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Review

The Evolution of Nanofluids in Automotive Applications: Current State and Future Directions

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Abstract

The continuous advancement of automotive technology has intensified the demand for innovative materials that improve vehicle performance, energy efficiency, and sustainability. Nanofluids colloidal suspensions of nanoparticles within conventional base fluids have gained considerable attention due to their remarkable thermal and tribological properties. This review examines the current progress in nanofluid research, emphasizing their potential to enhance heat transfer, thermal management, and fuel economy in automotive systems. Nanofluids containing nanoparticles such as Al_2O_3, CuO, and carbon-based materials dispersed in base fluids like water or ethylene glycol have demonstrated superior thermal conductivity, enabling more compact and efficient heat exchangers, radiators, cooling systems, and engine lubricants. The review further explores their tribological advantages in minimizing friction and wear, as well as their contribution to improved combustion efficiency and reduced emissions in fuel systems. Despite these promising outcomes, challenges remain regarding nanoparticle dispersion stability, cost, and long-term performance. Economic factors, including raw material costs, synthesis requirements, and lifecycle considerations, also influence their practical adoption. Future research should focus on optimizing synthesis and stabilization techniques, assessing environmental implications, and developing hybrid nanofluids to maximize efficiency across diverse automotive applications. Overall, this review highlights the transformative potential of nanofluids in advancing automotive technologies while underscoring the need for continued research to address existing limitations and enable practical implementation.

Keywords

Nanofluids, Automotive cooling systems, Thermal management, Heat transfer enhancement, Tribological properties, Nanoparticle dispersion stability

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1. Introduction

The rapid evolution of automotive technologies has intensified the demand for advanced materials and fluid systems that can support higher performance, improved energy efficiency, and greater environmental sustainability. Among the emerging solutions, nanofluid suspensions of nanoparticles dispersed in conventional base fluids have attracted significant attention for their ability to enhance key thermophysical properties. Their improved thermal conductivity, heat capacity, and flow behavior make them promising candidates for a broad range of automotive applications, including engine cooling, brake systems, heat exchangers, and battery thermal management. This review provides a critical assessment of current nanofluid research within the automotive field, outlines their demonstrated benefits, discusses the challenges that still limit widespread adoption, and highlights areas where further investigation is needed to support their integration into next-generation vehicles.

The foundational work of Maxwell [1] first demonstrated that embedding solid particles in liquids could improve thermal conductivity, addressing the long-standing limitations of conventional heat-transfer fluids and motivating the search for new media suitable for compact or microscale heat exchangers. Achieving a stable, uniform dispersion of particles in liquids remained a major challenge for decades. This changed in 1995, when Choi and Eastman [2] introduced the term “nanofluid” to describe a new class of engineered fluids containing nanoparticles on the scale of a few nanometers. Since then, advances in nanotechnology have expanded the development and application of nanomaterials ultrafine solids with size-dependent behaviors distinct from their bulk counterparts across fields ranging from medicine and agriculture to industrial engineering.

When properly stabilized, nanofluids behave as colloidal systems in which the suspended nanoparticles significantly enhance heat-transfer performance [3-5]. This improvement contributes to greater energy efficiency and enables the design of smaller, lighter, and more effective heat-exchange equipment [6-11]. Recent studies focused on automotive systems further reinforce these advantages. For instance, Patel et al. [12] examined the use of nanofluids in radiator coolants, lubricants, and fuel systems, while Gülüm et al. [13] reported meaningful reductions in radiator size and weight when high-performance nanofluids were used. Research on hybrid nanofluids—fluids containing two or more types of nanoparticles shows additional gains in thermal conductivity, stability, and overall heat-transfer effectiveness, making them particularly attractive for engine cooling and diesel-engine thermal management [14].

Despite these encouraging findings, several practical challenges remain. These include ensuring long-term dispersion stability, managing the increased pumping power associated with higher viscosity, addressing cost considerations, and understanding performance under real automotive operating conditions [15-17]. In parallel with these technical challenges, the economic viability of nanofluids has become increasingly relevant for their adoption in real automotive systems. Recent reports emphasize that nanoparticle costs, synthesis procedures, stabilization requirements, and system maintenance all contribute to the total lifecycle cost of nanofluid-based cooling or lubrication systems. While many formulations demonstrate clear thermal advantages, their practical implementation will depend on achieving cost-effective production routes and minimizing operational expenses without compromising reliability. Together, these issues underscore the need for continued targeted research.

Since the introduction of nanofluids, numerous studies have explored their potential to enhance heat-transfer processes across a wide range of systems [18-20]. Many of these investigations have shown that nanofluids improve convective heat transfer and offer measurable performance gains under both laminar and turbulent flow conditions [21-26]. As the demand for efficient heat transfer continues to grow, researchers have evaluated nanofluids in diverse applications such as electronic cooling [27], refrigeration systems [28], solar thermal collectors [29,30], and industrial cooling towers [31], with consistently promising results [32]. Conventional thermal fluids—water, oils, and ethylene/propylene glycol remain essential in engineering, yet their inherently low thermal conductivity limits their ability to meet rising performance requirements. Traditional enhancement strategies, including extended surfaces, surface vibration, and flow manipulation, have reached their practical limits. Consequently, efforts have shifted toward modifying the thermophysical properties of base fluids through the addition of high-conductivity solid particles, a strategy shown to significantly improve heat-transfer performance [33-38].

Although research on nanofluids has grown steadily, a complete and focused assessment of their role in automotive systems is still missing. Most earlier reviews looked at general heat-transfer applications or examined only one component at a time, which leaves important questions unanswered about how nanofluids perform across engine cooling, lubrication, fuel systems, and newer electric vehicle technologies. In this review, we draw on recent studies to bring these areas together and highlight emerging developments in electric vehicle thermal management, including battery cooling strategies, cold-plate designs, and the thermal control of power electronics. We also discuss advances in hybrid nanofluids that are being tailored to handle the higher heat loads found in modern automotive applications. By comparing these developments with the conclusions of earlier reviews, we show how the field has moved beyond basic thermophysical improvements toward application-driven design and performance optimization. The goal of this work is to connect these scientific advances with the practical challenges faced by today’s automotive industry—from reducing weight and emissions to improving energy efficiency and managing the thermal demands of next-generation powertrains. Through this approach, the review offers a clearer and more integrated picture of how nanofluids can contribute to more efficient and sustainable automotive technologies.

2. Nanomaterials for Nanofluid Development: Types and Applications

Nanofluids are advanced colloidal suspensions consisting of nanoparticles dispersed in a base fluid, with the particles typically smaller than 100 nm. The thermophysical behavior of nanofluids is governed by both the intrinsic properties of the base fluid and the characteristics of the dispersed nanoparticles. Key influencing factors include nanoparticle size, shape, concentration, synthesis route, and surface chemistry, as well as the compatibility between the nanoparticle and base fluid. Common base fluids used in nanofluid preparation include water, ethylene glycol, propylene glycol, and their binary mixtures, selected for their favorable heat-transfer characteristics and chemical compatibility [39-42]. These conventional fluids are well established in cooling and thermal systems but possess limited thermal conductivity. Incorporating nanoparticles with high surface area and superior conductivity into such fluids markedly enhances energy transport and overall thermal performance. Nanoparticles employed in nanofluid development can be broadly categorized into ceramic, metallic, and carbon-based types.

