

Review Article

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Functional Additives and Polymer-Based Strategies for High-Performance Engine Oils

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Abstract

Reducing friction and wear is crucial for maintaining engine efficiency and prolonging its lifespan. Modern engine oils achieve this through a carefully balanced combination of base oils and additives that work together to maintain viscosity, protect surfaces, and enhance overall performance. Recent research highlights the role of nanoparticles, viscosity index improvers, and bio-based thickeners in reducing friction, enhancing thermal stability, and improving load-bearing capacity. Yet, conventional additives can struggle under extreme conditions, such as high shear or high temperature. Viscosity index improvers (VIIs) are essential polymeric additives used to stabilize the temperature–viscosity behavior of lubricants. Their ability to enhance viscosity at elevated temperatures while maintaining fluidity at low temperatures enables broad operational performance across automotive, industrial, and hydraulic systems. Emerging smart polymers, including polymer brushes and supramolecular networks, could be studied to provide adaptive viscosity control and superior stability. This review consolidates current insights on base oils, additive technologies, and advanced polymeric systems, examining their mechanisms, benefits, and potential to shape the next generation of high-performance lubricants. Additionally, the research revealed that the polymer's molecular weight, structure, and polarity can significantly impact its ability to enhance the viscosity index and reduce friction.

Keywords Viscosity index improver, Polymer additives, Lubricant formulation

1. Introduction

Minimizing friction between moving engine components is crucial for reducing energy losses, enhancing fuel efficiency, and prolonging equipment life. Lubricants play a central role in achieving this by creating a protective film that limits wear, abrasion, and direct metal-to-metal contact. Because engines operate across a wide range of temperatures and loads, developing advanced lubricants that maintain appropriate viscosity and effectively ad-

dress tribological challenges has become technologically and economically important [1].

Engine oil consists primarily of a base oil, typically accounting for more than 80% of the formulation, and is enhanced with a tailored package of additives. These base oils can originate from petroleum or alternative feedstocks and vary widely in molecular composition, degree of saturation, and response to temperature changes. To harmonize these variations, the American Petroleum In-



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stitute (API) introduced a six-group classification system in 1993, categorizing base oils by their sulfur content, saturate level, and viscosity index rather than by production route [2]. This classification is based on physical and chemical properties, not on the production method.

Group I oils are conventionally produced through refining or re-refining of mineral oils and are described in standards such as ISIRI 3299 [3]. More advanced groups—II through V—are typically obtained through catalytic hydrotreating, hydrocracking, or hydro-isomerization. Groups II and III exhibit significantly higher purity and lower sulfur content compared to Group I, with Group III being designated as having a very high viscosity index (VHVI). Group IV includes synthetic poly-alpha-olefins (PAOs), while Group V encompasses all other non-PAO synthetics such as esters, glycols, and specialty naphthenic oils [3].

Enhancing base oil performance relies heavily on multifunctional additives that impart detergency, anti-wear behavior, oxidation resistance, and improved viscosity control. In recent years, nanoparticles have garnered considerable attention due to their ability to reduce friction and wear. However, their performance strongly depends on particle characteristics such as concentration, size, and shape. Zinc oxide nanoparticles, for example, have shown notable improvements in load-bearing capability and wear protection [4]. Complementary research involving bio-based thickeners such as beeswax and ethyl cellulose suggests that optimal lubrication also depends on selecting compatible combinations of base oils and gelling agents [5].

Operational studies repeat the importance of selecting suitable additive systems. Mitan et al. observed that a widely used additive produced an 11.11% increase in viscosity mineral oil after 300 km of engine use, compared with only a 1.25% increase in semi-synthetic oil, along with reduced water contamination [6]. Other investigations into nano-additives such as graphite and silver have shown that these particles can lower friction through combined rolling and sliding mechanisms, improve load-carrying capacity, and reduce power consumption compared to untreated oil [4].

Viscosity index improvers (VIIs) are another essential class of additives, formulated to counteract the natural decrease in oil viscosity at elevated temperatures. By helping lubricants maintain film thickness over a broad thermal window, VIIs are critical for the reliable performance of multigrade engine oils, hydraulic systems, and gear lubricants [7].

