UNDER PRESSURE: THE NEW CHEMISTRY OF ANTI- WEAR ADDITIVES

Abstract

Lubricants play an important role in reducing friction and extending the lifespan of equipment used in automotive, industrial, and hydraulic systems. Traditional antiwear (AW) and extreme pressure (EP) additives often rely on sulfur, phosphorus, and metal-based compounds, many of which raise environmental concerns because they do not biodegrade easily and can emit harmful emissions. Newer additive technologies, such as ionic liquids, nanoparticles, and bio-based formulations, offer a more environmentally friendly alternative by forming strong protective tribofilms at surfaces under friction. Additionally, improvements to bio-based additives have addressed many of their earlier limitations, including poor oxidation resistance and limited performance at extreme temperatures. As a result, these next-generation AW and EP additives deliver high performance while reducing the environmental impact compared to older lubricants.

I. Introduction

As the lubricant gap height (h) decreases from the hydrodynamic to the boundary lubrication regime, the fluid film becomes too thin to support the applied load, preventing surface asperities from interacting [1, 2]. In this scenario, direct metal-to-metal contact occurs, leading to high shear stresses and frictional heating at the interface [1]. Since hydrodynamic pressure is no longer enough to prevent wear, protection depends on chemical reactions between the lubricant additives and the surface. AW and EP additives react with the substrate under thermal and mechanical stress to form protective tribofilms that reduce surface damage and friction, as seen in Figure 1 [1, 2].

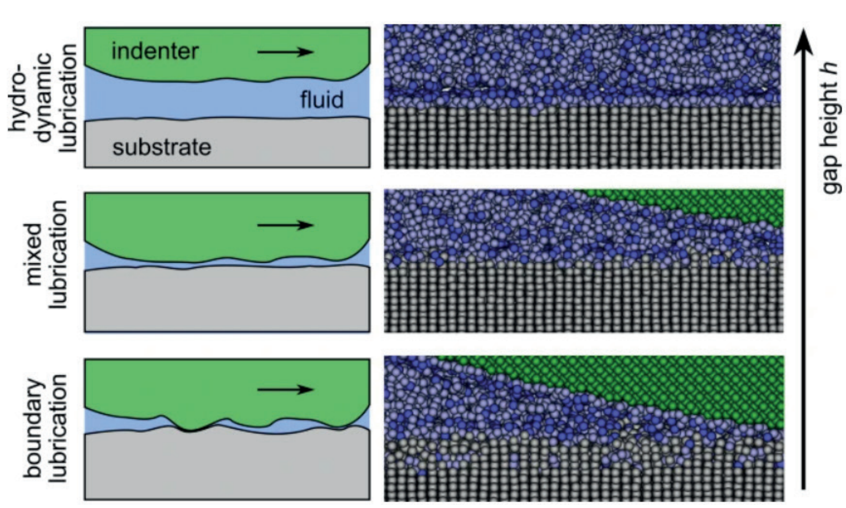

Figure 1. Illustration of the three lubrication regimes and how the thickness of the lubricant film between two moving surfaces changes during operation [2].

Traditional AW and EP additives, including zinc-, sulfur-, and phosphorus-containing compounds, have provided effective wear protection for decades. However, growing environmental concerns and stricter regulations have increased interest in alternative technologies. Many conventional additives can contribute to environmental contamination, emissions-system issues, or disposal challenges, creating pressure to develop more sustainable solutions [13,20].

At the same time, modern equipment continues to demand higher levels of performance. Engines operate under greater thermal and mechanical stresses, while industrial gear systems and hydraulic equipment are expected to achieve longer service intervals and improved efficiency. Emerging technologies such as electric vehicles (EVs) introduce additional lubrication challenges, requiring formulations that can provide excellent thermal stability and wear protection while supporting sustainability goals [1,16,18].

As a result, researchers and lubricant manufacturers are exploring next-generation additive technologies that combine high performance with reduced environmental impact. Promising developments include ionic liquids, nanoparticle additives, phosphorus-free chemistries, and bio-based lubricant formulations derived from renewable resources [12,20]. Studies have shown that these technologies can improve friction and wear performance while offering advantages such as biodegradability, reduced toxicity, and lower dependence on fossil-based materials [18].

II. Overview of Antiwear and Extreme Pressure (EP) Additives

Antiwear (AW) and extreme pressure (EP) additives are essential components of modern lubricant formulations. While base oils provide lubrication and cooling, these additives improve performance under demanding conditions by protecting metal surfaces when lubricant films are too thin to prevent contact. Without AW and EP additives, machinery would experience increased friction, accelerated wear, reduced efficiency, and shorter service life [1].

AW additives primarily operate under boundary lubrication conditions, where limited lubricant film thickness causes surface interaction. They react with metal surfaces to form protective tribofilms that reduce metal-to-metal contact and minimize wear. These additives are widely used in automotive engines, hydraulic systems, compressors, and other applications involving repeated surface contact [1].

EP additives provide protection under more extreme conditions, including high loads, temperatures, and contact pressures. They react with metal surfaces to form durable protective compounds that prevent severe damage such as scuffing, welding, and catastrophic wear. Unlike AW additives, EP additives activate primarily under critical pressure and temperature conditions, providing protection when conventional lubrication is insufficient [15]. A comparison of AW and EP properties can be found in Table 1.