- Ceramic nanoparticles such as Al_2O_3, TiO_2, SiO_2, SiC, ZnO, and Fe_3O_4 are widely studied due to their excellent thermal stability, resistance to oxidation, and good dispersion behavior in polar base fluids. They offer balanced improvements in both conductivity and chemical durability, making them suitable for long-term heat-transfer applications [43,44].
- Metallic nanoparticles including Cu, Al, Ag, Au, and Fe provide exceptional thermal conductivity and are capable of significantly enhancing convective heat transfer. However, their higher density, cost, and tendency to oxidize can limit large-scale use in closed-loop systems [45-47].
- Carbon-based nanoparticles such as carbon nanotubes (CNTs), graphene, graphene oxide (GO), and carbon black are increasingly popular for next-generation nanofluids. Their outstanding thermal conductivity, mechanical strength, and aspect ratio contribute to superior heat-transfer enhancement, although achieving stable dispersions without aggregation remains a major challenge [40,41,48].

To ensure homogeneous dispersion and prevent nanoparticle agglomeration, surfactants or stabilizing agents are typically incorporated into nanofluids. Typical stabilizers include ionic surfactants, such as Sodium Dodecyl Sulfate (SDS) and Cetyltrimethylammonium Bromide (CTAB), polymeric dispersants, and surface modifiers specifically tailored to the chemistry of the nanoparticles and the base fluid [43,45]. Additionally, physical techniques such as ultrasonication and pH control are often applied to enhance suspension stability. Stable dispersion is essential for maintaining consistent thermal conductivity, viscosity, and flow behavior—parameters critical for reliable performance in automotive cooling systems, heat exchangers, and other thermal management devices [46,48]. The effective performance of nanofluids depends on the careful selection of the base fluid, nanoparticle type, and stabilization approach. A comprehensive understanding of how these factors interact is essential for developing stable, efficient, and purpose-specific nanofluids suited to advanced applications such as automotive thermal systems and renewable-energy technologies [42,48].

2.1 Analysis and Characterization of Al_2O_3/TiO_2 Nanolubricants

Recent studies have widely examined Al_2O_3/TiO_2-based nanolubricants for enhancing the thermal and tribological performance of automotive engine oils. In these studies, commercial synthetic oils, such as Castrol EDGE Professional A5 5W-30, are commonly employed as base lubricants to evaluate the effects of nanoparticle additives on thermo-oxidative stability and lubrication behavior [49,50]. The incorporation of TiO_2 and Al_2O_3 nanoparticles provides notable advantages due to their excellent tribological properties as solid lubricants and their ability to enhance heat dissipation through superior thermal conductivity. Moreover, both materials are cost-effective and are known to function as combustion catalysts that promote more complete and efficient fuel burning in internal combustion engines [49,50]. The TiO_2 (anatase) and Al_2O_3 (γ-phase) nanoparticles commonly utilized in nanolubricant formulations typically possess particle diameters in the range of 8-12 nm and exhibit the properties summarized in Table 1. Experimental findings generally indicate that particles within the 5-15 nm range provide the most effective rolling behavior while minimizing abrasive wear, whereas larger nanoparticles (20-30 nm and above) tend to increase surface scratching and reduce overall tribological performance. These differences in density, surface area, and thermal conductivity significantly influence the overall performance and dispersion stability of hybrid nanolubricants. Researchers have noted that van der Waals interactions among nanoparticles can induce agglomeration, which negatively affects lubrication efficiency and long-term stability [49]. Hence, proper dispersion and stabilization techniques remain essential for maintaining uniform suspension quality. Hybrid Al_2O_3/TiO_2 nanolubricants are generally prepared by dispersing small fractions of nanoparticles commonly around 0.05 wt% Al_2O_3 and 0.05 wt% TiO_2 into a base oil along with surfactants such as oleic acid, which act as dispersants to improve particle compatibility and prevent sedimentation [50]. Oleic acid is widely adopted because it provides effective surface modification and steric stabilization without altering the viscosity or chemical integrity of the base oil. Studies have shown that optimized nanolubricant formulations containing approximately 0.1 wt% nano-additives can reduce frictional power losses by up to 53% and lower fuel consumption by nearly 16%, demonstrating their potential for enhancing energy efficiency and component durability in engines [50].

Table 1. Characteristics of TiO_2 and Al_2O_3 nanomaterials.

Property	TiO_2	Al_2O_3
True density	4.23 g/cm³	3.70 g/cm³
Specific surface area	77.37 m²/g	130 m²/g
Thermal conductivity	8.4 W/m·K	40 W/m·K
Specific heat capacity	697 J/kg·K	773 J/kg·K

To assess the structure, composition, and dispersion quality of Al_2O_3/TiO_2 nanolubricants, researchers commonly employ several complementary analytical and characterization techniques. X-ray diffraction (XRD) is used to verify the crystalline phases of TiO_2 and Al_2O_3, ensuring that no phase transformation occurs during preparation. Fourier transform infrared spectroscopy (FTIR) helps identify surface functional groups and confirms the chemical interaction between nanoparticles, surfactants, and the base oil. Scanning electron microscopy (SEM) or transmission electron microscopy (TEM) provides visual evidence of nanoparticle morphology and agglomeration behavior, while zeta potential analysis quantifies the electrostatic stability of the suspension. In practical terms, absolute zeta potential values of approximately ±30 mV or higher are generally regarded as sufficient to maintain long-term colloidal stability, even under the elevated temperatures and shear stresses present in engine lubrication environments. Studies also note that surfactants such as oleic acid may undergo gradual degradation through oxidative breakdown or partial desorption from nanoparticle surfaces during extended operation, which can reduce dispersion stability over time.

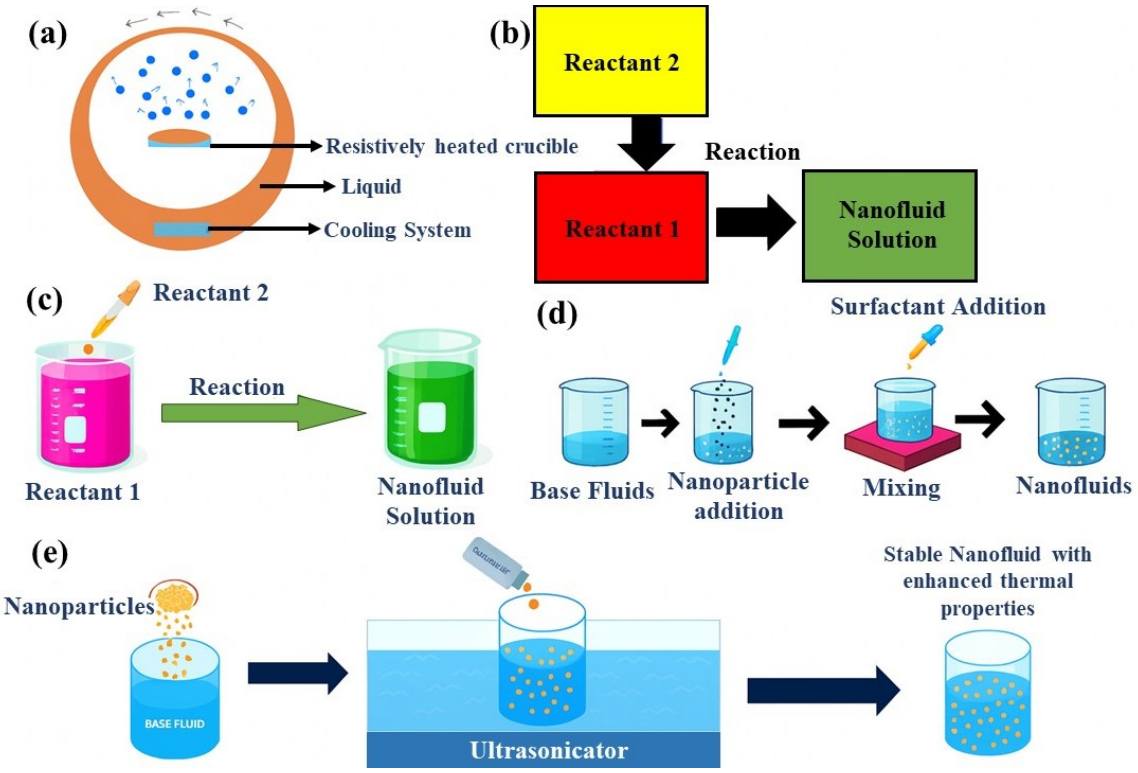

Figure 1. Schematic representation of the preparation and stabilization process of based nanolubricants.