Given the limitations of conventional additives under extreme conditions, recent research has turned toward smart polymer systems as next-generation solutions. This

review highlights the capabilities of polymer brushes, reversible supramolecular networks, and other adaptive polymeric structures that exhibit exceptional shear stability and self-regulating viscosity behavior. Their underlying mechanisms, synthesis strategies, and tribological performance are studied, along with current challenges and the future outlook for implementing these smart lubricants in demanding industrial environments.

2. Key Functional Additives and Their Roles

Functional additives form the backbone of modern lubricant formulations, with each component fulfilling a specific role to enhance performance, durability, and protection. Viscosity modifiers ensure that oils maintain an optimal viscosity across a wide temperature range, though their effectiveness is limited by shear instability under high mechanical stress. Complementary additives, including detergents, anti-wear agents, antioxidants, friction modifiers, corrosion inhibitors, and antifoaming agents, work collectively to preserve cleanliness, reduce component degradation, and maintain the lubricant's chemical integrity throughout service life [8].

Nanotechnology-based additives have garnered increasing attention due to their potential to enhance thermal and mechanical properties. For example, incorporating only 0.1% copper oxide nanoparticles into SAE20W50 oil increased thermal conductivity by 3%. It elevated the flash point by 7.9% without altering the oil's viscosity. However, achieving a stable dispersion remained a key challenge, best addressed through ball milling [9]. Traditional additives, such as Zinc dialkyldithiophosphates (ZDDP), remain indispensable due to their robust anti-wear and antioxidant properties, despite concerns about phosphorus-related catalyst poisoning and zinc-induced corrosion remaining unresolved. Despite ongoing efforts to replace or reduce ZDDP, its minimum required concentration has remained at 0.08% due to a lack of equally effective substitutes [10].

Studies exploring alternatives have shown mixed results. Mahdi et al. demonstrated that a synthetic borate ester (BDDP) provides anti-wear protection but is less effective than conventional ZDDP. At the same time, Ferguson's work revealed that ZDDP begins to decompose at 150 °C thermally yet remains stable after brief exposure to 200 °C [10, 11]. Notably, ZDDP maintained its protective performance even when contaminated with 0.1% soil [10]. Further analysis using advanced spectroscopy showed that degradation of ZDDP in a marine engine reduced phosphorus availability and impaired protective film formation, leading to increased iron wear particles and cylinder damage [12]. In parallel, research evaluating zinc oxide and carbon nanotube-modified oils investigat-

ed how these hybrid components influence friction, wear resistance, thermal conductivity, and viscosity under realistic tribological conditions [13].

Sustainable lubrication strategies have focused on biodegradable thickeners such as nanoclays and nanocellulose, with oleic acid serving as both a stabilizer and friction-reducing agent. In PAO oils and nanogreases, oleic acid consistently reduced friction and wear at low speeds. However, its behavior became increasingly load-dependent under more severe operating conditions due to surface adsorption dynamics [14]. A similar interest in titanium dioxide nanoparticles (10–25 nm) has been demonstrated, showing that low concentrations (0.3–0.5 wt%) can significantly reduce friction by up to 86% in pin-on-disc tests, acting as rolling micro-bearings. However, excessive amounts cause agglomeration and increased wear [4, 13]. Peña-Parás et al. further observed that particle size relative to surface roughness is critical; only particles smaller than surface scratches yield meaningful improvements in friction and wear [15].

Carbon-based nanomaterials also show considerable promise. Ettefaghi et al. found that functionalizing carbon nanotubes with didecylamine improves dispersion and stability, enabling increases of 13.2% in thermal conductivity and 6.7% in flash point at a concentration of just 0.1%. However, performance declines at higher loadings due to aggregation [16]. Similarly, MoS₂-hBN nanolubricants synthesized through microwave processing exhibited excellent viscosity, thermal stability, oxidation resistance, and wear reduction at only 0.05 wt%, maintaining performance even after prolonged aging at 100 °C [17]. Research by Ettefaghi et al. found that adding carbon nanomaterials, such as nanotubes and nanoballs, to engine oil can significantly enhance its thermal conductivity and reduce wear. Among the various methods used to stabilize the distribution of particles within the oil and prevent their aggregation or sedimentation, functionalizing the carbon nanotube with didecylamine and using ball milling were identified as the most effective methods. Furthermore, they reported that adding 0.1% MWCNT improved the thermal conductivity and flash point of the nanolubricants by up to 13.2% and 6.7%, respectively [16]. However, they also noted that these benefits are concentration-dependent, as using excessive amounts of nanomaterial leads to aggregation and can harm the oil's lubricating performance [16].