AW and EP additives differ mainly in the severity of conditions they are designed to handle. AW additives protect surfaces during moderate boundary lubrication, while EP additives provide additional protection under extreme loads and pressures. Many lubricant formulations use both to maintain performance across a range of operating conditions. As shown in Figure 2, contact geometry affects pressure profiles (P) and gap heights (H), with regions of high pressure and severe film thinning requiring more reactive EP chemistry, while areas with lower stress levels can rely on AW protection [3, 7]. AW and EP additives are widely used throughout industry. Automotive engines rely on antiwear additives to protect valve trains, pistons, and bearings from long-term wear. Industrial hydraulic systems use AW additives to protect pumps and valves from damage caused

Table 1: Comparison of properties between AW and EP additives [15].

Feature / Property	Antiwear (AW) Additives	Extreme Pressure (EP) Additives
Operating Conditions	Moderate loads and continuous sliding in boundary lubrication	Heavy loads, shock loading, and extreme thermal environments
Activation Trigger	Frictional heat generated by moderate surface-to-surface contact	Intense localized heat and high shear stresses under heavy loading
Chemical Reaction	Adsorbs or reacts mildly with the metal to form a thin, protective tribofilm	Reacts chemically with the metal to form high-shear-strength metal-salt films
Primary Objective	Reduces gradual wear and extends overall component lifespan	Prevents catastrophic failure, including micro-welding, scuffing, and seizing

by repeated operation. Gearboxes, transmissions, and heavy industrial equipment often require EP additives because of the high loads experienced by gear teeth and bearing surfaces. These applications demonstrate the critical role that additive technology plays in maintaining equipment reliability and reducing maintenance costs [1,17].

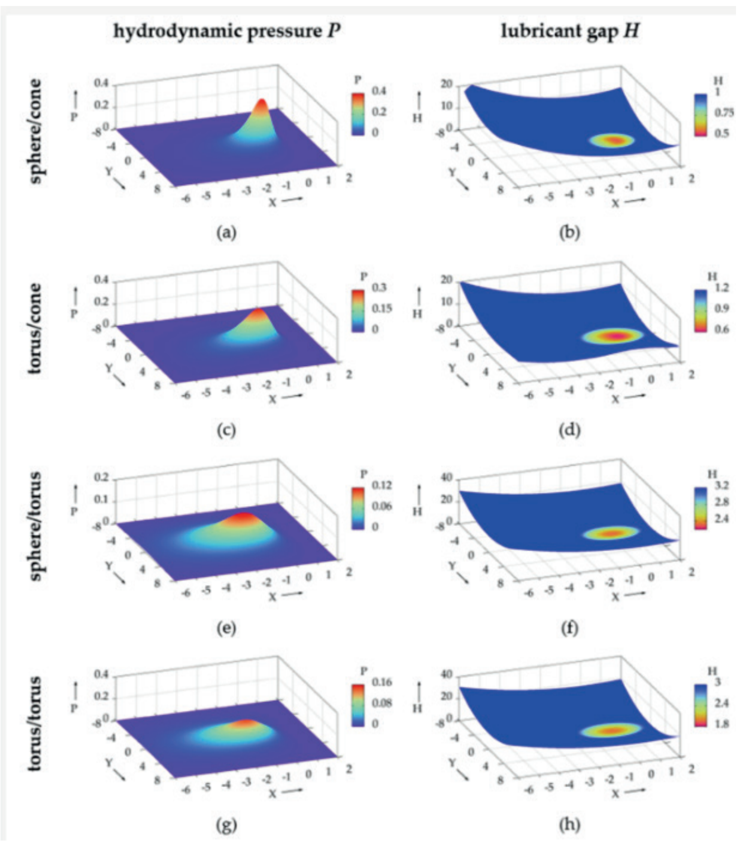

Figure 2: Numerical simulation profiles showing the distribution of hydrodynamic pressure P (left) and the corresponding lubricant gap height H (right) across different contact geometries under varying mechanical stresses [3].

As machinery becomes more advanced, the demands placed on lubricant additives continue to increase. Higher operating temperatures, increased power densities, and stricter efficiency requirements have created a need for improved additive technologies. Understanding the functions and limitations of traditional AW and EP additives provides an important foundation for examining the development of next-generation lubricant systems that can meet future performance and environmental requirements [1,15].

III. Environmental Concerns of Conventional Additives

While traditional antiwear (AW) and extreme pressure (EP) additives have played a critical role in protecting machinery and improving lubricant performance, growing environmental concerns have highlighted several limitations associated with conventional additive technologies. Many widely used lubricant additives contain sulfur-, phosphorus-, chlorine-, or metal-based compounds that can pose environmental challenges during use, disposal, or accidental release into the environment. As governments and industries place greater emphasis on sustainability, lubricant manufacturers are increasingly seeking alternatives that reduce environmental impact while maintaining the high levels of performance required in modern equipment [13].