Collectively, these techniques have been instrumental in correlating microstructural features with the improved thermal conductivity, viscosity behavior, and frictional performance of Al_2O_3/TiO_2 nanolubricants [50]. Although this review does not provide detailed surface analyses, previous studies employing techniques such as X-ray Photoelectron Spectroscopy (XPS) and Energy-Dispersive Spectroscopy (EDS) have offered crucial evidence of tribochemical film formation, supporting the proposed lubrication mechanisms reported for Al_2O_3/TiO_2 nanolubricants. The commonly reported formulation of approximately 0.05 wt% Al_2O_3 and 0.05 wt% TiO_2 reflects an optimized balance between thermal and tribological performance. Al_2O_3 contributes primarily to enhancing thermal conductivity because of its higher intrinsic conductivity and larger specific surface area, while TiO_2 is more effective in boundary lubrication due to its chemical stability and ability to form protective surface films under load. Using both nanoparticles in equal proportions helps combine these complementary effects while avoiding excessive particle loading, which could increase viscosity or promote agglomeration. This ratio has therefore been adopted in several studies as a practical compromise

that supports both heat dissipation and wear reduction in engine lubrication systems. As illustrated schematically in Figure 1, the preparation and stabilization process typically involve surfactant addition, mechanical stirring, and ultrasonic dispersion to obtain a homogeneous and stable hybrid nanolubricant formulation suitable for engine applications.

A cross-study examination shows recurring patterns: (i) particle size and morphology matter nanoparticles ~10-100 nm generally give the best balance of surface reactivity and film formation, (ii) loading follows a non-linear trend where low-to-moderate concentrations typically maximize benefit while very high concentrations risk aggregation and abrasive wear, and (iii) stabilization is decisive chemical functionalization or strongly adsorbed layers produce the most reliable long-term stability compared to surfactants or purely mechanical dispersion. Thermal-property gains (thermal conductivity) are often modest and must be balanced against viscosity increases that can harm flow and pumping performance.

Sources of contradiction and open questions. Where studies disagree, three factors commonly explain the difference: short vs. long test durations, undisclosed or differing base-oil additive packages which interact with nanoparticles, and differences between simple bench tribology and realistic engine-condition tests. To help readers interpret the literature we suggest that authors clearly report particle size distribution, loading units, stabilization method, base oil composition, and test protocol.

Studies consistently report that nanoscale additives outperform micron-sized ones. For instance, nano-WS_2 additives reduced friction ~26% more than micro-sized WS_2. Nanoparticles (<100 nm) can enter asperity contacts and form low-friction tribofilms much more easily than bulk powders. In fact, ~5 nm Cu NPs gave significantly better friction reduction than larger Cu particles in base oil. In general, additives in the 10-100 nm range tend to yield the best friction/wear performance. TiO_2 and ZnO NPs greatly improve lubrication, whereas larger particles often fail to enter the contact zone [51].

Multiple reports emphasize that chemical functionalization dramatically improves nanolubricant stability. Aithal et al. (2025) [51] show that oleic-acid/oleylamine (OA/OAm) ligand coatings on CuO NPs reduce sedimentation by ~75% compared to uncoated CuO. This steric coating maintained dispersion under shear, leading to 44-60% lower friction and 29-64% lower wear vs. raw CuO NPs. In contrast, simple surfactant-based dispersions or mechanical mixing tend to fail over time. Excess free surfactant can raise viscosity and friction, while too little surfactant lets NPs aggregate. Similarly, a tribology review reports that TiO_2 and ZnO NPs often suffer from agglomeration in oil-based media, leading to inconsistent performance unless properly surface functionalized or dispersed using stabilizers.

3. Methods of Nanofluid Preparation

Nanofluids are colloidal suspensions of solid nanoparticles dispersed in base fluids such as water, ethylene glycol, or oils. These nanoparticles, typically metallic or non-metallic, exhibit high thermal conductivity and enhance the overall thermophysical properties of the base fluid. Two primary methods are employed for nanofluid preparation: the one-step and two-step techniques, each with distinct advantages and challenges. The two-step method is the most widely adopted due to its simplicity, scalability, and cost-effectiveness. In this approach, nanoparticles are first synthesized using physical or chemical methods such as sol-gel, hydrothermal, chemical precipitation, or mechanical milling. In the second stage, the nanoparticles are dispersed into the base fluid through magnetic stirring, high-shear mixing, or ultrasonication often for several hours to ensure homogeneous suspension. Although this method can lead to particle agglomeration due to high surface energy, the addition of surfactants or dispersants helps maintain colloidal stability. Its adaptability makes it particularly suitable for automotive applications, where fluids can be formulated or reconditioned on-site to meet manufacturer specifications [52-57]. Conversely, the one-step method integrates nanoparticle synthesis and dispersion into a single process. A representative example is the Submerged Arc Nanoparticle Synthesis System (SANSS), in which nanoparticles are generated directly within the base fluid, eliminating the need for drying, handling, or transportation [53]. This approach minimizes oxidation and aggregation, producing highly stable nanofluids with improved uniformity. However, it faces limitations such as residual precursor contamination, high production cost, and poor scalability. Trace precursor contamination from one-step systems such as SANSS can have important implications for long-term corrosion behavior in automotive cooling circuits. Even low residual levels of metal salts, unreacted ions, or synthesis by-products may alter the pH or ionic strength of the nanofluid over time, increasing the susceptibility of aluminum, brass, and copper components to localized corrosion. Aluminum alloys are particularly sensitive to chloride and sulfate residues, while brass and copper may undergo accelerated dezincification or pitting in the presence of reactive anions. Several studies note that such contaminants can weaken the protective oxide layers on these metals, especially under high-temperature, high-flow operating conditions. These effects highlight the need for careful purification or post-processing of SANSS-derived nanofluids before they are considered for automotive use. These issues hinder its large-scale industrial implementation, especially for automotive lubricants and coolants, where purity and formulation consistency are critical [54,55,58].

Recent research (2023-2025) continues to refine both techniques. Advanced hybrid methods now combine ultrasonic dispersion with surface functionalization to improve nanoparticle stability and heat-transfer performance. Studies also highlight that optimizing particle concentration (typically below 1 vol%) and ensuring surface compatibility are

essential to prevent viscosity increase or sedimentation. Emerging work in the field focuses on developing continuous-flow reactors and greener synthesis approaches to produce nanofluids with consistent properties while reducing environmental and economic costs [59-61].