The researchers depict that 0.05 wt% MoS₂-hBN nanolubricants synthesized through an energy-efficient microwave method are optimal, producing a maximum viscosity of 12.87 mPa·s at 100 °C and a shear rate of 200 s⁻¹ [17]. Aging tests at 100 °C for 120 h showed that this nanolubricant maintained good thermal stability, reduced

friction and wear, and exhibited improved oxidation resistance and thermal conductivity compared to 20W40 CD/SE GL-4 oil, confirming its promise for high-temperature and high-performance lubrication applications [17].

To experimentally verify these improvements in tribological performance, a pin-on-disc tribometer test was employed to assess engine oil quality by measuring friction and wear between sliding surfaces under lubrication (as shown schematically in Fig. 1), where lower friction and minimal wear according to ASTM G99 indicate superior oil performance.

Polymeric additives remain central to viscosity control. Studies on polyethylene glycol (PEG) have shown that low concentrations, particularly around 3%, enhance the viscosity index of paraffinic oils, as confirmed by uniform polymer distribution observed through Raman spectroscopy and microscopy. At higher concentrations, however, PEG tends to aggregate, limiting its effectiveness [18]. The functionality of nanoscale additives ultimately depends on their ability to form durable tribofilms; spherical particles perform best due to their tendency to roll rather than clump, although some are limited by environmental concerns because they may introduce additional sulfur, ash, or phosphorus into the lubricant system [1]. Together, these studies demonstrate how functional additives, ranging from traditional chemistries to advanced nanomaterials, interact to alter lubricant behavior under thermal, mechanical, and chemical stress.

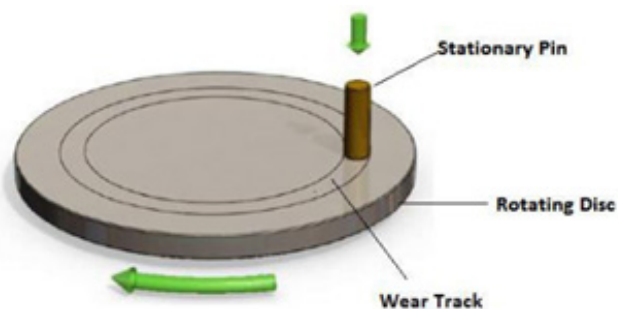


Fig 1. Tribometer test by pin-on-disc [13]

3. The Fundamentals of Shear Stability in Lubricants

Shear stability refers to a polymer's ability to resist mechanical degradation when exposed to intense shear stress in engines and hydraulic systems. It depends largely on molecular weight and chemical structure—high-molecular-weight polymers provide strong thickening effects but are generally more susceptible to chain scission. Under severe shear, carbon-carbon bonds may break homolytically, producing smaller radical fragments that reduce the

polymer's thickening ability. For this reason, shear stability is commonly assessed by measuring viscosity loss after repeatedly forcing an oil sample through a standardized nozzle geometry [19]. Effective viscosity improvers must preserve low viscosity for cold starts while maintaining adequate viscosity at high temperatures to sustain oil film thickness and prevent excessive consumption [8, 19]. High-performance VIIs therefore require both thermal and mechanical resilience.

Beyond viscosity retention, certain VIIs offer secondary advantages such as lowering pour point or improving dispersancy, depending on their chemical architecture. Porous polymer materials—including polymer foams and melt-blown fibers—have also drawn interest for their high surface area and nano- to microscale porosity, which may enable new mechanisms of viscosity modification in addition to their established roles in oil absorption and filtration applications [20].

Super alkaline phenolates also contribute to lubricant durability through antioxidant, anti-scale, and detergent functions. Engine tests using 10W40 oil formulated with the V-7130 additive showed strong performance for SL/SF oils, and replacing isononyl phenol with propylene trimers further enhanced colloidal stability and solvency capacity [21]. These improvements underline the importance of alkyl chain length in maintaining additive stability under demanding conditions.

Nanostructured additives can additionally bolster shear stability by reinforcing lubricant films at the microscopic level. Studies on polyvinylpyrrolidone (PVP)-modified detonated nanodiamonds (DNDs) have shown that even extremely low concentrations (0.001–0.005 wt%) significantly enhance lubricant behavior [22]. The modified DNDs improved dispersion stability, reduced surface roughness by a factor of six, lowered wear rate by 260%, and increased viscosity and flash point, illustrating their capability to strengthen tribofilms and improve thermal strength [22].