Environmental concerns surrounding lubricant additives include poor biodegradability, toxicity, and their effects on emissions-control systems. Conventional petroleum-based lubricants and some additive chemistries can persist in soil and water after disposal or accidental leakage, leading to stricter regulations such as EU Ecolabel, EPA Vessel General Permit (VGP) requirements for Environmentally Acceptable Lubricants (EALs), and REACH standards that promote biodegradable, low-toxicity alternatives [16]. Additionally, phosphorus- and sulfur-containing additives like ZDDP can poison catalytic converters and particulate filters, requiring low-SAPS formulations that maintain wear protection while meeting stricter emissions regulations such as Euro 6/VII and EPA Tier 3 [15]. As shown in Figure 3, enclosed pin-on-disc tribometer testing allows researchers to measure airborne wear debris and volatile emissions during sliding contact, helping evaluate how lubricant formulations affect emissions and particle formation before real-world use [4]

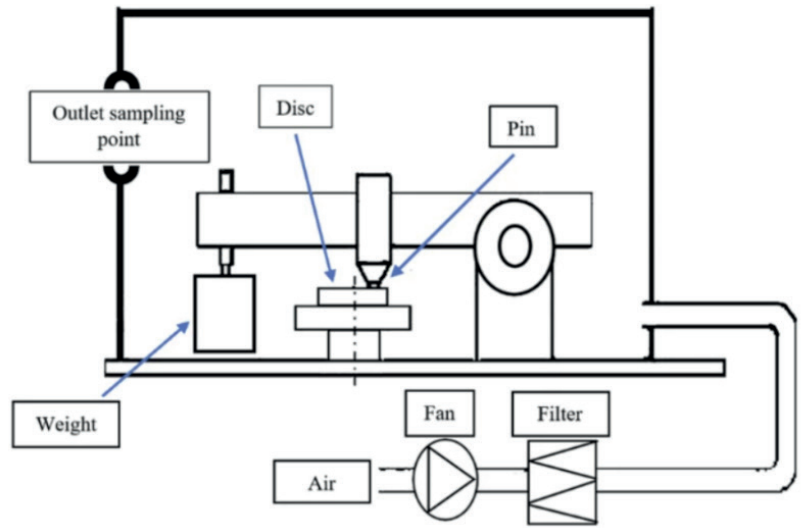

Figure 3: Schematic diagram of an enclosed pin-on-disc tribometer configuration featuring an integrated air filtration and sampling network designed to evaluate airborne wear particles and environmental emission factors during testing [4].

The growing demand for environmentally acceptable lubricants has encouraged the development of new formulations designed to minimize ecological risks. Environmentally acceptable lubricants (EALs) are engineered to provide effective lubrication while also exhibiting characteristics such as biodegradability, low toxicity, and reduced bioaccumulation potential. These lubricants are especially important in environmentally sensitive applications, including marine equipment, industrial gear systems, forestry machinery, and hydraulic systems that operate near water sources or natural ecosystems. Modern EAL formulations demonstrate that environmental performance and lubricant effectiveness do not necessarily have to be mutually exclusive goals [13].

Renewable and bio-based lubricant technologies have emerged as another promising approach for addressing environmental concerns. Unlike conventional petroleum-derived products, renewable lubricants are often produced from vegetable oils or other renewable feedstocks. These materials offer advantages such as improved biodegradability and reduced dependence on fossil resources. Advances in lubricant chemistry have improved the oxidation stability, thermal performance, and wear protection capabilities of renewable lubricants, making them increasingly viable for a wider range of industrial and automotive applications [19].

Despite these advances, several challenges remain. Sustainable lubricant technologies must meet the same demanding performance standards as traditional products while remaining economically competitive and compatible with existing equipment. Factors such as raw material availability, formulation costs, long-term stability, and system compatibility continue to influence the adoption of environmentally friendly additives and lubricants. Nevertheless, ongoing research suggests that future lubricant systems will increasingly prioritize sustainability alongside tribological performance [20].

As environmental regulations continue to evolve and industries pursue more sustainable operating practices, the development of cleaner lubricant technologies has become a major focus of lubricant research. Modern additive development increasingly seeks to achieve a balance between wear protection, equipment reliability, regulatory compliance, and environmental responsibility. This shift has played a significant role in driving the search for next-generation AW and EP additives capable of meeting both performance and sustainability objectives [15].

The increasing complexity of modern machinery, stricter environmental regulations, and demand for greater efficiency have created a need for next-generation AW and EP additives [1]. While traditional additives have provided reliable wear protection for decades, newer engines and industrial systems operate under higher temperatures, pressures, and longer service intervals, requiring improved performance and durability [1, 7]. Modern additives must balance wear reduction, energy efficiency, emissions-system compatibility, and environmental safety. Regulatory requirements, including limits on toxicity and biodegradability, have further encouraged the development of alternative additive chemistries with reduced environmental impact [16]. At the same time, advanced formulations are being designed to lower friction, improve fuel economy, and extend equipment life while maintaining strong wear protection [19]. As shown in Figure 4, these mechanical, chemical, and environmental challenges have driven research into innovative lubricant technologies, including nano-additives, that can meet the demands of future lubrication systems [2].

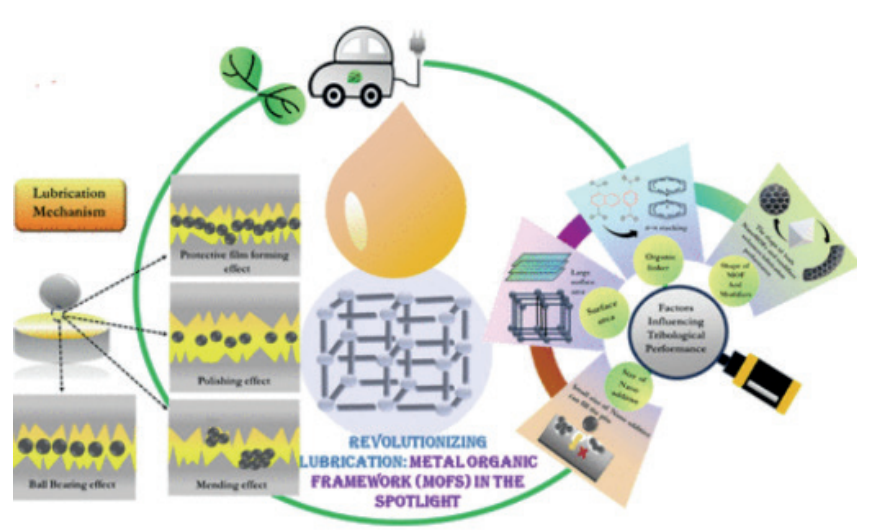

Figure 4: Structural factors, micro-level lubrication mechanisms, and macro-level sustainability goals driving next-generation additive design [5].