A concise summary of selected studies highlighting recent developments in nanofluid preparation methods is presented in Table 2. These works illustrate the progression from conventional two-step dispersion to more advanced hybrid and surface-functionalized techniques designed to enhance stability, reproducibility, and performance in diverse base fluids. In general, the selection of a preparation technique depends on the target application, nanoparticle type, and production scale. Recent reports indicate that two-step processing is currently the most practical route for industrial-scale production, with pilot facilities capable of generating between 500 and 2,000 liters per batch depending on the nanoparticle system. Estimated production costs for automotive-grade nanofluids prepared via this method range from 8 to 18 USD per liter, influenced by nanoparticle pricing, surfactant usage, and energy demand during dispersion. For context, conventional ethylene glycol coolant typically costs less than 4 USD per liter, highlighting the economic gap that still limits large-scale adoption. Nevertheless, ongoing developments in continuous-flow dispersion, bulk nanoparticle synthesis, and greener surfactant systems are expected to reduce costs and improve the viability of nanofluid production for automotive applications. For automotive systems, the two-step approach remains the preferred choice because it provides an optimal balance between performance, stability, and cost efficiency while supporting the standardization required for industrial formulation and servicing.

Table 2. Summary of selected studies on nanofluid preparation methods.

Nanofluid System	Preparation Method	Base Fluid	Key Findings / Remarks	Ref.
Hybrid Al_2O_3-TiO_2/oil	Two-step	Engine oil	Improved lubrication and reduced frictional losses in engines.	[52]
Ag nanofluid	One-step (SANSS)	Ethylene glycol	Direct synthesis produced stable dispersion without oxidation.	[53]
Al_2O_3/water	Two-step	Water	Demonstrated enhanced heat transfer with prolonged sonication.	[54]
Cu/EG	One-step (vapor condensation)	Ethylene glycol	Reported high thermal conductivity; limited scalability.	[55]
Various nanofluids	Two-step	Water, EG	Discussed challenges in laboratory-scale to industrial scale-up.	[56]
Hybrid nanofluids	Two-step+surfactant	EG/water mixture	Reported improved thermal stability and reduced sedimentation.	[57]
Single & hybrid nanofluids	Two-step	Various	Reviewed methods for enhanced reproducibility and stabilization.	[58]
Al_2O_3 and CuO nanofluids	Two-step	Water	Identified ultrasonication as key factor in maintaining stability.	[59]
Functionalized nanofluids	Hybrid method	Water-based	Highlighted eco-friendly synthesis and reduced agglomeration.	[60]
Hybrid nanofluids	Two-step+surface modification	Oil, EG	Demonstrated high thermal conductivity with improved dispersion.	[61]

3.1 Greener Synthesis Methods and Continuous-Flow Production

Greener synthesis approaches have gained increasing attention in recent nanofluid research, reflecting the need for environmentally responsible production routes. Several recent studies report the use of plant extracts, biodegradable surfactants, and low-toxicity reducing agents to fabricate metal oxide and hybrid nanoparticles with reduced chemical waste and lower energy demand. Green-reduced Al_2O_3, ZnO, and Ag nanoparticles produced using botanical extracts such as neem, aloe vera, and tea polyphenols have shown promising stability and thermophysical performance when dispersed in water or glycols. These bio-assisted methods eliminate hazardous by-products and offer better control over particle size, which is essential for maintaining long-term stability in automotive cooling and lubrication systems. Moreover, the use of natural dispersants such as gum arabic or cellulose derivatives has demonstrated improved steric stabilization, further supporting their suitability for large-scale applications. In parallel, continuous-flow reactor technologies have emerged as a scalable alternative to traditional batch synthesis. Microreactor and milli-reactor systems allow precise control of reaction time, temperature, and mixing conditions, enabling consistent nanoparticle size distribution and reducing the risk of agglomeration. Recent advancements include modular continuous-flow platforms capable of producing metal oxide, carbon-based, and hybrid nanoparticles in liter-per-hour quantities with high reproducibility–an important requirement for automotive-grade nanofluids. These systems also offer advantages in

process safety, energy efficiency, and real-time monitoring, making them suitable candidates for industrial adoption. As the automotive sector moves toward more sustainable and standardized coolant and lubricant formulations, continuous-flow synthesis provides a promising pathway for scaling nanofluid production while maintaining uniform quality and minimizing environmental impact.

4. Properties of Nanofluid

The development of nanofluids is largely driven by the goal of enhancing the thermophysical properties of conventional base fluids particularly thermal conductivity to achieve higher heat transfer efficiency. Through careful modification of these properties, nanofluids can be tailored to meet specific performance requirements in various engineering systems [62,63]. Extensive theoretical and experimental investigations have been conducted to examine their key properties, most notably thermal conductivity, viscosity, and specific heat capacity, which are fundamental to the effective utilization of nanofluids in energy and automotive applications.

A wide range of nanoparticles has been explored, including metal oxides (Al_2O_3, CuO, TiO_2), metals (Ag, Cu), magnetic materials (Fe_3O_4), and carbon-based nanostructures such as multi-walled carbon nanotubes (MWCNTs) and graphene [64-71]. Each type contributes differently to enhancing the thermal behavior and flow characteristics of the base fluid, depending on particle size, morphology, and concentration.

4.1 Thermal Conductivity

Nanofluids have attracted significant attention as advanced heat transfer media, particularly for automotive cooling and lubrication systems, due to their superior thermal conductivity compared with conventional fluids. The enhancement in thermal conductivity is influenced by several factors, including nanoparticle type, volume fraction, particle size and shape, base fluid, temperature, and dispersion stability [65-67]. Experimental findings consistently indicate that increasing nanoparticle concentration enhances the effective thermal conductivity of the fluid. For instance, Mohammadi et al. [65] and Pang [72] reported that Al_2O_3 and CuO nanofluids based on engine oil exhibited enhancements of approximately 5-8% at 2 vol% and 10.4% at 3.5 vol% for Al_2O_3 coolant systems, respectively. Similarly, Kole and Dey [73] observed that aluminum nitride nanoparticles produced a 75.2% improvement at 3 wt%, confirming the strong dependence of thermal conductivity on particle loading and composition. Other investigations such as those by Ahmed et al. [66], Moghaieb et al. [68], and Moldoveanu et al. [67] have demonstrated similar enhancements across different nanofluid systems. These studies show that nanoparticle material, morphology, and the quality of dispersion play crucial roles in improving thermal performance.

The enhancement of thermal conductivity in nanofluids can be explained using several classical models. The Maxwell model is one of the earliest and most widely used formulations to estimate the effective thermal conductivity of solid-liquid mixtures. It considers the nanoparticle concentration (φ) as the primary factor influencing heat conduction, and is expressed as:

$$k_{nf} = k_{bf}\left(\frac{\left(k_p + 2k_{bf} + 2\phi\,(k_p - k_{bf})\right)}{\left(k_p + 2k_{bf} - \phi\,(k_p - k_{bf})\right)}\right) \quad (1)$$

where k_{nf} is the thermal conductivity of the nanofluid, k_{bf} is the thermal conductivity of the base fluid, k_p is the thermal conductivity of the nanoparticle, and ϕ is the particle volume fraction.

