monoesters

Monoesters are synthesised through the reaction of monofunctional fatty acids with monofunctional alcohols [130]. They exhibit lower-temperature fluidity and reduced viscosity compared with raw

vegetable oils due to their lower molecular weight and simpler structure. The molecular structure of monoesters, including polarity, saturation, and chain length, directly influences their characteristics. Viscosity often increases with chain length and degree of saturation, whereas it decreases with degree of unsaturation, branching, and smaller alcohol groups [134]. de Araujo-Silva et al. [135] found that fatty acid isoamyl esters derived from crude soybean oil deodoriser distillate exhibited low viscosity, high VIs (163–175), and low pour points (−6 to −9 °C). The moderate flash point (178 °C) and oxidative stability (37–53 min) suggest that monoesters are unable to withstand high-temperature environments. Esipovich et al. [130] examined the influence of fatty acid content and alcohols on the characteristics of esters. They found that saturated oils (palm, coconut) yielded esters with good oxidation stability but poor low-temperature performance, whereas unsaturated oils (sunflower, soybean, rapeseed) exhibited the opposite characteristics. They found that increased levels of alcohol esters conferred advantageous properties on bio-based lubricants.

Indeed, Feng et al. [136], found that increasing the alkyl chain length of alcohol enhanced the low-temperature performance and oxidative stability. Boyekong et al. [137] discovered that castor oil monoester (MECO) surpassed palm kernel oil monoester (MEPKO) due to the hydroxyl functionality in ricinoleic acid, which offered intrinsic oxidative stability. Moreover, lower molecular cohesion and higher volatility may lead to reduced adsorption strength, potentially resulting in a limited load-carrying capacity within the boundary lubrication regime [138]. Higher volatility can lead to premature oil loss under elevated thermal conditions.

4.2.1.2 Diesters

Diesters involve the reaction between dicarboxylic acids and diols and are generally suitable for use in cold-flow conditions compared with monoesters [131–132]. Fortunato et al. [141] highlighted that diesters derived from saturated fatty acids with short-chain diols (linear and branched) could improve both low-temperature properties and oxidative stability of bio-based lubricants. Branched diesters exhibited lower crystallisation temperatures compared with linear diesters due to disrupted molecular

packing, thereby lowering the pour point. Ahmed et al. [139] obtained similar findings and found that branched dicarboxylate diesters enhanced both the low-temperature and tribological performance. The synthesised products were found suitable for use as hydraulic fluids, as they met the requirements of the ISO VG 32 lubricant standard. The literature shows that diesters are generally more structurally versatile than monoesters due to the presence of two ester groups and a central diol or dicarboxylic acid backbone that allows tailoring of viscosity, polarity, volatility, and crystallisation behaviour more effectively. However, their performance is dependent on the structure–property relationship of the lubricant. Longer saturated chains will increase the viscosity, flash point, and fire point, but reduce the crystallisation behaviour. The presence of unsaturated fatty acids can reduce the pour point but can deteriorate the oxidative stability [133–134].

Salih et al. [143] found that longer mid-chain esters (i.e., the acyloxy group) and increase in the polarity of ricinoleic acid-based diesters improved the low-temperature performance (pour point: $-53.26\text{ }^{\circ}\text{C}$) and friction reduction performance (81.3 %). Since diesters have higher polarity than monoesters, they promote stronger adsorption on the metallic surfaces and improve film strength, thereby increasing their efficiency in reducing friction. Their study also revealed that shorter mid-chain esters had higher oxidative stability (onset temperature: $28.9\text{ }^{\circ}\text{C}$) but tended to have higher volatility than long-chain diesters. These findings aligned with those of Ouyang et al. [142], who reported that medium-chain structures exhibited greater oxidative stability than long-chain diesters. The mixed-chain diester was found to provide a balance between low-temperature performance (pour point: $-57\text{ }^{\circ}\text{C}$) and oxidative stability (onset temperature: $196.6\text{ }^{\circ}\text{C}$).

4.2.1.3 Polyol esters

Polyol esters involve the reaction of fatty acids with polyhydric alcohols such as neopentyl glycol (NPG), trimethylolpropane (TMP), and pentaerythritol (PE). The removal of hydrogen in the beta position (β -hydrogen) and the presence of a central quaternary carbon make polyol esters stable at high temperatures. Polyol esters are widely regarded as one of the most promising bio-based synthetic esters

as they provide a suitable balance of low volatility, good hydrolytic stability, high VIs, lower pour points, and good thermo-oxidative stability [136–137]. Esters with high molecular weight acids or high polyol function typically have low volatility [146]. Ramos Moreira et al. [145] emphasised that the use of polyols without β -hydrogens in the triacylglycerol structure (TMP and NPG) effectively produced oleic acid bio-based lubricants with high thermo-oxidative stability, achieving onset temperatures between 258 and 285 °C. The polyol esters also exhibited similar or better friction reduction and anti-wear performance compared with commercial oil. The anti-wear performance and load-carrying capacity of PE esters produced from Jatropha oil were found to be lower than those of other esters (TMP, trimethylolethane (TME)). In addition, PE esters also possessed excellent thermo-oxidative stability that matched the specifications of ISO VG 68 hydraulic fluids [147].

Raof et al. [148] reported that polyol esters with longer fatty acid chains and mono-unsaturation structures demonstrated superior resistance to oxidative degradation. Their results showed that polyol esters (C18 triesters) exhibited higher oxidation stability (> 500 h) and greater thermal stability than mineral oil (374 h). Sornvoratop et al. [149] revealed that bio-transformer oil from trimethylolpropane triester (TMPTE) met the IEC 62770 transformer oil specifications for dielectric breakdown voltage, viscosity, and flash point, but performed poorly in pour point and oxidative stability. To solve this issue, they blended polyol esters from different plant-based oils and found that the optimal formulation was achieved at 70/30 wt% palm kernel oil (PK)-TMPTE/sunflower oil (SF). Their findings revealed that the polyol ester blends balanced the oxidative stability (15 h) with low-temperature performance (pour point: –10 °C) and the blends fulfilled standard specifications. These findings highlight the importance of balancing steric hindrance and with the unsaturation level generated from the polyols and plant-based oils.