IV. Advanced Antiwear Additive Technologies

The increasing demands placed on modern machinery have encouraged the development of advanced antiwear (AW) technologies that extend beyond traditional additive chemistries. Conventional antiwear additives have been highly effective in reducing friction and protecting metal surfaces, but changing performance requirements and environmental considerations have motivated researchers to explore new approaches. Modern antiwear technologies aim not only to reduce wear but also to improve energy efficiency, enhance thermal stability, extend lubricant life, and reduce environmental impact. As a result, significant research efforts have focused on developing innovative additive systems capable of meeting the complex requirements of next-generation lubrication systems [15].

Among the most promising developments in antiwear technology is the use of ionic liquids as lubricant additives. Ionic liquids are salts that remain in a liquid state at relatively low temperatures and possess unique physical and chemical properties that make them attractive for tribological applications. Unlike many conventional additives, ionic liquids can be specifically designed by selecting different combinations of positively and negatively charged ions, allowing researchers to tailor their properties for particular lubrication requirements. This flexibility has generated considerable interest in their potential use as replacements or supplements for traditional antiwear additives [20].

One of the primary advantages of ionic liquids is their ability to form protective tribofilms on metal surfaces. During operation, these tribofilms act as barriers that reduce direct metal-to-metal contact and minimize wear. Research has shown that ionic-liquid additives can significantly reduce friction and wear while maintaining excellent lubrication performance under a variety of operating conditions. Because these protective films form through chemical interactions at the surface, they can provide effective protection even when lubricant films become very thin during boundary lubrication conditions [20]. The step-by-step mechanism of this process, tracing the path from initial asperity contact to full chemical maturation of the iron phosphate layer, is illustrated in Figure 5 [6].

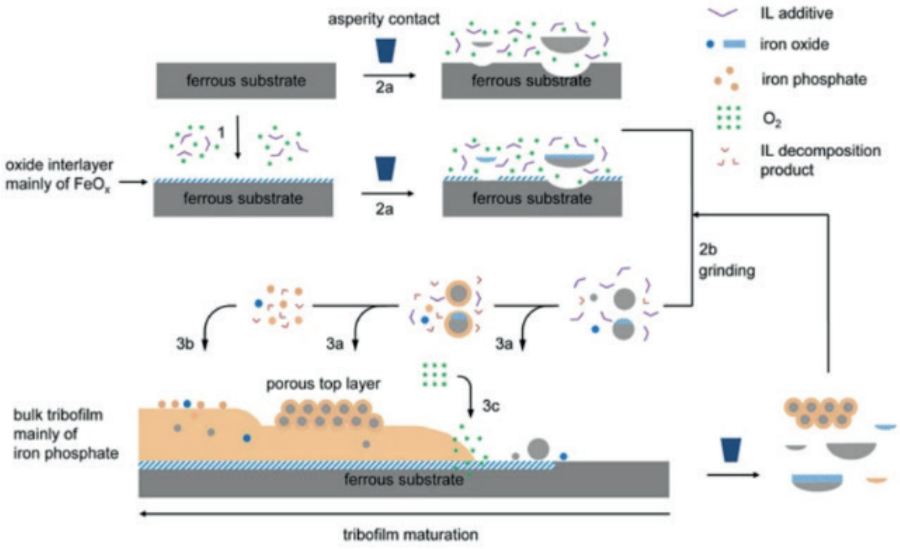

Figure 5: Schematic mechanism of ionic liquid (IL) additive decomposition and subsequent tribofilm maturation on a ferrous substrate [6].

Experimental studies have further demonstrated the effectiveness of ionic liquids in reducing wear and improving lubricant performance. Investigations evaluating ionic-liquid additives have reported reductions in friction and wear compared with base lubricants lacking advanced additive systems. In addition to their wear-reduction capabilities, ionic liquids often exhibit excellent thermal stability, allowing them to maintain performance under elevated temperatures that may degrade conventional lubricant additives. This combination of wear protection and thermal durability makes ionic liquids particularly attractive for demanding industrial and automotive applications [12].

Despite their promising performance, ionic liquids also have some limitations that must be addressed before they can be widely used in commercial lubricants. Their relatively high production cost remains a major challenge, and some ionic liquids have raised concerns regarding toxicity, biodegradability, and corrosion depending on their chemical composition. In addition, compatibility with existing lubricant formulations and engineering materials requires further investigation. For these reasons, current research is focused not only on improving the tribological performance of ionic liquids but also on developing safer, more cost-effective, and environmentally friendly formulations suitable for practical applications [20].