To better understand how molecular architecture governs shear response, molecular dynamics simulations have been used to explore the interactions between polymers, base oils, and shear forces [23]. These models accurately reproduced experimental viscosity and traction data, offering a predictive framework for designing future high-performance lubricants with optimized molecular structures [23].

Recent developments in ionic polymer additives further demonstrate the potential for molecular engineering to enhance shear stability. Poly(ionic liquid)-based copolymers synthesized from stearyl methacrylate and 2-(diethylamino)ethyl methacrylate, followed by protonation, showed improved corrosion resistance, viscosity behavior,

and tribological performance when blended with PAO10 oil. The best performance was achieved with a 5 wt% PDS-P13 formulation, which formed a stable mixture, significantly reduced friction and wear, and created a protective tribochemical film on steel surfaces [24]. To put it simply, shear stability in lubricants is determined by the polymer structure, molecular interactions, and resistance to mechanical and thermal degradation.

4. Traditional Viscosity Modifiers: limitations and positive aspects

Traditional viscosity modifiers such as polymethacrylates, olefin copolymers, and hydrogenated styrene–diene copolymers are widely used in engine oils to enhance shear stability and ensure acceptable performance across a range of temperatures.

One line of research investigated the impact of ethylene-vinyl acetate (EVA) copolymers on palm kernel methyl ester (PKME), revealing that EVA, particularly at an optimal treatment rate of 4%, enhances lubrication by forming a thicker protective film between the sliding surfaces [25]. These results highlight a key positive aspect of traditional viscosity modifiers: they can be successfully adapted for use in renewable, vegetable-based oils, supporting their potential as environmentally friendly lubricant alternatives [25].

Shear stability remains a critical performance measure for viscosity modifiers, and comparative studies illustrate important differences between common polymer classes. Mihaljuš-Sklepić reported that olefin copolymers provide better shear stability than polymethacrylates and hydrogenated styrene–isoprene copolymers after 90 shear cycles. However, they require higher concentrations to reach the same viscosity level [19]. In contrast, oils containing hydrogenated styrene–polyisoprene copolymers experience substantial viscosity loss at high shear cycles, which can compromise oil performance and prevent the formulation from meeting specification standards [19]. These findings underscore both the strengths and limitations of traditional additives: some offer durability under shear, while others degrade more rapidly.

Further investigation into hydrogenated poly(isoprene-co-styrene) viscosity index improvers revealed that blending them into various paraffinic base oils enhances viscosity index even at low concentrations [26]. Rheological testing demonstrated predominantly viscous behavior and pseudoplastic flow characteristics, well captured by the Ostwald–de Waele model [26]. This confirms that traditional VIIs can deliver predictable, controllable flow behavior that is an important advantage in automotive lubrication.

In addition to classical linear polymers, highly branched

Table 1. Main classes of polymeric viscosity index improvers

Polymer Type	Key Properties	Typical Applications
Poly(methacrylates) (PMA)	Customizable, excellent low-temperature behavior	Premium engine oils, hydraulic fluids [7]
Olefin Copolymers (OCP)	High thickening; cost-effective	Engine oils, gear oils, hydraulics [33]
Hydrogenated Styrene–Diene Polymers (HSD)	Superior shear stability	High-performance synthetic lubricants[27]
Styrene–Maleic Anhydride (SMA)	Dual dispersant/VI improver functionality	Diesel engine oils[27, 34]

polyethylene (BPE) has emerged as a promising multi-functional additive capable of both viscosity modification and friction reduction [27]. This dual functionality addresses a known limitation of many traditional VIIs, which typically improve viscosity but do not significantly reduce friction.

Broader evaluations of commercial polymer additives, including Koltan, Viscotek, Paraton, and Hitec, provide deeper insight into how molecular weight and chemical structure influence final oil performance [28]. Measurements of specific, intrinsic, and relative viscosity, along with thickening efficiency and shear stability, revealed that the activation energy for polymer dissolution increases as the concentration decreases, indicating stronger polymer-oil interactions at lower treatment rates. Optimal behavior was observed at polymer concentrations between 0.5% and 0.7%, where activation energy remained relatively stable across temperatures [28]. Overall, these results reinforce that polymer design parameters strongly control viscosity behavior, shear resistance, and rheology at both high and low temperatures.