While the Maxwell model effectively predicts the behavior of spherical nanoparticles in dilute suspensions, it does not account for particle shape. The Hamilton-Crosser model extends the Maxwell approach by introducing a shape factor (n) that considers the geometry of nanoparticles [59]. The model is expressed as:

$$k_{nf} = k_{bf}\left(\frac{\left(k_p + (n-1)k_{bf} - (n-1)\phi\,(k_{bf} - k_p)\right)}{\left(k_p + (n-1)k_{bf} + \phi\,(k_{bf} - k_p)\right)}\right) \quad (2)$$

where n is defined as:

$$n = \frac{3}{\psi} \quad (3)$$

Here, ψ (sphericity) represents the ratio of the surface area of a sphere (having the same volume as the particle) to the actual surface area of the nanoparticle. A smaller value of ψ (less spherical shape) corresponds to a higher n, indicating greater thermal enhancement due to the increased surface contact between the particles and the fluid. These models provide theoretical validation for the observed experimental trends and confirm that both particle concentration and shape significantly influence the thermal conductivity of nanofluids. However, real systems often deviate from these predictions due to factors such as particle aggregation, interfacial resistance, and non-homogeneous dispersion, which are not fully captured in classical formulations. Classical models such as Maxwell and Hamilton-Crosser provide a useful starting point, but they inherently assume steady-state conduction and do not capture the temperature-dependent

variations in thermal conductivity that are commonly reported in nanofluid experiments. In practice, the effective thermal conductivity of nanofluids increases with temperature due to enhanced Brownian motion, reduced fluid viscosity, and stronger micro-convection effects none of which are represented in these early models. More advanced approaches now incorporate mechanisms such as Brownian diffusion, thermophoresis, interfacial liquid layering, and particle-fluid slip, which become particularly important in the typical automotive operating range of 80-130 °C. These improved models offer better agreement with experimental data and provide a more realistic basis for predicting nanofluid behavior in high-temperature engine cooling and lubrication systems. Recent studies incorporating surface modification and hybrid nanoparticle systems have shown better agreement between theoretical predictions and experimental data [74-78]. Advanced computational models now combine molecular dynamics simulations and experimental fitting to capture the combined effects of Brownian motion, thermophoresis, and interfacial layering on effective thermal conductivity. These developments further support the application of nanofluids in thermal management systems, where optimizing particle design and dispersion remains central to maximizing performance.

4.2 Viscosity

Viscosity is a fundamental parameter governing the convective heat transfer and flow behavior of fluids. Even slight variations in viscosity can substantially affect thermal transport and pumping performance in engineering systems. For nanofluids, viscosity is primarily influenced by nanoparticle concentration, particle size, temperature, and dispersion stability. Mathematically, several models have been developed to describe the viscosity behavior of nanofluids. The classical Einstein model (Equation 4) provides a reliable estimation for dilute suspensions, assuming spherical particles and negligible interparticle interactions [77]:

$$\eta_{nf} = \eta_o(1 + 2.5\phi) \quad (4)$$

where η represents the viscosity of the nanofluid, η_0 is the viscosity of the base fluid, and ϕ is the nanoparticle volume fraction. However, the Einstein model becomes less accurate at higher concentrations where particle interactions are no longer negligible. To account for this, Kunitz (1926) proposed an empirical correlation that more accurately represents the viscosity of concentrated suspensions up to approximately 50% solid volume fraction [79]:

$$\eta_{nf} = \eta_o(1+0.5\phi)/(1-\phi)^4 \quad (5)$$

This relationship better predicts the non-linear increase in viscosity with concentration and is often used to approximate nanofluid behavior in dense dispersions.

The rheological properties of nanofluids specifically their resistance to flow is influenced by shear forces acting between moving surfaces or within confined flow channels. These forces alter the internal friction of the fluid, making viscosity a key factor in assessing its thermal and mechanical performance. Experimental studies, such as those by Pak and Cho [80], have shown that viscosity can increase dramatically with nanoparticle addition, reporting up to a two-hundredfold increase for γ-Al_2O_3/water nanofluids at higher concentrations. Increased nanoparticle agglomeration typically leads to higher viscosity, resulting in larger pressure drops and greater pumping power requirements. This negatively impacts the overall energy efficiency of systems employing nanofluids. Furthermore, viscosity is strongly temperature-dependent generally decreasing with rising temperature though at elevated particle loadings, this relationship can become complex.

While base fluids such as water, ethylene glycol, and oil usually exhibit Newtonian flow behavior, the introduction of nanoparticles can induce non-Newtonian characteristics. This transition is often attributed to the formation of a nanolayer around the particles, which modifies the effective viscosity and shear response of the suspension. As described by Bhanvase et al. [19], this nanolayer effect alters interfacial friction and flow uniformity, particularly in systems operating under variable shear conditions. Overall, while the incorporation of nanoparticles enhances heat transfer capability, it also increases viscosity, which may offset performance gains if not optimized. Achieving the right balance between thermal conductivity enhancement and viscosity control remains a critical design consideration in developing nanofluids for automotive and industrial thermal systems. To better quantify this trade-off, many studies use the Performance Evaluation Criterion (PEC), which compares the relative increase in heat-transfer coefficient to the increase in frictional or pumping power. A PEC value greater than 1 indicates that the thermal benefits outweigh the hydraulic penalty, while values below 1 suggest that viscosity-related losses dominate. Reported PEC values for common nanofluids such as Al_2O_3/water and CuO/EG vary widely depending on concentration, flow regime, and temperature, underscoring the need to optimize nanoparticle loading rather than maximizing it. Incorporating PEC-based assessments helps determine whether a nanofluid formulation provides a genuine net energy advantage in automotive cooling or lubrication systems.

The models summarized in Table 3 provide useful frameworks for estimating the viscosity of nanofluids under different conditions. However, most classical correlations were originally developed for micron-scale suspensions and may not fully capture the effects of nanoscale interactions, temperature dependence, or non-Newtonian behavior. Recent studies

highlight that viscosity can vary significantly with nanoparticle surface modification, surfactant type, and hybrid composition. Therefore, advanced models integrating experimental data with empirical or machine learning approaches are being developed to better predict the rheological behavior of nanofluids in real operating environments.

Table 3. Summary of classical viscosity models for particle-laden fluids, including their mathematical forms, applicable concentration ranges, and key assumptions relevant to nanofluid behavior.

Model	Equation	Applicable Range / Assumptions	Key Features / Remarks	Ref.
Einstein (1906)	$\eta_{nf} = \eta_0 (1 + 2.5\varphi)$	Valid for dilute suspensions ($\varphi<0.02$); spherical, non-interacting particles	Linear relation between viscosity and volume fraction; simple and widely used for low concentrations	[78]
Kunitz (1926)	$\eta_{nf} = \eta_0 (1 + 0.5\varphi)/(1 - \varphi)^4$	Moderate to high particle concentrations ($\varphi \leq 0.5$)	Accounts for non-linear increase in viscosity with concentration; empirical correlation	[79]
Batchelor (1977)	$\eta_{nf} = \eta_0 (1 + 2.5\varphi + 6.2\varphi^2)$	Low-to-moderate concentrations	Considers hydrodynamic interactions among particles	—
Brinkman (1952)	$\eta_{nf} = \eta_0 / (1 - \varphi)^{2.5}$	Moderate φ (up to 0.4)	Extends Einstein's model by including crowding effects	—
Krieger–Dougherty (1959)	$\eta_{nf} = \eta_0 (1 - \varphi/\varphi_m)^{[-[\eta]\varphi_m]}$	Concentrated suspensions; φ_m = maximum packing fraction	Empirical model for high concentrations and complex particle shapes	—
Thomas (1965)	$\eta_{nf} = \eta_0 (1 + 2.5\varphi + 10.05\varphi^2 + 0.00273e^{(16.6\varphi)})$	Broad concentration range	Fits experimental data for suspensions with strong interparticle forces	—