Beyond ionic liquids, researchers are exploring a variety of advanced additive chemistries designed to improve both tribological performance and overall system efficiency. Recent sustainable lubricant research has highlighted the development of multifunctional additives capable of simultaneously reducing friction, minimizing wear, and supporting environmental objectives. These emerging technologies often rely on improved surface chemistry and more efficient tribofilm formation to achieve superior performance compared with traditional formulations. Such innovations demonstrate how lubricant additives are evolving from simple protective agents into highly engineered performance-enhancing components [15].

Another important trend in antiwear technology is the development of additives that contribute to improved fuel economy. Friction within engines and mechanical systems represents a significant source of energy loss. By reducing friction more effectively, advanced antiwear additives can improve overall system efficiency while still providing the necessary level of wear protection. Recent developments in engine lubricant technology have demonstrated that carefully engineered additive packages can simultaneously enhance fuel economy and maintain excellent protection against component wear. These dual benefits are increasingly important as industries seek to reduce energy consumption and operating costs while maintaining equipment reliability [19].

The continued advancement of antiwear technology reflects the changing priorities of modern lubrication science. Future additive systems must provide exceptional wear protection while supporting goals related to sustainability, efficiency, and equipment longevity. Ionic liquids, multifunctional additives, and fuel-economy-enhancing technologies represent important examples of how researchers are addressing these challenges. As development continues, advanced antiwear technologies are expected to play a central role in the creation of next-generation lubricant systems capable of meeting increasingly demanding performance requirements [15,19].

V. Advanced Extreme Pressure Additive Technologies

Extreme pressure (EP) additives are essential for protecting machinery operating under severe conditions where high loads and temperatures can cause direct metal-to-metal contact. Unlike antiwear additives, which primarily function under moderate boundary lubrication conditions, EP additives are designed to activate when operating conditions become extreme. Under these circumstances, EP additives react chemically with metal surfaces to form protective layers that prevent scuffing, welding, and catastrophic wear [15].

Extreme pressure additives include several different chemical types, each providing protection in a different way. Sulfur-containing additives are the most common in industrial gear oils because they react with metal surfaces at high temperatures to form iron sulfide layers that reduce friction and prevent metal-to-metal contact. Phosphorus-containing additives, such as phosphate esters and zinc dialkyldithiophosphate (ZDDP), form phosphate-rich protective films that improve both wear resistance and EP performance. Boron-containing additives have also received attention because they can improve wear resistance and increase the stability of these protective films. Although chlorinated additives were once widely used because of their excellent load-carrying ability, their use has declined due to environmental concerns. As a result, modern lubricants increasingly rely on sulfur-, phosphorus-, and boron-based additive systems that provide effective protection while meeting current environmental requirements [23].

As industrial equipment becomes more advanced, the demands placed on EP additives continue to increase. Modern gearboxes, transmissions, and heavy-duty machinery often operate under higher loads and greater mechanical stresses than previous generations of equipment. These conditions require additive systems capable of providing reliable protection while maintaining lubricant performance over extended service intervals. Research has shown that traditional EP technologies may need to be supplemented with more advanced additive chemistries to meet these evolving requirements [17].

Recent developments in lubricant technology have focused on improving the effectiveness of EP additives through innovative formulation strategies. Rather than relying on a single additive, modern lubricant systems often use carefully balanced additive packages that work together to provide enhanced load-carrying capacity, wear protection, and thermal stability. These synergistic formulations can create stronger and more durable protective films on metal surfaces, improving equipment reliability under demanding operating conditions [15]. The progressive evolution and growth profile of these durable, anti-scuffing chemical layers during mechanical shearing are experimentally measured and tracked in Figure 6.

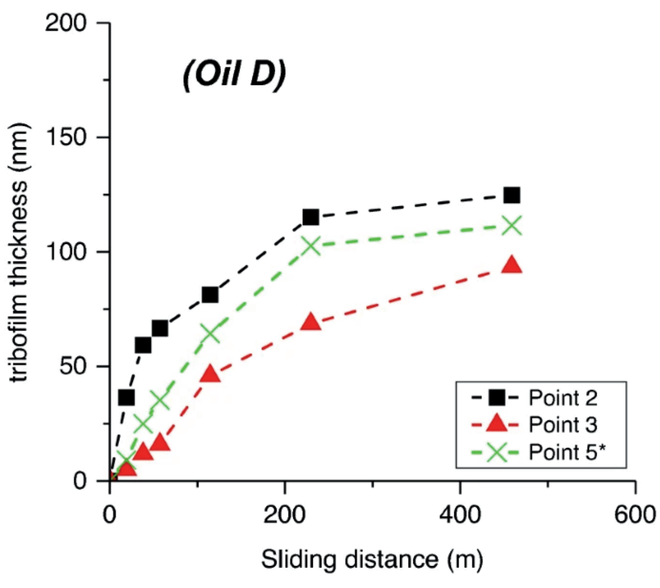

Figure 6: Evolution of protective tribofilm thickness as a function of sliding distance for an additive-treated formulation (Oil D) [7].

The performance of EP additives depends on the formation of protective tribofilms on the metal surface. During operation, high contact pressures and localized temperatures cause the additives to react with the metal, producing a thin chemical layer that reduces wear and prevents surface damage. As sliding continues, parts of this layer are removed and new material forms, allowing the tribofilm to continually renew itself. Studies using techniques such as X-ray photoelectron spectroscopy (XPS) and X-ray absorption near-edge structure (XANES) have shown that sulfur additives mainly produce sulfide-rich films, while phosphorus additives form iron phosphate compounds. The composition and thickness of these films have a direct effect on the load-carrying capacity and wear resistance of the lubricant [24].