Briefly, traditional viscosity modifiers offer clear benefits, including shear stability, viscosity enhancement, and compatibility with diverse base oils; yet they also face limitations such as concentration-dependent performance and susceptibility to mechanical degradation.

5. Mechanisms of action (viscosity modification, film formation, shear stability)

Polymeric viscosity improvers (VIIs) function primarily by altering their conformation with temperature. At low temperatures, polymer chains contract into compact coils, limiting their influence on viscosity. In contrast, at higher temperatures, they swell, increasing their hydrodynamic volume and thereby raising viscosity [29]. The extent of this response is highly dependent on the polymer archi-

tecture, specifically whether it is linear, star-shaped, or block copolymer, which also affects shear stability and long-term performance [29].

Although coil expansion has long been accepted as the main mechanism behind viscosity improvement, direct physical evidence has been limited. Recent studies using advanced characterization tools such as Small-Angle Neutron Scattering challenge this traditional view, showing that significant viscosity index enhancement can occur even without measurable coil expansion [30]. These findings suggest that alternative structural or intermolecular mechanisms may contribute to the thickening behavior of VIIs.

Temperature-sensitive behavior also plays a central role in the function of pour point depressants (PPDs), which prevent wax-related flow issues at low temperatures. Two major categories, alkyl aromatic polymers and polymethyl acrylates, act through different mechanisms to inhibit wax crystallization [8]. Alkyl aromatic polymers adsorb onto forming wax crystals to hinder their growth and aggregation, while polymethyl acrylates co-crystallize with wax, limiting crystal size. Although these additives cannot entirely prevent crystallization, they effectively delay it, lowering the pour point and improving cold-flow performance [8].

Mechanistic insights also guide the design of polymer-enhanced hydraulic fluids. A multiscale atomistic–continuum model combining Brownian Dynamics and Lattice Boltzmann methods has shown how dipole and non-dipole polymers behave under shear [31]. Non-dipole polymers couple more efficiently with bulk flow and expand more readily under shear, whereas dipole-containing polymers remain more compact due to intermolecular interactions. These structural responses influence flow resistance and energy efficiency, helping inform next-generation hydraulic fluid formulations [31].

In waxy crude oil treatment, the mechanism of polymeric flow improvers depends strongly on maintaining the correct balance of chemical and physical interactions. Octadecene–maleic anhydride copolymers synthesized with varying monomer ratios and modified with long-chain alcohols demonstrated improved flow behavior when they possessed an optimal hydrophobic–lyophobic balance, low crystallinity, and melting characteristics compatible with crude wax [32]. These features help disrupt wax deposition by interfering with the nucleation and growth of crystals.

It can be concluded that modern polymeric additives operate through a range of mechanisms, including conformational changes, crystal growth inhibition, shear-responsive behavior, and molecular compatibility with wax structures.

6. Recent advancements

Common viscosity modifiers, such as olefin copolymers (OCPs), remain widely used due to their effectiveness and low cost (as shown in Table 1) [27, 33]. Although recent studies suggest that transitioning from linear to hyperbranched polymer topologies can enhance shear stability, the potential of these polymers as multifunctional additives, particularly those capable of simultaneously reducing friction, remains largely unexplored. This gap highlights the need to expand the functional scope of traditional polymeric modifiers [27, 33].

Beyond viscosity modification, lubricant formulations also rely on super-alkaline additives, whose performance is assessed through a combination of standardized and specialized tests, including centrifugation for colloidal stability and viscosity monitoring [21]. A comparison between isododecyl phenol–based and isononyl phenol–based additives reveals a design trade-off: the former offers superior viscosity behavior, whereas the latter provides better colloidal stability. Despite these differences, both additives exhibit comparable antioxidant performance, detergency, and resistance to carbonization, with the isododecyl phenol variant showing a slightly longer resistance to sludge formation [21]. These findings demonstrate how fine-tuning the molecular structure can influence additive stability without compromising core functionality.

Biobased polymer additives present another promising route for enhancing shear stability and multi-functional performance. Musa et al. synthesized a neem-oil-derived homopolymer and a copolymer incorporating nanocrystalline cellulose (NCC), confirming polymerization through FTIR analysis of olefinic peak disappearance [35]. The copolymer exhibited higher thermal stability than the homopolymer and performed optimally at a

concentration of 2%, resulting in an improved viscosity index of 111.1 and a reduced pour point of -14°C . These results demonstrate that renewable polymer structures can improve both viscosity–temperature behavior and cold-flow properties [35].