4.2.2 Electrical properties of bio-based oils

Electrical properties are a critical criterion for selecting bio-based oils in EV bearing, as they directly affect reliability under combined mechanical and electrical stress. Key parameters including dielectric

constant, electrical conductivity, and dielectric strength must be evaluated to ensure the lubricants meet both tribological and electrical requirements. The dielectric constant (relative permittivity) governs capacitive charge storage of the film, and it differs between hydrocarbon and ester chemistries. The presence of polar groups makes esters have higher dielectric constants and dissipation factors compared with mineral oil [150]. Palm-based NPG diester shows a relative permittivity of 2.91 compared to its precursor fatty acid methyl ester (FAME) at 2.87. This increase arises from replacing FAME's alkyl groups with the more polar NPG moiety, which enhance dipole-dipole interactions [151].

The dissipation factor, which quantifies dielectric losses, is strongly influenced by ester functionality and purity [152]. Thus, selecting a bio-based oil requires balancing a high dielectric constant with a low dissipation factor to achieve stable electrical behaviour under EV operating conditions. Due to their polar molecular structure, bio-based ester oils naturally experience greater dipolar relaxation and ohmic losses than non-polar mineral oils [153]. Studies by Hambali and Raof [151] provide evidenced that palm-based NPG diester possess higher dissipation factor (0.229) than that of commercial EV fluid (0.03), but present lower value than FAME precursor (7.64). Among monoesters, castor methyl ester displays a higher dissipation factor than palm kernel methyl ester, indicating a stronger molecular polarity due to castor oil's hydroxyl ricinoleic acid chains [137].

Besides that, the dielectric strength can be used as a screening test to identify whether the lubricant can prevent spark discharge under a high electrical field [120]. Dielectric strength of lubricant depends on the molecular structure, purity and test conditions [152]. Esters offer higher dielectric strength than hydrocarbons due to polarity and boiling point [149]. Saji et al. [150] developed monoester blends from pongamia and neem esters, which significantly reduced the dielectric loss (97 %), improved the breakdown voltage (27 %), and had higher oxidative stability compared with the base natural ester, outperforming commercial transformer oils. At the formulation level, blending strategies can further improve electrical properties. Sornvoratop et al. [149] showed that TMP triester (TMPTE)-based

polyol ester, especially blends of palm kernel and sunflower oil esters deliver high dielectric strength compared to mineral oils.

Moisture sensitivity of esters fundamentally will alter their electrical properties compared to mineral oil. Their hygroscopic nature remains a key challenge, making esters highly susceptible to water absorption, especially in humid environments [149]. Walker et al. [154] demonstrated that natural esters possess superior dielectric strength and moisture tolerance compared to mineral oil, whereas synthetic esters were more moisture-sensitive and exhibited weaker breakdown performance. Tenbohlen and Koch [155] confirmed that natural esters have up to 20 times higher water solubility than mineral oil yet maintain strong dielectric strength below ~20 % relative saturation. Okamoto et al. [156] highlighted that ester chemistry (mono-, tri-, tetra-ester linkages) governs moisture sensitivity and the temperature dependence of breakdown voltage (BDV). Their study showed that natural esters, despite high water uptake, retain better tolerance and stronger BDV, with partial recovery at high temperatures due to reduced viscosity suppressing streamer discharge propagation. In contrast, tetra-esters exhibit continuous BDV decline under heat because of their multiple ester linkages. These studies highlight that ester chemistry dictates the balance between moisture adsorption, viscosity effects, and dielectric strength, which ultimately determines electrical reliability under humid conditions.

Besides that, ageing processes fundamentally alter the electrical properties of esters through thermal, oxidative, and hydrolytic degradation. The breakdown voltage of the diester and polyol ester decreased significantly after electrical ageing, while mineral oil and PAO remained relatively constant [123]. The degradation of ester generates polar secondary degradation products, including acidic and polar by-products, which increase dielectric loss through enhanced ionic conduction and interfacial polarisation, and raise the acidity and viscosity of the fluid [152, 156]. These changes raise the dissipation factor and conductivity, and alter the relative permittivity [158]. Moreover, the accumulation of moisture during ageing further compromises dielectric integrity of the esters. Electrically degraded ester oils

absorbed water and promotes the formation of conductive chains that trigger breakdown discharge at lower applied voltage [123]. Comparative ageing studies confirm that polyol ester retains higher resistivity and breakdown voltage than diesters, thereby offering superior electrical reliability under prolonged stress.

4.3 Thickener system design for bio-based greases

Thickener system design is a critical factor in the development of bio-based greases because the thickener not only converts the base oil into a semi-solid lubricant but also influences the properties of the grease in terms of consistency, dropping point, thermal stability, rheology, and lubrication stability [159]. Thickener is dispersed into the base oil to form a three-dimensional (3D) network structure that immobilises the oil through capillary forces, physical entanglement, and oil–thickener interactions [160]. This network determines the softness or hardness of the grease, which is commonly expressed by the National Lubricating Grease Institute (NLGI) grade. The NLGI grade is vital for selecting the right grease for specific applications, as shown in **Table 6** [161]. The most frequently used grease in electric motor applications is NLGI grade 2. The thickener’s consistency also allows the grease to act as a seal for mechanical parts that protect the contact surfaces from external contaminants such as moisture, solid particles, and corrosive environments [144–145].

Moreover, thickeners determine the non-Newtonian flow behaviour of the grease that provides the grease with a yield stress. This means that the grease behaves like a soft solid under low stresses but begins to flow like a viscous fluid when the applied shear stress exceeds the structural strength of the thickener network [119]. During operation, mechanical working disrupts the thickener structure and promotes the gradual release of oil from the network to lubricate the contact surface. Once the oil is lost, the thickener matrix can slowly collapse. Thus, an effective thickener system is required to balance the oil retention and control oil bleeding. Thickeners with an extremely weak structure network may cause excessive oil separation, whereas those with an overly strong network may restrict lubricant replenishment and contribute to starvation under extreme operating conditions [146–147].