Advanced gear systems provide a clear example of the need for improved EP technologies. Planetary gearboxes and other highly loaded transmission systems experience significant contact stresses that can accelerate wear if adequate protection is not provided. Research examining lubricant additives for gear protection has emphasized the importance of optimizing additive chemistry to ensure both long-term durability and efficient operation. As equipment performance requirements continue to increase, lubricant formulations must provide higher levels of protection without compromising other important characteristics such as oxidation stability and efficiency [17].

Several studies have shown that combining different EP additives often provides better protection than using a single additive alone. For example, lubricant formulations containing sulfur-, phosphorus-, and boron-based additives produce stronger and more stable tribofilms than formulations containing only one additive. These combinations also reduce friction and improve wear resistance under boundary lubrication conditions. This shows that the overall performance of a lubricant depends not only on the individual additives but also on how well they work together. Because of this, modern lubricant formulations are carefully designed to achieve the best balance between protection, durability, and overall lubricant performance [25].

The performance of EP additives is commonly evaluated using standardized tribological tests such as the Four-Ball Extreme Pressure test, the FZG gear test, and the Timken OK load test. These tests measure properties including weld load, wear scar diameter, and resistance to scuffing under high-load conditions. Results from these studies have shown that industrial gear oils containing well-balanced EP additive packages provide better load-carrying capacity, lower wear, and improved gear durability than base oils without additives. Researchers also use techniques such as scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) to examine worn surfaces and relate tribofilm formation to improvements in lubricant performance [26].

The development of advanced EP technologies reflects the broader trend toward high-performance lubricant systems that combine durability, efficiency, and sustainability. Continued research in this area is expected to produce additive technologies capable of meeting the growing demands of modern industrial and automotive applications while maintaining excellent wear protection under extreme operating conditions [15,17].

VI. Bio-Based and Sustainable Additives

Growing concerns about environmental sustainability have encouraged the development of bio-based and sustainable lubricant additives as alternatives to traditional petroleum-derived products. These additives are typically produced from renewable feedstocks such as vegetable oils and other biological resources, offering the potential to reduce dependence on fossil fuels while improving biodegradability. As industries seek to lower their environmental impact, bio-based additives have become an increasingly important area of lubricant research and development [17].

One of the primary advantages of bio-based lubricants is their reduced environmental footprint. Compared with conventional lubricants, many renewable products are more readily biodegradable and generally present lower risks to ecosystems in the event of leaks or accidental releases. In addition, renewable feedstocks can often be replenished more sustainably than petroleum resources, making them attractive for long-term industrial use. Advances in lubricant chemistry have also improved the oxidation stability and performance of bio-based formulations, allowing them to compete more effectively with conventional products in demanding applications [9].

Despite these advantages, bio-based lubricants also have several limitations. Many vegetable oil-based lubricants have lower oxidation stability and poorer performance at high temperatures than conventional mineral oils, which can reduce their service life. They may also exhibit poor low-temperature flow properties and can be more expensive depending on the feedstock and processing methods. Ongoing research is focused on improving these limitations through chemical modification and advanced additive technologies [9,17].

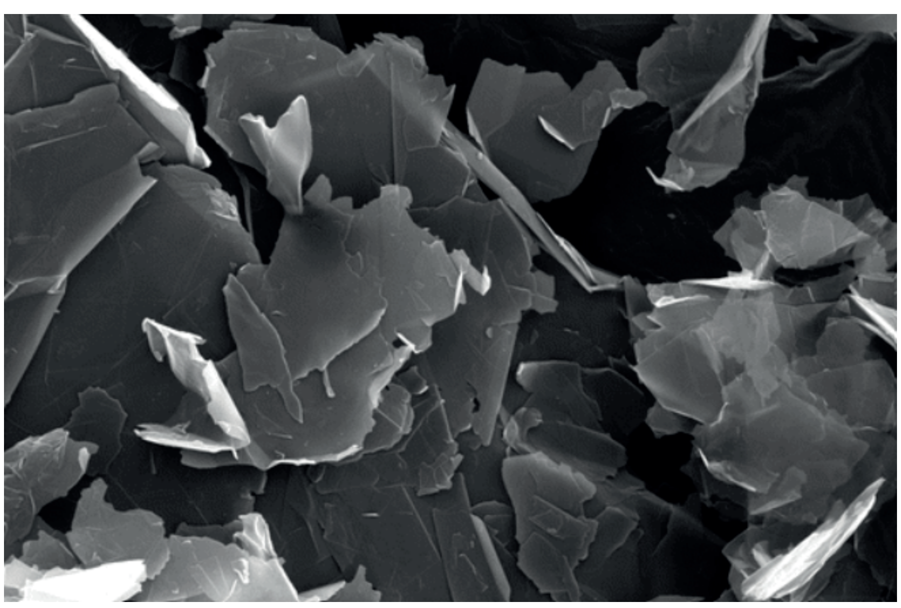

Figure 7: FE-SEM micrograph displaying the surface morphology of the graphene nanoplatelets used as nano-additives [8].

Recent research has further expanded the capabilities of sustainable lubricants through the incorporation of nanoparticles. Studies involving palm oil-based biolubricants have demonstrated that nanoparticles such as graphene, titanium dioxide, and aluminum oxide can significantly improve lubricant performance by forming protective tribofilms on rubbing surfaces, filling microscopic surface asperities (mending effect), and reducing direct metal-to-metal contact. These mechanisms lower friction and wear while improving thermal stability [21]. The combination of renewable base materials and advanced nanotechnology highlights the potential for sustainable lubricants to achieve both environmental and performance objectives [9]. The structured flake morphology of the graphene nanoplatelets utilized to achieve these enhanced tribological properties is shown in the microscopic analysis in Figure 7.