Recent efforts to integrate sustainable materials have led to the exploration of cellulose-based biopolymers, particularly cellulose nanocrystals (CNC) derived from flax, wood, and wheat straw [1]. Their nanoscale dimensions, high mechanical strength, and low density make CNCs attractive as green lubricant additives. Studies show that adding only 0.1% CNC to SAE40 oil can significantly enhance performance, reducing friction under both high-speed, low-load conditions and low-speed, high-load conditions. Wear rate reductions of up to 69% have been observed at low speeds; however, increasing the CNC concentration to 0.5% delivers a smaller friction benefit compared to the optimized 0.1% level [1]. These results suggest that biopolymer additives can deliver meaningful performance gains when carefully formulated.

Complementing these developments, new synthetic terpolymers produced via free radical polymerization of alkyl acrylate, styrene, and vinyl pyrrolidone have been evaluated as pour point depressants and viscosity index improvers [36]. Terpolymers incorporating tetradecyl acrylate performed especially well in reducing pour point, while using acrylates with longer alkyl chains led to higher viscosity indices [36]. Such structure–property relationships emphasize the importance of molecular design in optimizing lubricant performance.

Further innovation arises from the synthesis of Core-Crosslinked Star Copolymers using an arm-first RAFT polymerization strategy, which enables the direct generation of star-like architectures in base oil without requiring additional purification steps [37]. By adjusting the molecular weight of the arms and the type of crosslinker, researchers produced copolymers with varying arm numbers and performance profiles. Higher molecular weights of the arms improved the viscosity index but decreased shear stability, with the optimal balance achieved using PMA arms of approximately 20,000 g/mol [37]. These findings demonstrate how advanced polymer architectures can be tuned to meet competing requirements in modern lubricant formulations.

In summary, current polymeric additives, ranging from conventional OCPs to biopolymers, terpolymers, and star-shaped copolymers, reflect a path for optimizing lubricant performance.

7. Applications and future trends of polymeric additives

Researchers analyzed the behavior of dipole and non-di-

pole polymers under shear flow using a hybrid atomistic–continuum model, providing molecular-level insights relevant to lubricant formulation. By simulating linear polymer chains using Brownian Dynamics and Lattice Boltzmann methods across multiple shear rates, the study demonstrated that dipole–dipole interactions maintain polymers in a more compact state while non-dipole chains stretch more easily, couple more efficiently with shear, and generate less resistance. These characteristics make non-dipole polymers particularly attractive for hydraulic fluid applications [31]. Overall, random forces dominated polymer motion, and the modeling strategy offers valuable guidance for designing next-generation lubricants and other complex polymer–colloid systems.[31].

Building on the concept of tailoring molecular interactions for enhanced lubrication, a pyrene-based gelator was shown to self-assemble in lubricant oil, forming a semi-solid gel with unique shear-thinning properties that reduce friction and wear. Its performance is further improved by adding multi-element-doped carbon nanospheres, which create a durable protective layer on contacting surfaces and increase load-bearing capacity [38]. Additionally, the gel exhibits strong photothermal activity under near-infrared light, suggesting multifunctional applications where controlled heating or adaptive lubrication may be desirable [38].

Nanomaterial-based additives provide an additional pathway for advanced lubrication technologies. The incorporation of graphene oxide (GO) nanosheets was found to decrease the dynamic viscosity of engine oil by 2–14% over most temperatures, particularly above 40 °C, due to the sheets' ability to slip between fluid layers. Although slight viscosity increases can occur at 0 °C at higher GO concentrations because of agglomeration, GO still raises the viscosity index by up to 7%, providing a shear-stable alternative to conventional polymer viscosity modifiers [39]. Enhanced thermal conductivity (4–15%) with increasing GO loading and temperature further improves heat transfer and engine warm-up efficiency. GO also reduces friction and wear through mechanisms such as interlayer sliding, tribofilm formation, and surface repair. In boundary lubrication, GO nanosheets create a third-body layer that prevents metal-to-metal contact, while in hydrodynamic conditions, they decrease effective viscosity by promoting easier fluid-layer sliding [39].

Ultimately, future trends will likely emphasize multifunctional, adaptive, and environmentally resistant additives that perform well under demanding operating conditions.