Thickener systems are commonly classified into soap-based and non-soap-based thickeners, as shown in **Fig. 8**. Soap-based thickeners include simple, complex, and mixed soaps. Simple soap thickeners are generally formed through the reaction of a fatty acid with a metal hydroxide such as lithium, calcium, sodium, and aluminium [165]. Complex soaps such as lithium, calcium, and calcium sulphonate complexes are formed through the reaction of multiple fatty acids (such as mono and dicarboxylic acids) with a metal ion, resulting in a more stable gel-like structure than simple soaps [166]. Mixed soaps such as lithium–calcium and sodium–calcium are formed through the reaction of fatty acids with two or more metal hydroxides into one structured phase. These soaps are designed to combine the performance advantages of different metal soaps within a single thickener network [167]. Lithium-based grease remains dominant in the commercial market for multi-purpose industrial and automotive applications, accounting for 71 % of the global grease consumption. Lithium-based grease dominates the grease market due to its numerous advantages, including excellent temperature resistance, water resistance, and mechanical stability [168]. However, concerns related to lithium availability, cost and sustainability have promoted studies on the development of alternative thickener systems [169].

Non-soap-based thickeners are commonly divided into organic (polyurea and polytetrafluoroethylene (PTFE)) and inorganic (silica and clay) types. Among these, polyurea has received significant attention as a high-performance alternative to lithium soap thickeners. Polyurea thickeners are formed by the reaction of diisocyanates with amines, producing urea linkages that can form rod-like crystals, fine fibres, or nanotubular structures [153–154]. These structures contribute to their comprehensive performance such as high dropping point, excellent thermo-oxidative stability, good mechanical and colloidal stability, good water resistance, excellent tribological performance under high speeds and temperatures, and the ability to extend the bearing lifespan [154–157]. In addition, inorganic particles such as silica (fumed or amorphous silica) and clays (bentonite or montmorillonite) are another route for developing thermally stable greases. These materials can

provide strong physical networks through particle–particle interactions and surface adsorption of oil molecules, thereby improving chemical stability and providing excellent load-carrying capacity and high melting point [175]. However, they have low colloidal stability and oil compatibility. Poor dispersion stability may lead to unstable rheology and weak oil release under operating conditions [159–160]. Researchers are focusing on tailoring the morphology and microstructure to improve the grease’s high-temperature stability, anti-corrosion capability, and tribological performance to ensure long-term mechanical durability [117, 177–178].

Table 6 NLGI classification of lubricating greases based on consistency [161]

NLGI grade	Work	
	penetration (tenth of a millimeter)	Consistency
000	445 – 475	Very soft
00	400 – 430	
0	355 – 385	Soft
1	310 – 340	Soft
2	265 – 295	Creamy texture (buttery)
3	220 – 250	Semi-solid
4	175 – 205	Stiff
5	130 – 160	Stiff
6	85 – 115	Hard solid

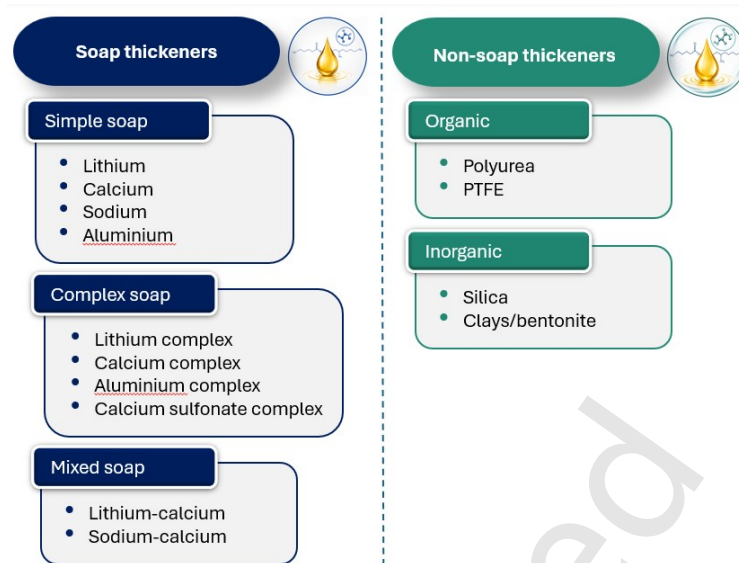


Fig. 8 Categories of thickeners.

4.3.1 Soap-based thickeners

Numerous scholars have paid great attention to the relationship between the microstructure of thickeners and the properties of grease, including yield stress, dropping point, and oil separation. Saatchi et al. [180] clarified that the morphology of thickeners played a significant role in their ability to bind with the base oil molecules. They revealed that a lithium complex with a rod-like structure bled steadily, whereas calcium sulphonate with a spherical structure delayed bleeding. Their results indicated that a higher thickener aspect ratio spaced the oil molecules apart at the point of structural opening, thereby improving the grease's ability to resist oil separation. Temperature processing can be used to control the thickener morphology and improve grease performance. During the cooling process of the grease solution to ambient temperature, a slow cooling rate was preferable to form longer fibres of the lithium grease [181]. The structural complexity will improve the grease's stability and provide higher temperature stability. Lehninger et al. [166] found that lithium greases containing both mono- and dicarboxylic acids had a higher dropping point (240 °C) than simple lithium 12-hydroxystearate (190 °C). Lithium complex soap with a spiral fibre structure was found to provide a superior dropping point (338 °C) and low oil separation compared with calcium sulphonate complex soap, polyurea, and bentonite. Zhou et al. [165] found that the good compatibility of lithium complex soap with the base

oil provided a high elastic modulus and the highest yield stress, thereby reducing the ability of the oil to bleed and minimising grease degradation.