Recent studie [81] provide specific values for property enhancements in nanofluids, which vary widely with particle type and concentration. For example, metal-oxide nanoparticles (Al_2O_3, TiO_2, ZnO, CuO) typically give moderate conductivity gains ~5-30% above the base fluid at vol% of a few percent. By contrast, highly conductive particles can yield much larger effects: Cu nanoparticles ~75-100 nm in water produced ~23.8% higher thermal conductivity at only 0.1% volume fraction. Noble metals are even more potent: Ag nanoparticles ~96 nm achieved ~20.8% increase in water at an extremely low 0.000017% vol. Hybrid fluids with two or more particle types can amplify this further–for instance a ternary hybrid (MWCNT/CuO/SiO_2) gave a ~37.1% conductivity boost at ~4 vol%, and a CuO-MgO binary system showed a 29.6% higher conductivity than single-CuO fluid at 0.5% total concentration [82]. Carbon-based nanofluids (CNTs, graphene) often exhibit some of the largest enhancements, though those data depend strongly on dispersion and surfactants. In contrast, all these conductivity gains typically come with small or negative changes in specific heat capacity. In general, adding solid particles with lower heat capacity than water tends to reduce the mixture's Cp: experimental data show that without special additives, the specific heat of Al_2O_3- or TiO_2-water nanofluids decreases as particle fraction increases.

Improved conductivity often comes at the cost of higher viscosity, which penalizes pumping power. Viscosity generally rises rapidly with particle concentration far more strongly than thermal conductivity leading to increased flow resistance. NP concentration increases, NF viscosity also increases, leading to flow resistance, so that greater viscosity increases power requirements of the pumping system and pressure losses. This trade-off is echoed in recent studies: for instance, a heat-exchanger study with nanofluids found that raising the volume fraction gave diminishing returns, reducing coolant outlet temperature substantially by ~44.6% at optimum but also reducing a composite efficiency index by 5.8-11.7% due to viscosity-related losses [83]. Conversely, carefully optimized nanofluids can still save pumping energy when their heat transfer gain outweighs the viscosity penalty. Razavi et al. [84] reported that a 5 wt% CuO/water nanofluid at 80 °C had 43.3% higher conductivity and achieved a 17.1% reduction in heater power consumption compared to water. Influence of key parameters on nanofluid properties:

Increasing NP concentration generally increases thermal conductivity (often nonlinearly) but also strongly raises viscosity. The balance depends on particle type and size. For example, small increases in loading (≈0.5-1 vol%) often yield significant conductivity gains with modest viscosity rise, while very high loadings (>5 vol%) can dramatically increase viscosity with only marginal conductivity benefit. The cited literature emphasizes that gains in conductivity usually require higher pumping power due to this viscosity penalty.

Most nanofluids show increasing thermal conductivity and decreasing viscosity at higher temperatures. This is because base fluid conductivity usually rises with T, and viscosity falls. We now note that temperature is commonly included in conductivity models [85].

The stability of the nanoparticle suspension is critical. Over time, agglomeration or sedimentation can degrade thermal performance. Recent reviews [86] stress that agglomeration, long-term stability, and compatibility with the fluid are concerns that need to be addressed for reliable operation.

The thermophysical properties of the base liquid strongly influence the effect of adding nanoparticles. Water-based nanofluids start with higher baseline conductivity and heat capacity, so absolute gains in W/m·K are often larger in water than in oils or glycols at the same NP loading. Conversely, adding NPs to a low-conductivity fluid can yield larger relative improvements. Predictive models explicitly use the base-fluid thermal conductivity and viscosity as inputs. While our review cites examples in both water and ethylene glycol media, we now emphasize that comparison of studies must account for the base fluid properties.

For thermal conductivity, the classic Maxwell and Hamilton-Crosser equations and their extensions are widely used as baselines. These models incorporate the conductivities of the base fluid and particles, and sometimes particle shape (Hamilton-Crosser). More recent modifications include effects of particle clustering, interfacial nanolayers, and Brownian motion (Wasp, Kleinstreuer, Xuan models). We also mention emerging machine-learning models, which have been applied to predict conductivity and viscosity from large experimental datasets. For viscosity, the Einstein model for dilute suspensions and its extensions (Brinkman, Mooney, Krieger-Dougherty) remain reference points. These models often under-predict the steep viscosity increases seen experimentally, so empirical correlations or neural-network models are often used instead. Our revised text now cites key examples of both analytical formulas and data-driven models.

5. Effect of Nanoparticles on Tribological Properties of Fluids

Friction and wear are critical factors that contribute to energy loss, component failure, and reduced operational efficiency in mechanical and industrial systems. To mitigate these effects, lubricants are employed to minimize surface contact and facilitate smoother relative motion between components. Conventional lubricants are often formulated with chemical additives designed to enhance anti-wear, anti-oxidation, and load-carrying capabilities [81]. In recent years, nanoparticles have emerged as advanced lubricant additives capable of significantly improving the tribological performance of base fluids. Their small size, large surface area, and unique mechanical properties allow them to interact effectively with surface asperities and modify the lubrication regime. Studies have shown that incorporating nanoparticles into lubricants can reduce the coefficient of friction and wear rate, leading to improved energy efficiency and component longevity [82-90]. The primary cause of friction is the mechanical interlocking and adhesion of rough surface asperities during contact. Nanoparticles alleviate this effect by filling microcavities and surface irregularities, creating a thin protective film that separates the contacting surfaces. This film reduces direct metal-to-metal interaction, thus minimizing adhesive wear and frictional heating. Moreover, some nanoparticles act as rolling elements or nano ball bearings, forming a dynamic layer that facilitates smoother sliding motion and lowers shear resistance [83]. In addition to their mechanical role, nanoparticles can also promote the formation of tribochemical films through surface reactions under high pressure and temperature conditions. These protective layers enhance surface hardness and reduce material transfer, further improving the durability of lubricated interfaces. Among various nanomaterials, TiO_2, Al_2O_3, CuO, graphene, and MoS_2 are among the most widely studied due to their excellent load-bearing capacity, stability, and ability to withstand high operating temperatures.