Despite their advantages, the widespread adoption of bio-based additives still faces several challenges. Performance consistency, compatibility with existing lubricant systems, raw material availability, and production costs can all influence implementation. Manufacturers must ensure that sustainable additives provide the same level of protection and reliability expected from traditional formulations before they can be widely adopted across industries [20].

Nevertheless, continued research and technological advancements suggest that bio-based additives will play an increasingly important role in the future of lubrication. By combining renewable resources with innovative additive technologies, sustainable lubricant systems offer a promising path toward reducing environmental impact while maintaining the high levels of performance required by modern industrial and automotive applications [9,11].

VII. Performance and Environmental Evaluation

The development of next-generation antiwear (AW) and extreme pressure (EP) additives requires careful evaluation of both tribological performance and environmental impact. Historically, lubricant additives were judged primarily on their ability to reduce friction, minimize wear, and protect machinery under demanding operating conditions. While these performance characteristics remain critical, modern lubricant technologies must also satisfy increasing expectations related to sustainability, environmental responsibility, and regulatory compliance. As a result, researchers now evaluate advanced additive systems using a combination of performance-based and environmental criteria to determine their overall effectiveness [15].

One of the most important measures of additive performance is wear reduction. Antiwear additives are designed to form protective tribofilms that prevent direct metal-to-metal contact, while EP additives protect surfaces under extreme loading conditions. Laboratory testing commonly evaluates the ability of additives to reduce wear scar size, decrease friction coefficients, and improve load-carrying capacity. Standard tribological tests used for this purpose include the four-ball wear test, pin-on-disk test, and ball-on-disk test, which assess friction, wear resistance, and lubricant performance under controlled operating conditions [22]. Research involving advanced additive technologies has demonstrated that many emerging formulations can provide wear protection equal to or better than conventional additives. In particular, studies examining ionic-liquid additives have shown significant reductions in friction and wear while maintaining excellent thermal stability and lubricant performance under a range of operating conditions [12].

Another critical performance metric is energy efficiency. Friction within engines, transmissions, and industrial machinery represents a major source of energy loss. Lubricant additives that reduce friction can improve fuel economy and decrease overall energy consumption. Recent developments in advanced antiwear technology have demonstrated that carefully engineered additive packages can simultaneously improve wear protection and fuel efficiency. This dual benefit is particularly important in automotive applications, where manufacturers are under increasing pressure to reduce fuel consumption and greenhouse gas emissions while maintaining engine durability and reliability [19].

The evaluation of EP additives focuses heavily on their ability to protect heavily loaded components such as gears and bearings. Modern gear systems often operate under extremely high contact pressures that place significant demands on lubricant formulations. Research investigating lubricant additives for planetary gear protection has emphasized the importance of additive chemistry in maintaining surface integrity and preventing failure under severe operating conditions. Effective EP additives must provide reliable protection while also maintaining lubricant stability and long-term performance throughout extended service intervals [17]. The distribution of these severe structural loads across a typical planetary assembly, highlighting the high contact stresses that demanding EP additives must mitigate, is modeled in Figure 8.

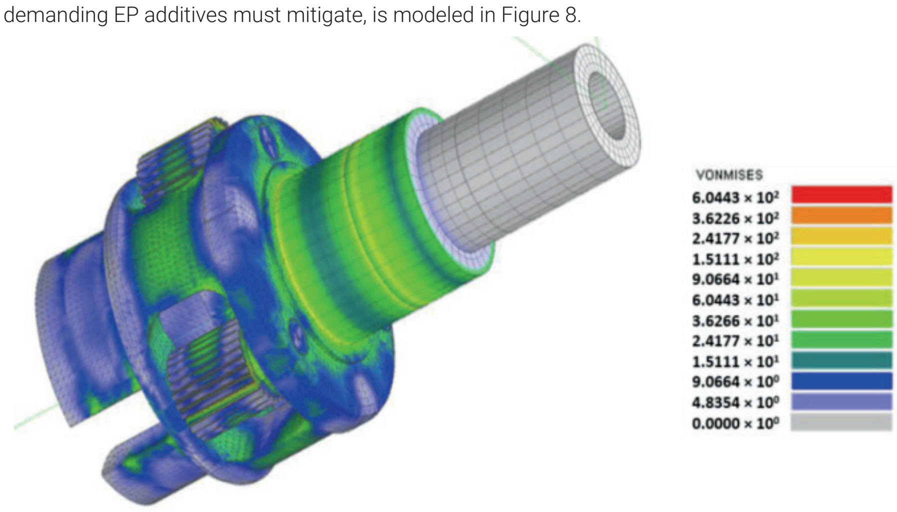

Figure 8: Von Mises stress distribution and contact pressure modeling across a highly loaded planetary gear component assembly [19].

Environmental performance has become equally important in the assessment of new additive technologies. Researchers increasingly examine factors such as biodegradability, toxicity, resource sustainability, and emissions-system compatibility when evaluating lubricant formulations. Sustainable lubricant technologies seek to reduce environmental impact without sacrificing the tribological performance required by modern machinery. This shift has encouraged the development of additive systems that provide excellent wear protection while minimizing ecological risks associated with production, use, and disposal [15].