In contrast, Li et al. [177] found that the porous agglomerate morphology of calcium sulphonate complex soap provided excellent colloidal stability compared with fibrous structures (polyurea and lithium), thereby enabling a multi-level pore storage mechanism for the base oil. Stable fibrous or agglomerate structures (calcium sulphonate, lithium, and polyurea) provided excellent oil retention compared with lamellar or particle-based thickeners (PTFE, bentonite, and nanosilica). Kozdrach [175] revealed that calcium stearate grease exhibited stronger viscoelastic properties and a better balance of low-temperature fluidity than lithium and aluminium stearate greases. Stronger viscoelastic properties are required to ensure that the grease can resist structural changes under the influence of applied forces. Moreover, Jia et al. [182] demonstrated that the molecular polarity influenced the growth process of calcium carbonate thickener. During this process, the shape of the thickener gradually changed from flake to rod and the aspect ratio was increased. They performed molecular dynamics simulation and provided evidence that the molecules of lauric acid and lauric amine were adsorbed upright on the surface of the thickener, which enhanced the hydrophobic lipophilicity of the thickener, as shown in **Fig. 9**. The higher thickener aspect ratio and strong surface lipophilicity can simultaneously improve low-temperature fluidity and high-temperature stability of calcium sulphonate grease.

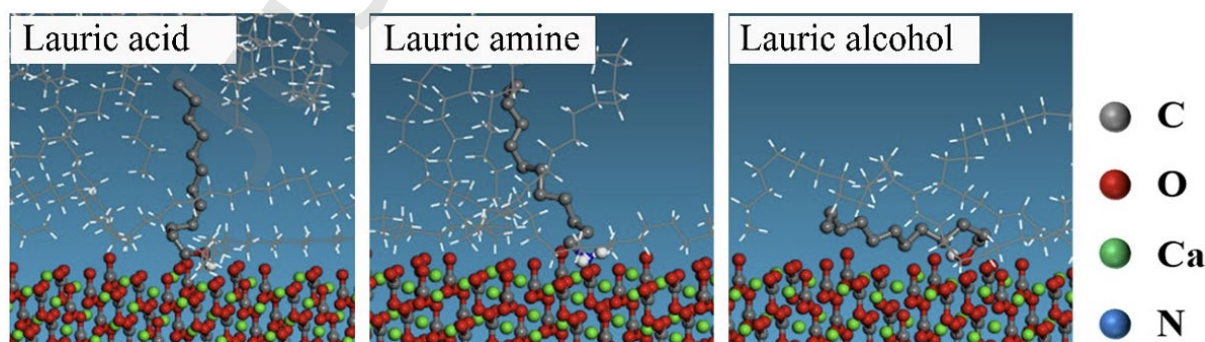


Fig. 9 Adsorption model of different organic molecules on the surface of the calcium sulfonate thickener [182].

In addition, the microstructure and concentration of thickeners influence the formation of the lubricating film thickness. Wang et al. [183] showed that the effect of thickener content was more pronounced with higher base oil viscosity and under higher speed conditions. A higher thickener content increased the lubricating film thickness by 10-fold, thereby improving the load-carrying capacity. Although large fibres with dense entanglement improved the load-carrying capacity, they reduced the fluidity and recoverability of the grease. Li et al. [177] discovered that the effects of thickener type were most effective at low speeds and elevated temperatures. Rapeseed oil thickened by calcium stearate was found to have better anti-wear performance than other soap thickeners (lithium stearate and aluminium stearate). This phenomenon is attributed to the stronger viscoelastic properties of the grease, which minimise structural changes during operating conditions [175]. Zhou et al. [165] found that calcium sulphonate complex grease exhibited optimal tribological performance due to the synergistic effect between the thickener-deposited film and the tribochemical film composed of iron oxide, iron sulphide, iron sulphate, and calcium oxide. This aligned with the findings of Wu et al. [184], who found that calcium sulphonate grease had lower wear than lithium grease due to the large area of layered thickener, forming a deposited film.

The thickener reactants can also influence the grease performance. Negi et al. [118] formulated calcium complex grease using pentaerythritol tetraoleate ester with different types of complexing agents such as sebacic acid and azelaic acid. They discovered that sebacic acid in polyol ester grease provided the best anti-wear performance (10.6 % reduction) whereas the mixture of sebacic acid and azelaic acid in a molar ratio of 2:1 reduced the COF by 19.8 %. Based on their results, azelaic acid was not preferred as a complexing agent in calcium complex grease since it yielded inferior tribological performance. Their findings aligned with those of Ren et al. [185], who found that lithium complex grease prepared with azelaic acid as a complexing agent resulted in fluctuating friction curves due to unstable film thickness under harsh working conditions. They also demonstrated that the presence of boric acid as complexing agents enhanced the tribological performance. The fibre soap network was

further strengthened with the presence of boric acid since it allowed the formation of coordination bonds between the oxygen atom of carboxyl and the boron atom of lithium tetraborate, which enhanced the lipophilicity of the soap. The synergisms between boric acid and dodecanedioic acid resulted in enhanced structural strength, optimised physicochemical properties, and improved tribological performance. This contrasted the results of Sun et al. [186], who found that the antagonistic effects of boric acid on the calcium carbonate in the thickener resulted in poor tribological performance under high-load conditions. This contradiction highlights that the lubrication mechanisms of grease depend on the synergistic interactions between the thickener's deposited film and tribochemical film layers.

A recent study discovered that lithium complex grease was highly sensitive under electrified conditions compared with aluminium complex and calcium sulphonate greases. Lithium grease exhibited a significant increase in friction by 72 % and wear increased by 1248–1684 % due to micro-arc and pitting. Calcium-based greases exhibited the lowest impedance and highest conductivity, thereby enabling better charge transport behaviour at the grease-metal interface [187]. Moreover, lithium-calcium complex grease was found to be less suitable for EV motor bearings due to its high resistivity. This characteristic will promote the electrical charge at the bearing contact surface, thereby resulting in higher bearing noise levels [18]. Conductive additives are required to ensure that the greases can effectively redistribute electrical current within the lubricant and force the current to pass through the asperity contacts [116].