6. Role of Nanofluids in Automotive Engine Systems

Nanofluids, owing to their unique thermal, chemical, and tribological properties, have become increasingly relevant in modern automotive systems. Their ability to enhance heat transfer, improve lubrication, and optimize fuel combustion makes them promising candidates for next-generation vehicle technologies. In automotive applications, nanofluids are primarily employed as fuel additives, lubricant enhancers, and heat transfer media in cooling and transmission systems. Beyond performance gains, their adoption also supports environmental objectives by improving combustion efficiency and reducing harmful emissions [84]. The addition of nanoparticles to conventional fuels such as diesel or gasoline has been shown to enhance combustion efficiency and engine performance. Nanoparticles function as oxygenated catalysts, promoting more complete fuel oxidation and shortening ignition delay, which collectively improve both power output and emission characteristics. For example, Elkelawy et al. [87] investigated $Mn(EIN)_4(NCS)_2$ nanoparticles (≈15 nm) dispersed in a diesel-biodiesel blend and observed a 20% increase in brake thermal efficiency, along with reductions of 60% and 62% in CO and HC emissions, respectively. In a related study, Elkelawy et al. [88] used AgSCN nanoparticles as a fuel additive and found that a 400 ppm concentration substantially improved combustion performance and emission quality. These findings collectively highlight the catalytic and oxygen-enrichment roles of nanoparticles in promoting cleaner and more efficient combustion processes. To evaluate the economic feasibility of nanofluid applications, researchers have introduced the Price Performance Parameter (PPP), which provides a comparative metric of thermal conductivity enhancement relative to cost. The PPP is defined as:

$$price\ performance\ parameter = \frac{\frac{k_{nf}}{k_{bf}}}{cost\ of\ nanofluid\ per\ liter} \times 1000 \quad (6)$$

where k_{nf} and k_{bf} are the thermal conductivities of the nanofluid and base fluid, respectively [89]. Alirezaie et al. [91] examined Fe-EG and MgO-EG nanofluids with varying particle sizes and reported that MgO-based nanofluids offered superior economic performance due to their lower cost and higher thermal enhancement. Similarly, Esfe et al. [92] investigated single-walled carbon nanotube (SWCNT) and Fe_3O_4 hybrid nanofluids in ethylene glycol and concluded that the hybrid combination achieved a better PPP than either monofluid alone. Mukherjee et al. [93] experimentally evaluated Al_2O_3-water nanofluids and observed a tenfold increase in PPP as nanoparticle concentration increased from 0.01% to 1%, emphasizing that economic optimization must balance concentration, cost, and thermal performance. In addition to fuel systems, nanofluids have shown strong potential as coolants in automotive thermal management. Kulkarni et al. [94] used Al_2O_3 nanoparticles in a 50:50 water-ethylene glycol mixture to enhance the performance of diesel-electric generator cooling systems. Their results indicated a 3% increase in heat exchanger efficiency, although cogeneration efficiency slightly decreased by 0.92% at a 6 vol% concentration. Naraki et al. [95] further demonstrated that CuO-water nanofluids increased the heat transfer coefficient by 8% in a car radiator at low nanoparticle concentrations. Subsequent experimental studies confirmed even greater improvements. Chavan and Pise [96] reported a 40-45% enhancement in radiator heat transfer coefficient using Al_2O_3-water nanofluids at 1 vol%, while Chougule and Sahu [97] observed enhancements of 52.03% and 90.76% for Al_2O_3 water and CNT-water nanofluids, respectively, at the same concentration. Similarly, Hussein et al. [98] examined SiO_2-water and TiO_2-water nanofluids and found substantial improvements in cooling efficiency, demonstrating their suitability for high-performance automotive cooling systems. Overall, nanofluids have proven effective in improving the thermal, combustion, and tribological performance of automotive engines. However, large-scale commercialization depends on addressing challenges related to long-term stability, cost optimization, and potential material compatibility issues. Future research should emphasize multi-objective optimization, integrating thermophysical, economic, and environmental factors to enable the practical deployment of nanofluids in automotive and hybrid powertrain systems.

The studies summarized in Table 4 collectively demonstrate the versatility of nanofluids in enhancing automotive energy systems. Improvements in heat transfer, fuel combustion, and tribological behavior underscore their potential to reduce fuel consumption and emissions while improving thermal management efficiency. However, economic viability—often quantified through the Price Performance Parameter—remains a central consideration for industrial adoption. Achieving a balance between cost, performance, and long-term stability will be key for scaling nanofluid technologies in commercial vehicles and hybrid powertrains.

Table 4. Summary of key studies on nanofluid applications in automotive engine systems.

Nanoparticle / Additive	Base Fluid / Application	Main Findings	Ref.
$Mn(EIN)_4(NCS)_2$	Diesel–biodiesel blend	20% ↑ brake thermal efficiency; 60–62% ↓ CO and HC emissions	[87]
AgSCN	Diesel–biodiesel blend	400 ppm improved combustion, emissions, and performance	[89]
Fe, MgO	Ethylene glycol	MgO–EG nanofluid showed better cost-effectiveness based on PPP	[91]
SWCNT, Fe_3O_4	Ethylene glycol	SWCNT–Fe_3O_4 hybrid nanofluid had superior PPP and stability	[92]
Al_2O_3	Water	PPP increased tenfold as concentration rose from 0.01% → 1%	[93]
Al_2O_3	50:50 Water–EG	3% ↑ heat exchanger efficiency; slight (0.92%) ↓ in cogeneration	[94]
CuO	Water	8% ↑ overall heat transfer coefficient in car radiator	[95]
Al_2O_3	Water	40–45% ↑ radiator heat transfer coefficient at 1 vol%	[96]
Al_2O_3, CNT	Water	52.03% ↑ for Al_2O_3–water; 90.76% ↑ for CNT–water nanofluid	[97]
SiO_2, TiO_2	Water	Enhanced radiator cooling efficiency and heat transfer	[98]

7. Nanofluid as Engine Fuel

The application of nanofluids as fuel additives has gained increasing attention due to their ability to enhance combustion characteristics, improve fuel economy, and reduce emissions. When dispersed in conventional or biodiesel fuels, nanoparticles act as catalysts that promote better atomization, faster oxidation, and more complete combustion. The resulting effects include improved brake thermal efficiency (BTE), reduced brake specific fuel consumption (BSFC), and lower concentrations of carbon monoxide (CO) and unburned hydrocarbons (HC). Devarajan et al. [99] investigated the influence of Ag_2O nanoparticles blended with neem oil biodiesel at concentrations of 5 ppm and 10 ppm in a two-cylinder, four-stroke diesel engine operating at 1500 rpm and 4.5 kW. The addition of Ag_2O nanofluid led

to improvements in brake specific fuel consumption and ignition delay, along with significant reductions in CO, HC, and smoke emissions. However, a rise in NO_x emissions was observed at higher engine loads, which the authors attributed to elevated combustion temperatures. In another study, Kumar et al. [100] examined a ferrofluid blend composed of Pongamia biodiesel (B20), ferrous-based nanoparticles, and citric acid in a single-cylinder, four-stroke diesel engine at 1500 rpm. A 1% ferrofluid addition resulted in an 8% reduction in BSFC and a notable decrease in NO_x emissions, suggesting enhanced combustion efficiency and catalytic oxidation effects. Ghanbari et al. [101] evaluated the effects of hybrid carbon nanotube (CNT) and silver (Ag) nanoparticles at concentrations of 40, 80, and 120 ppm in diesel fuel using a constant-speed engine at 2000 rpm. The study reported a 25.32% increase in NO_x emissions compared to pure diesel, indicating that while nanoparticle addition improves combustion completeness, it can also intensify in-cylinder temperatures, leading to higher nitrogen oxide formation. Similarly, Debbarma and Misra [102] tested Fe_2O_3 nanoparticles as additives in a diesel-biodiesel (80:20) blend using a modified compression ignition engine. The results revealed that nano-additive inclusion enhanced the calorific value, viscosity, and density of the fuel while reducing BSFC by 2.71%. These improvements demonstrate the dual role of iron-based nanoparticles in enhancing both energy content and fuel atomization behavior.