Bio-based lubricants represent a notable example of how performance and sustainability can be evaluated together. Recent studies involving nanoparticle-enriched palm oil biolubricants have demonstrated that sustainable formulations can achieve impressive tribological results. The addition of nanoparticles such as graphene, titanium dioxide, and aluminum oxide has been shown to reduce friction by approximately 26–34% and decrease wear by 13–30% while also improving thermal stability. These findings suggest that environmentally friendly lubricant technologies can provide performance levels comparable to, and in some cases exceeding, those of traditional lubricant systems [18].

Ultimately, the success of next-generation AW and EP additives depends on achieving an effective balance between performance and environmental responsibility. Modern lubricant formulations must protect equipment, improve efficiency, and support sustainability goals simultaneously. Research conducted across a variety of advanced additive technologies indicates that these objectives are increasingly achievable through innovative chemistry and formulation strategies. As lubricant technology continues to evolve, comprehensive performance and environmental evaluation will remain essential for identifying additive systems capable of meeting the demands of future industrial and automotive applications [9,10].

VIII. Industrial Applications and Challenges

Antiwear (AW) and extreme pressure (EP) additives are widely used in automotive, industrial, and manufacturing applications where reliable lubrication is essential for reducing friction, minimizing wear, and extending equipment service life. They are commonly incorporated into engine oils, hydraulic fluids, and industrial gear lubricants, where they protect components operating under high loads, elevated temperatures, and severe boundary lubrication conditions [1].

As operating conditions become more demanding, lubricant additives must provide effective wear protection while maintaining long-term performance. Modern machinery operates at higher temperatures, greater contact pressures, and with extended oil drain intervals, requiring additives that remain chemically stable and continue to form protective tribofilms throughout the lubricant's service life. Maintaining this performance over prolonged operating periods remains a significant challenge [17].

Another important challenge is compatibility. Advanced additives must function effectively with different base oils, existing additive packages, seals, and metallic components without causing corrosion, deposit formation, or adverse chemical interactions. This is particularly important for emerging technologies such as ionic liquids, nanoparticles, and bio-based additives, which may require careful formulation before they can be incorporated into commercial lubricants [12,20].

Economic considerations also influence the adoption of next-generation additives. Many advanced additive technologies involve complex synthesis methods or expensive raw materials, increasing production costs compared with conventional additive chemistries. Although these additives often provide improved tribological performance, their widespread industrial implementation depends on achieving a balance between performance benefits and cost-effectiveness [20].

Environmental regulations present an additional challenge for lubricant manufacturers. Industries increasingly require lubricant formulations with improved biodegradability, lower toxicity, and reduced environmental impact while maintaining high levels of wear protection. Developing additive systems that satisfy both performance and sustainability requirements remains an active area of research [13].

Overall, while AW and EP additives continue to play an essential role in modern industrial applications, future developments will depend on overcoming challenges related to long-term durability, compatibility, cost, and environmental sustainability. Addressing these issues will be critical for the successful implementation of next-generation lubricant additive technologies [20].

IX. Future Trends and Conclusion

The future of antiwear (AW) and extreme pressure (EP) additives is being driven by the need to improve both tribological performance and environmental sustainability. As machinery becomes more advanced and environmental regulations become increasingly stringent, lubricant research is focusing on multifunctional additives that can simultaneously reduce friction, minimize wear, improve energy efficiency, and lower environmental impact [20].

Emerging technologies such as ionic liquids, bio-based lubricants, and nanoparticle-enhanced formulations show considerable potential for next-generation lubrication systems. Ionic liquids offer tunable surface chemistry and effective tribofilm formation, while renewable lubricants provide improved biodegradability and reduced dependence on petroleum resources. The incorporation of nanoparticles has further enhanced lubricant performance by improving wear resistance, friction reduction, and thermal stability [19,20]. The interaction of these advanced materials within sustainable lubricant systems is illustrated in Figure 9.

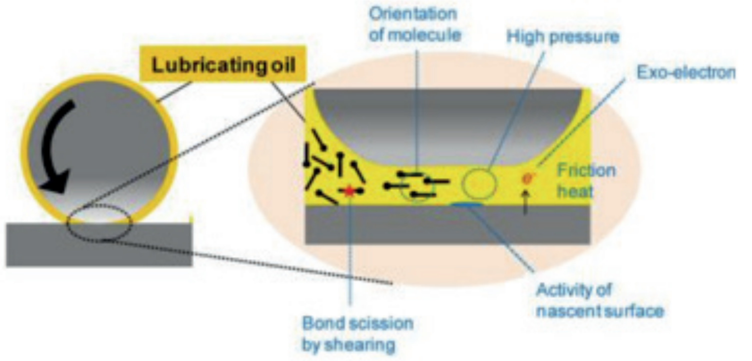

Figure 9: Comprehensive roadmap and evaluation framework for the development of sustainable, high-performance, next-generation lubricant additives [14].

Despite these advances, challenges related to cost, large-scale production, long-term durability, and compatibility with existing lubricant formulations remain barriers to widespread industrial adoption. Continued research is therefore needed to develop additive systems that combine high performance, economic viability, and environmental sustainability [20].

Overall, future AW and EP additive technologies are expected to integrate advanced chemistries with sustainable design principles, supporting the development of lubricant formulations that provide reliable equipment protection while meeting evolving industrial and environmental requirements [9,11].

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