4.3.2 Non-soap thickeners

Many attempts have been made to formulate polyurea greases and identify the effects of thickener microstructure on the grease properties. Ren et al. [164] showed that the type of amine and ratio strongly influenced the grease performance. They synthesised polyurea grease by reacting diphenylmethane diisocyanate (MDI) with various organic amines, including octadecylamine, cyclohexylamine, and p-toluidine. They demonstrated that organic amine combinations (cyclohexylamine/p-toluidine) produced greases with a high dropping point (305 °C) and excellent

colloidal stability. Other research groups have shown that the type of diisocyanate used in polyurea influences the structural integrity of the network. Chen et al. [170] synthesised polyurea grease through the reaction of different diisocyanates such as MDI, hexamethylene diisocyanate (HDI), and toluene diisocyanate (TDI) with octadecylamine. Their results showed that aromatic MDI produced compact and stable networks (short-rod fibres), resulting in a higher dropping point (262 °C), the lowest oil separation (2.7 %), and the highest yield stress and recovery rate (79.5 %). Ding et al. [171] added another dimension by showing that mechanical shearing during grease preparation altered the structure. They found that the thickeners formed by the reaction of MDI-octylamine prepared through stirred heat treatment altered the morphology from nanotubes to long-pitch twisted fibres, producing more stable grease with higher consistency.

Moreover, longer fibres can further improve the structural stability of the thickener network, which can be achieved by increasing the polymerisation degree of the base oil and using a low polarity of the base oil. Wang et al. [169] revealed that a higher degree of base oil (commercial polyether oil) polymerisation induced more hydrogen bonds and improved the thickener's binding ability with the base oil. Mechanical shearing during the synthesis of polyurea greases was also found to influence the microstructure and grease properties. Wang et al. [173] highlighted the importance of selecting the base oil for lubricating greases. The strongest binding ability of polyurea with the base oil was achieved with a non-polar base oil (PAO40), which has a 3D network structure composed of long fibres. The structural strength reduced in the order of PAO40 (yield stress: 153.11 Pa) > alkyl naphthalene oil (yield stress: 118.36 Pa) > polyether oil (yield stress: 73.07 Pa), showing distinct characteristics of microstructure from long fibres to rod-shaped fibres to short rod-shaped fibres.

Clay thickeners are required to undergo surface modification through acid activation or organophilic treatment to improve their dispersion and oil compatibility. Intercalation of montmorillonite clay with organic cationic surfactants will expand the interlayer spacing and transform hydrophilic clay into organophilic or hydrophobic [188]. Hasan et al. [189] systematically studied how different types of

acid activation such as nitric acid (HNO_3), hydrochloric acid (HCl), and sulphuric acid (H_2SO_4) altered the surface chemistry of bentonite. The activation process successfully enhanced the surface area and porosity of the treated bentonite, which was confirmed by the removal of aluminium layers from the lattice of the bentonite. The increment in pore size facilitated the oil and thickener interactions during the preparation of the lubricating grease. Nitric acid treatment was found to be the most effective activation as it possessed the highest dropping point and mechanical stability. Compared with other soap-based thickeners, montmorillonite grease exhibited the lowest structural viscosity and moderately strong viscoelastic properties [175]. This thickener also offered strong thixotropic properties where the network can be disrupted under shear and gradually recovered when the stress was removed, as shown in **Fig. 10**. These findings corroborated with those of Liu et al. [190], who discovered that nanosilica grease possessed superior instantaneous thixotropy with a recovery rate of 125 and 118 % at 50 and 150 °C, respectively, outperforming lithium and polyurea greases. This characteristic is beneficial in applications where the grease must be softened during sliding and recover after shear stops [176].

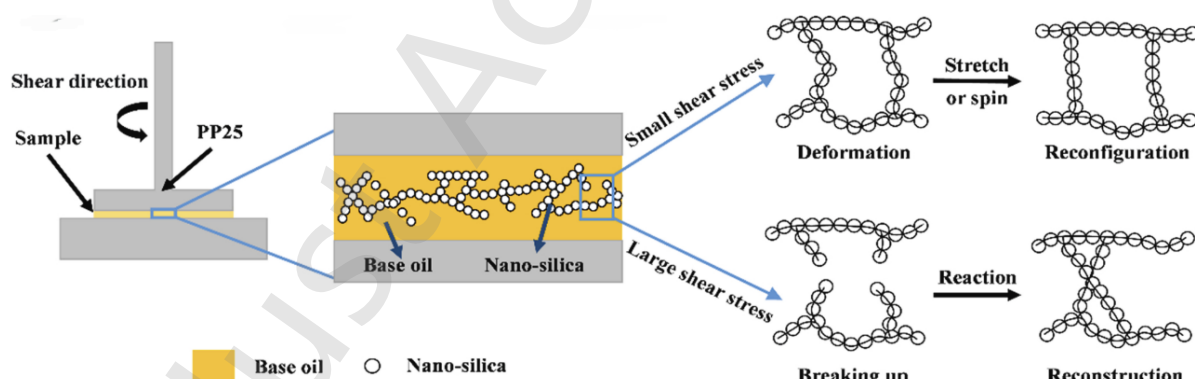


Fig. 10 Dynamic evolution of the microstructural changes of greases under different shear stresses [190].

Liu et al. [190] demonstrated that nanosilica grease provided excellent tribological performance compared with lithium and polyurea greases. The oil film tended to break under harsh conditions, where the rheological properties of the grease, such as strength and thixotropy, played a critical role in the formation of tribochemical films. This finding was complemented by the results of Kozdrach [175] who agreed that silica thickeners (amorphous silica and montmorillonite) had superior load-

carrying capacity to soap-based thickeners due to their ability to balance between flowability and film durability. Furthermore, integrating nanomaterials with non-soap thickeners enhanced microstructural stability and tribological performance. Hao et al. [191] developed a composite by grafting MoS₂ within the organically modified montmorillonite thickener framework. This synergistic combination prevented agglomeration of MoS₂ within the matrix, resulting in improved stability and significantly enhanced friction reduction (68 %) and anti-wear performance (83 %) compared with mechanically mixed grease.