8. The potential of smart polymers to create shear-stable, adaptive lubricants

The fundamental weakness of traditional viscosity mod-

ifiers (VMs), such as olefin copolymers, is their susceptibility to mechanical shear in critical components, including gear contacts and hydraulic pumps. This shear force permanently severs the polymers' long molecular chains, a process known as chain scission, leading to an irreversible loss of viscosity. Such degradation directly compromises engine protection and operational efficiency, motivating the exploration of more robust polymer architectures.

In line with these efforts, one study examined how different polymer end-groups influence shear viscosity using ~670 kg/mol polycyclooctadiene dissolved in two solvents at three reduced concentrations ($c/c^* = 0.125, 0.25, 0.5$). By comparing samples at equal concentration, the researchers ensured that the polymers occupied the same effective volume, even though higher mass concentrations were needed in solvents where the chains were more compact. These investigations highlight how polymer architecture strongly governs fluid behavior, particularly in sprays where extensional flow becomes critical [40]. Polymer additives can significantly alter spray properties by increasing resistance to breakup, resulting in thicker ligaments and a reduced spray angle even at very low concentrations (≤ 0.05 wt%). Notably, end-associative polymers achieve this mist-suppressing effect with potentially greater resistance to mechanical degradation than non-associative systems, offering an added safety advantage [40].

Further advancements in polymer design are exemplified by smart polymers, which benefit from the responsiveness of polymer brushes enhanced by interactions with surfactants. These synergistic interactions improve surface functionality, enabling advanced applications such as low-energy, highly stable antifouling coatings. A tailored fluorinated polymer-brush system demonstrated substantial gains in durability and environmental resistance, with field evaluations showing over 90 days of fouling prevention [41, 42]. Such results underscore how purposeful molecular engineering and brush–surfactant synergy are crucial for unlocking high-performance smart polymer technologies [41].

Complementary strategies for improving lubricant performance involve the use of copolymers such as octadecyl methacrylate–dodecene and octadecyl methacrylate–hexadecene, as well as their nanocomposites prepared with nanomontmorillonite. These additives function as pour-point depressants, flow improvers, and viscosity modifiers, with the nanocomposites consistently outperforming their pure-polymer counterparts [43]. The nanocomposites markedly reduced the pour point, reaching as low as –33 °C at 10,000 ppm, while simultaneously enhancing the viscosity index, apparent viscosity, and yield

stress, demonstrating the benefits of nanoscale reinforcement [43].

Expanding beyond conventional additives, supramolecular polymers represent an advanced class of materials built through dynamic, non-covalent bonds. Their unique properties in reshaping material science make them usable in fields such as biomedical engineering and environmental technology [44]. Despite their potential, challenges related to long-term stability and scalability remain important barriers to widespread application.

In summary, innovations ranging from associative polymers to nanocomposites and supramolecular systems illustrate the expanding methods available for enhancing lubricant performance and designing smart functional materials.

9. Conclusion

The performance of engine oils depends on both the quality of the base oil and the careful selection of additives. Additives play multiple roles, including reducing friction and wear, providing anti-oxidation protection, improving detergency, and inhibiting corrosion, rust, and foaming. Anti-wear additives form protective films on metal surfaces, reducing component wear and extending engine life. Pour point depressants, such as alkyl aromatic polymers and polymethyl acrylates, improve low-temperature flow but cannot completely prevent wax formation. The effectiveness of additives also depends on particle size, dispersibility, and concentration, as poor dispersion can reduce the friction-reducing and wear-reducing benefits of the additive. Viscosity index (VI) improvers are critical for maintaining optimal oil viscosity across a wide temperature range. Although their effect is often attributed to polymer coil expansion at higher temperatures, recent studies show that coil growth is not strictly necessary for significant VI enhancement. A key limitation of traditional polymer-based VI improvers is their susceptibility to mechanical shear, which can break polymer chains and lead to permanent viscosity loss. Emerging technologies, including star-shaped polymers and multifunctional shear-resistant additives, address this challenge by improving durability and maintaining viscosity under stress. By integrating traditional additives with innovative polymer designs, lubricants can achieve improved performance, longer service life, and reduced environmental impact. Overall, continued research into additive mechanisms and advanced polymer architectures is essential for creating the next generation of high-performance engine oils.

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Consent for publication

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Competing interests

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