Previous studies provide evidence that the molecular structure of polyurea grease plays a significant role in the tribological performance. Wang et al. [173] highlighted that the base oil chemistry was crucial to optimise grease performance. They found that non-polar base oil produced long, tightly packed fibres that enhanced base oil binding, demonstrating outstanding thermal stability, tribological performance, and low-noise performance. In contrast, highly polar base oil produced short fibres with a weaker network due to the oil competing for hydrogen bonding sites, leading to higher oil separation and poorer tribological performance. Wu et al. [160] extended this perspective by varying the polymerisation degree of metallocene PAO oils. They revealed that high polymerisation oils produced longer fibres and looser networks. This allowed self-assembling structures and generated numerous short fibres under shear and new cross-linking, forming a denser network. This improved structural strength at high temperatures, enabling the continuous release of base oil at the contact surfaces and thereby enhancing tribological performance.

Furthermore, mechanical shearing directly modulates the balance between flowability and stability in polyurea greases. Ding et al. [171] revealed that static heat treatment produced nanotube structures that had higher oil bleeding and were favourable for high-speed lubrication. In contrast, stirred treatment produced twisted fibres with stronger thickening and stability, which were favourable for boundary lubrication. This morphological alteration under shear stresses demonstrates how controlled processing can change the microstructure of thickeners for specific mechanical requirements. Sha et

al. [172] further extended the morphological evolution through mechanical–thermal ageing, showing a structural transition from entangled fibres to large-diameter rods and, finally, to spherical aggregates. They found that the grease had the best tribological performance when fibrous and rod structures co-existed. However, continued degradation led to a decline in the tribological performance. A hydrogen-bonded eutectic polyurea system complexed with $\text{Ti}_3\text{C}_2\text{Tx}$ MXene demonstrated co-release of thickener and nanosheets at the tribological interface, increasing film thickness (up to 211 nm at 200 mm/s) and resisting squeeze-out under high pressure [11].

It can be deduced that the thickener system plays a decisive role in extending the grease's operational lifespan, which depends heavily on the thickener's ability to maintain structural stability. Researchers use different approaches to alter the microstructure of the thickener, such as chemical composition, processing conditions (mechanical shear, refining temperature, and cooling rate), and base oil–thickener interactions, to tailor grease performance for specific operating conditions. Development of bio-based EV greases requires integrating strong initial networks and resistance to structural degradation to ensure stability and adaptability under thermal, mechanical and electrical stresses. A critical gap exists in developing predictive frameworks that link microstructural evolution pathways to long-term stability under electrified tribological systems.

4.4 Additive strategies

Additives are incorporated into grease formulations to improve the intrinsic properties of the base oil and thickener system. The choice of additives is crucial as it depends upon the specific requirements for various conditions, including elevated temperatures and extreme and corrosive environments [168]. Typical additives used in lubricating greases include antioxidants, anti-wear (AW) agents, extreme-pressure (EP) agents, friction modifiers, and corrosion inhibitors. The effectiveness of these additives depends on the operating conditions and their compatibility with the base oil and thickener [192].

4.4.1 Antioxidants

Antioxidants are used as additives to delay oxidation and maintain the performance of lubricating grease. Antioxidant additives used in lubricant formulations can be broadly classified into primary radical scavengers, such as hindered phenols and aromatic amines, and secondary peroxide decomposers, such as sulphur-, phosphorus-, sulphur-phosphorus-, and molybdenum-containing compounds [193]. Grease-lubricated bearing failures occur due to multiple factors such as mechanical degradation, evaporation, oil leakage, contamination, and thermo-oxidative degradation [194]. Grease in bearings fails primarily when antioxidants have been consumed, especially at high operating temperatures [195]. Oil separation from the grease will begin once oxidation occurs, and the grease loses its lubricating ability when the oil separation reaches 50–60 % [196]. The grease reaches the end of its life when the lubricant can no longer provide sufficient lubrication, thereby causing bearing failures. Li et al. [197] highlighted that MgAl-layered double hydroxides (LDH) could be a beneficial green antioxidant for heavy-duty industrial grease. The LDH outperformed conventional additives, where the LDH extended the grease's service lifetime by 20 %. The LDH gave the best balance in oxidative stability and better low-temperature viscosity behaviour at the optimum concentration (2 %). This is attributed to the hydroxyl groups that can quench alkyl and alkoxide free radicals generated during lubricant oxidation.

The effectiveness of the antioxidant additives depends on the chemical reactivity and compatibility with the base oil or grease matrix. Xiong et al. [198] evaluated the influence of natural antioxidants such as ferulic acid and its ester derivatives (ethyl ferulate and isooctyl ferulate) on the oxidative stability of pentaerythritol oleate. They revealed that the anti-oxidation activity depended on physical factors such as solubility and dispersion. The longer alkyl chain (isooctyl ferulate) provided optimum oxidation performance and superior viscosity stability, showing a 300 % increase in the oxidation induction time (OIT) and the smallest viscosity growth rate (18.63 %) compared with the base oil. However, Miao et al. [199] found that the OIT improvement was independent of alkyl chain length in

polar oils such as synthetic ester base oil di-iso-octyl sebacate (DIOS) and soybean oil. In polar oil, the nitrogen–hydrogen (N–H) bond dissociation energy remained the primary determinant of performance. Conversely, in non-polar oils such as PAO and liquid paraffin, the OIT depended on the alkyl chain length. This occurred because the polarity of synthetic diphenylamine antioxidants matched that of the base oil. The polarity of diphenylamines decreased as the length of the alkyl chain increased, thereby enhancing solubility in non-polar oil. Moreover, they demonstrated that adding antioxidants reduced the wear rate by 50 % by preventing sludge and carbon deposition, thereby protecting the contact surfaces from severe oxidation. These studies indicate that the compatibility between the additive and base oil polarities influences the performance of the antioxidants.

4.4.2 Corrosion inhibitors

Corrosion inhibitors are used to prevent corrosion of the metal parts in contact with the lubricant. The polar constituent will adsorb on the metal surface to provide a protective film against corrosive agents [22]. Sulphonate detergents are multi-functional lubricant additives that provide anti-corrosion, cleaning, friction reduction, and wear resistance properties. Zheng et al. [200] developed calcium complex grease using different overbased sulphonates (calcium and magnesium) as thickeners. The mixture of overbased sulphonates enhanced corrosion resistance, as well as physicochemical, rheological, and tribological properties. Grease with a higher concentration of magnesium sulphonates had superior thermal stability and structural integrity. The high alkalinity of overbased sulphonates could neutralise acidic by-products from oxidation or moisture, protecting the surface against erosion. The polarity of sulphonates and the carbonate particles created protective coatings that enhanced the chemical stability of metal surfaces.

As mentioned in Section 3.3, IL have drawbacks, including corrosive potential and reduced efficiency at high temperatures. This is attributed to the hydrolysis of fluorine-containing anions and other halogen impurities during friction, forming a product such as hydrofluoric acid. These challenges can be mitigated by adding corrosion inhibitors and developing functionalised IL [201]. Su et al. [201]

added benzotriazole (BTA) as a corrosion inhibitor in fluorine-containing imidazolium IL (1-butyl-3-methylimidazolium hexafluorophosphate) as the base lubricant. Under current-carrying friction, they provided evidence that the BTA inhibited arc-induced electrical erosion and reduced the electrical contact resistance (ECR). This is because of the synergistic mechanisms between BTA and IL enable the formation of a chemisorbed protective film. Ma et al. [202] synthesised two novel IL, namely, (4- or 5-methyl-benzotriazole-1-ylmethyl)-octadec-9-enyl-ammonium bis(2-ethylhexyl) phosphate and (4(or 5)-methyl-benzotriazole-1-ylmethyl)-dioctyl-ammonium bis(2-ethylhexyl) phosphate as additives in PAO. The existence of long hydrocarbon chains enhanced their compatibility with less polar base oil and improved the solubility of the IL. Both of these IL exhibited anti-corrosion, anti-rust, and anti-wear properties as well as load-carrying capacity.

4.4.3 AW and EP agents

AW and EP agents are used to prevent surface damage by forming a chemical protective film on contact surfaces under boundary or extreme pressure conditions, thereby minimising friction and wear [203]. In grease formulations, these additives are vital because the base oil and thickener network alone are often insufficient to protect rolling contacts under the demanding operating conditions of EVs, including high speeds, elevated temperatures, and the presence of electrical currents [4]. Traditional AW and EP agents are commonly based on reactive elements such as chlorine, sulphur, and phosphorus, and they typically act through adsorption, thermal or mechanical decomposition, and tribochemical reactions, generating protective boundary films [20]. Among these additives, zinc dialkyl dithiophosphates (ZDDP) remain one of the most established benchmark additives in industrial oils and greases [204]. However, ZDDP do not behave independently in formulated lubricants and their performance is strongly dependent on interactions with other additives, surface chemistry, and operating conditions [184–187]. Hence, research is ongoing to use ZDDP as both practical and reference additives to understand additive behaviour under coupled mechanical and electrical stresses, as well as to guide the development of new AW and EP agents [49, 183, 188–189].

The synergistic and antagonistic effects of ZDDP with other additives strongly depend on the additive chemistry and concentration ratio. Reimers et al. [208] evaluated the effects of two different corrosion inhibitors such as calcium sulphonate and zinc carboxylate on the wear protection of AW and EP additives (ZDDP and trialkyl phosphate). Their results showed that zinc carboxylate synergistically enhanced ZDDP performance by acting as an oxygen donor to assist the formation of oxide and phosphate layers. In contrast, calcium sulphonate reduced the ZDDP effectiveness, indicating an antagonistic interaction that suppressed the formation of a zinc-containing boundary layer. Reimers et al. [207] examined the effect of additive ratio. They demonstrated that a ratio of 0.25 wt% of corrosion inhibitor to 1.0 wt% of ZDDP provided an optimal balance between wear protection and corrosion resistance. They found that corrosion protection was worse when using an excessive amount of corrosion inhibitor (0.5 wt%) compared with using ZDDP alone. These findings show that AW and EP agent performance must be evaluated in the context of formulation balance.

In addition, the grease matrix itself can influence the efficiency of AW and EP agents. Reddy et al. [205] critically compared the behaviour of ZDDP and molybdenum dithiocarbamate (MoDTC) additives in lithium complex and polypropylene greases. They found that the thickener chemistry could shift the additive response from effective to antagonistic. In the lithium complex thickener, the ZDDP formed only thin and unstable tribofilms, whereas the MoDTC was unable to generate effective MoS₂ films. This is due to the interference from the polar lithium ions, which may intercalate into iron oxide or phosphate surface layers and interfere with the formation of tribofilms. In contrast, the non-polar polypropylene grease promoted more effective tribofilm formation and reduced energy consumption by 30 %. These findings indicate that the performance of AW and EP agents in grease is governed not only by the chemical reactivity of the additive but also by the thickener chemistry and additive compatibility.

The growing demand for sustainable alternatives has shifted the focus towards nanoparticles and IL as promising candidates to replace or complement conventional AW and EP agents. Nanoparticle-

based additives have been widely explored as alternative AW and EP agents due to their remarkable potential in minimising friction and wear [203]. The underlying mechanisms for the reduction in friction and wear are through rolling, polishing, mending, third-body protection, surface deposition and tribofilm formation [112, 190]. Their performance depends on the particle size, morphology, concentration, surface functionalisation, dispersion stability and polarity of the base oil [212]. IL are also attractive due to their exceptional oil solubility and the ionic structure can promote strong surface adsorption of the tribofilm and charge transport [213]. For EV bearing greases, nanoparticles and IL are attractive because they enable simultaneous control of wear, load-carrying capacity, and electrical behaviour. This has been discussed in Section 3.3.

These findings demonstrate that AW and EP additive performance in grease is governed not only by the chemical reactivity of the additive but also by additive–additive interactions, thickener chemistry and the polarity of the base oil. This is particularly important for bio-based EV bearing greases, where polar ester base oils, thickener networks, and electrical function additives may compete for adsorption sites or alter tribofilm formation. The synergistic and antagonistic mechanisms between additives under electrical stresses require further systematic exploration.

5 Conclusions

This paper presents a comprehensive review of existing mitigation strategies for reducing electrical discharge damage in EV bearings, including motor and inverter design optimisation, bearing materials and surface engineering, and lubrication-based approaches. This review highlight that while significant progress has been made in mitigating electrical discharge damage in EV bearings, three main core scientific challenges persist particularly concerning:

- Core scientific challenge 1 lies in quantifying the optimal conductivity–dielectric-strength–wear window. Conductive additives dissipate charge but degrade beyond well-defined thresholds: carbon nanoparticles protect the contact up to 1 A, after which Joule heating drives agglomeration and oxidation [109]; IL greases raise the breakdown threshold from 1.4 V to 3.9 V, yet excess IL

dilutes base-oil viscosity and erodes dielectric strength [39]; composite formulations have shown promise, with hydrogen-bonded eutectic polyurea grease complexed with $\text{Ti}_3\text{C}_2\text{Tx}$ MXene reduced wear volume by 91 %, lowering contact resistance, and suppressed electrical erosion at low loadings, though higher concentrations intensified mechanical wear [11]. Insulating additives delay breakdown: nano-montmorillonite increases AC breakdown voltage by 21 % to 6.54 kV via electron trapping but cannot prevent voltage beyond their own limits [115]. The operational windows summarized in Table 4 remain additive-specific and rig-dependent, a unified quantitative framework that jointly maps conductivity, dielectric strength, and wear performance as functions of current density, and other operating conditions is still missing.

- Core scientific challenge 2 lies in understanding thickener-additive-electric field interactions. The electrically active medium in a bearing grease is not the base oil alone but three phase system of base oil, thickener, and additive, and the interactions between three phases govern the electro-tribological response. MWCNT obstruct lubricant flow into the contact, thinning the film and lowering the discharge threshold [1]; in hydrogen-bonded eutectic polyurea grease complexed with $\text{Ti}_3\text{C}_2\text{Tx}$, MXene nanosheets are released at the tribological interface together with the thickener itself so that the additive delivery is mediated by thickener structure [11]; silver nanoparticle grease shows the reverse direction of coupling, showing the additive carrier fluid decrease flow point, altering the rheology and thereby the film formation behaviour of the grease [43]. The research gap lies in the absence of a unified framework that quantitatively links thickener-additive-electric field interactions, leaving grease performance under realistic EV bearing environment poorly understood.
- Core scientific challenge 3 lies in assessing long-term ageing effects on dielectric properties. Electrical properties are service-dependent quantities, with discharge themselves acting as a degradation pathway. Ageing, however, degrades the grease structure even in the absence of discharge activity. At the base oil level, ester lubricants show significant breakdown voltage

decline after electrical ageing, coupled to moisture absorption, whereas mineral oil remains comparatively stable [123]. Under coupled mechanical-thermal ageing, the entangled ribbon-network of polyurea grease transform into coarser network, weakens viscosity, and triggers base oil bleeding and oxidation. Since the thickener network governs film continuity, the dielectric barrier separating bearing elements, the protection window of a grease is inherently time-dependent, and tribological decline begins once structural decay accelerates oil loss [172]. Current ageing protocols are dominated by thermal exposure and fail to capture the coupled thermal-electrical-mechanical effects with thickener network decay and dielectric properties. Defining standardized thermal-electrical-mechanical stress ageing tests that realistically predict the service life of bio-based grease formulations hence represents the third core challenge.

Bridging these core challenges lies not only in advancing fundamental understanding but converting it into practical engineering recommendations. Practical engineering solutions require matching mitigation strategies to the electrical environment. (i) Hybrid mitigation strategies: combining source-level filtering, grounding, and insulation with lubricant-level charge dissipation, offer complementary protection, reducing residual shaft-voltage while conductive greases convert remaining charge into low energy resistive currents. (ii) Grease selection should be voltage specific: high dielectric formulations work best under steady low-voltage stress, while conductive greases with tuned percolation networks are more effective when shaft voltage build-up is unavoidable. For systems that experience both regimes, functionalized thickener-additive blends offer a balanced solution, combining electrical protection with stable tribological performance.

Molecular dynamics simulations may further strengthen the mechanistic understanding of ester-thickener interactions, additive adsorption, tribofilm formation, and charge transport at lubricated interfaces. In parallel, thermal-cycling studies resolve how molecular architecture and processing history govern grease agglomeration pathways [181]. Beyond these bottom-up and empirical approaches, artificial intelligence (AI) and machine learning (ML) offer a complementary route to

rational design sustainable grease by linking base oil composition, thickener structure, additive chemistry, and operating conditions with tribological and electrical performance metrics. Recent studies have demonstrated that the use of Gaussian process regression (GPR) to predict lubricant film behaviour and guide lubrication optimization [214], a multi-feature fusion hybrid deep learning model (MFHDL) for additive monitoring [215], and ensemble ML for nanoparticle concentration tuning [216]. Xia et al. [217–218] further showed that ensemble and hybrid ML frameworks; stacking k-nearest neighbors (KNN), random forest (RF), gradient boosting decision tree (GBDT) base learners with synthetic minority oversampling technique (SMOTE) augmentation, or combining Sparrow Search Algorithm (SSA) with Gaussian Data Augmentation (GDA) and Least squares Support Vector Machine (LSSVM); can predict tribological performance and optimize additive ratios under small-sample conditions. Kernel-based and quantum ML approaches extend these ideas to early-cycle prediction, although the classical models remain more stable under cross-validation and quantum methods are sensitive to hyperparameter selection [219]. Li et al. [220] similarly combined neural networks with genetic algorithms (GA-BP networks) to predict scuffing failure in grease lubricated bearings.

Current studies focus either monitoring additive activity, optimizing parameters, predicting tribological and dielectric prediction separately. What is missing is a unified framework that integrates monitoring, prediction, and optimization across chemical, mechanical and electric domains. AI and ML are useful tools to transform grease research from trial-and-error formulation into predictive, data-driven optimization against multiple objectives, reducing costs and enabling sustainable, high-performance greases that simultaneously meet the physicochemical, tribological and electrical requirements of EV bearing applications [217–218]. Without training on electro-tribo-mechanical performance, predictions risk being disconnected from the failure mechanisms central to grease reliability. Integrating these approaches into a unified, interpretable framework will accelerate the

rational design of greases, advancing both performance and sustainability in next-generation EV systems.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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