More recently, Pusat et al. [103] explored TiO_2 nanoparticle-enhanced nanofluids for internal combustion engine cooling and performance optimization. At a 3.8 kW engine load, the addition of 0.6% TiO_2 resulted in a 40.8% improvement in the heat transfer coefficient (UxA value). The study also incorporated an artificial neural network (ANN) model, which predicted optimal heat transfer at a 0.26% nanoparticle concentration, demonstrating the potential of intelligent modeling approaches for future nanofluid-based thermal management systems. Therefore, the integration of nanofluids into engine fuels represents a promising approach to improving combustion efficiency and reducing harmful emissions. However, the balance between enhanced combustion and NO_x formation remains a challenge. Future research should focus on optimizing nanoparticle type, concentration, and surface functionalization to achieve cleaner and more efficient combustion with minimal adverse environmental impact. The studies summarized in Table 5 demonstrate the diverse potential of nanofluid-based fuel and cooling systems in improving combustion, energy efficiency, and heat transfer performance. While metallic and metal oxide nanoparticles such as Fe_2O_3, Ag_2O, and TiO_2 enhance catalytic and thermophysical behavior, hybrid nanostructures like CNT-Ag blends offer synergistic effects that further optimize performance. Nonetheless, the variability in NO_x emissions across studies emphasizes the need for precise control of nanoparticle composition and concentration to achieve cleaner, more efficient engine operation.

Table 5. Summary of studies on nanofluid applications as engine fuel.

Nanoparticle Type	Base Fuel/Blend	Concentration	Engine Type/Test Conditions	Main Findings	Ref.
Ag_2O	Neem oil biodiesel	5 ppm, 10 ppm	2-cylinder, 4-stroke (1500 rpm, 4.5 kW)	Improved BSFC, reduced ignition delay, CO, HC, and smoke; NO_x increased at high load	[99]
Ferrofluid (Fe-based NPs + citric acid)	Pongamia biodiesel (B20)	1%	1-cylinder, 4-stroke (1500 rpm)	8% ↓ BSFC, significant ↓ NO_x emissions	[100]
CNT + Ag (hybrid)	Diesel	40, 80, 120 ppm	Diesel engine (2000 rpm)	25.32% ↑ NO_x emissions vs. diesel; improved combustion	[101]
Fe_2O_3	Diesel-biodiesel (80:20)	Not specified	Modified CI engine	↑ Calorific value, viscosity, and density; ↓ BSFC by 2.71%	[102]
TiO_2	Coolant-based nanofluid (engine system)	0.26-0.6%	Engine load 3.8 kW	40.8% ↑ UxA (heat transfer); ANN predicted optimal at 0.26%	[103]

8. Current Status, Challenges and Future Directions

Numerous studies have investigated the potential of nanofluids to enhance the performance of automotive radiator systems. Subhedar et al. [104] examined the thermal performance of Al_2O_3-water: ethylene glycol (EG) nanofluid at different flow rates and nanoparticle concentrations. Their results revealed a significant 78% increase in the Nusselt number at a 0.8% volume fraction and 8.82 L/min flow rate, indicating substantial improvement in convective heat transfer. Similarly, Contreras and Bandarra [105] synthesized a multi-walled carbon nanotube (MWCNT)-water:EG nanofluid that achieved a 4.7% increase in heat transfer and a 4.4% improvement in the overall heat transfer coefficient at a 0.1% volume fraction. Zhou et al. [106] compared the heat transfer performance of γ-Al_2O_3, α-Al_2O_3, and ZnO nanofluids in a propylene glycol (PG) base fluid. They reported that the heat transfer coefficient initially increased and then declined at higher nanoparticle loadings, with the optimum enhancement occurring at 0.2% for γ-Al_2O_3, 0.3% for α-Al_2O_3, and 0.3% for ZnO. Arunkumar et al. [107] investigated Al_2O_3: MgO-water: EG and Al_2O_3:TiO_2-water:EG hybrid nanofluids, observing respective improvements of 7% and 27% in heat transfer coefficient at a 0.4% volume

fraction. Similarly, Bargal et al. [108] found that ZnO-water:EG and AlN–water:EG nanofluids enhanced the heat transfer coefficient and overall heat transfer rate by 8.6% and 13.2% at a 0.5 wt% concentration.

Sahoo et al. [109] evaluated brine-based nano-coolants containing silver (Ag) and Al_2O_3 nanoparticles in propylene glycol and ethylene glycol. Their results indicated that propylene glycol-based nanofluids outperformed ethylene glycol formulations, leading to a 4% reduction in radiator size and a 25.5% decrease in pumping power. Using computational fluid dynamics, Vajjha et al. [110] modeled flat-tube radiators with Al_2O_3 and CuO nanofluids, reporting a 94% increase in average heat transfer coefficient and an 82% reduction in required pumping power at 10 vol% Al_2O_3. CuO nanofluids at 6 vol% also showed an 89% enhancement in heat transfer and a 77% reduction in pumping power. In a later study, Vajjha et al. [111] confirmed similar findings, with 3 vol% Al_2O_3 and CuO nanofluids achieving 36.6% and 49.7% increases in heat transfer, respectively, at a Reynolds number of 5500. Further studies from Hatami et al. [112] compared four different nanoparticles (CuO, TiO_2, Fe_3O_4, and Al_2O_3) dispersed in a water-EG mixture, concluding that CuO and TiO_2 offered the best thermal performance. Their results also highlighted the effect of particle shape, identifying spherical nanoparticles as the most efficient for heat transfer enhancement. Similarly, Sahoo and Sarkar [113] synthesized hybrid nanofluids using Al_2O_3 combined with Ag nanoparticles for use in a louvered fin radiator. The hybrid formulation containing 0.5% Ag and 0.5% Al_2O_3 achieved the highest heat transfer rate, reducing radiator size by 3.7% and coolant flow rate by 3.1% compared to base fluids under equivalent heat transfer conditions. Collectively, these studies demonstrate the remarkable ability of nanofluids to enhance radiator heat transfer efficiency, reduce pumping power, and enable smaller, lighter, and more energy-efficient cooling systems. Their tunable thermophysical properties and adaptability make them highly attractive for next-generation automotive thermal management technologies.

Although the existing literature demonstrates considerable progress, several challenges continue to limit the widespread adoption of nanofluids in automotive systems. Long-term dispersion stability, material compatibility with aluminum and copper alloys, and the potential for corrosion or surfactant degradation under high-temperature cyclic operation remain important concerns. Economic viability also poses a barrier, as the cost of nanoparticle synthesis, stabilization, and lifecycle management is still higher than that of conventional coolants and lubricants. Future research should prioritize developing environmentally benign nanoparticles, improving large-scale synthesis routes, and optimizing hybrid nanofluid formulations that balance thermal enhancement with acceptable viscosity and pumping power. There is also a need for long-duration reliability studies, standardized testing protocols, and more advanced modeling tools to evaluate nanofluid behavior under real driving conditions. Addressing these gaps will be essential for translating laboratory-level benefits into durable and commercially viable automotive technologies. Practical applications of nanofluids in the automotive sector extend beyond radiator cooling and include engine lubrication, brake thermal management, turbocharger intercooling, exhaust gas heat recovery, and thermal control of power electronics and batteries in electric vehicles. Their ability to improve heat transfer, reduce frictional losses, and support compact and lightweight thermal systems makes them attractive for next-generation vehicle architectures. Hybrid nanofluids in particular show strong promise due to their improved stability and tunable thermophysical behavior. Looking ahead, several research priorities remain central to enabling practical deployment. These include ensuring long-term stability under high-temperature and high-shear conditions, reducing production and lifecycle costs, improving compatibility with aluminum and copper alloys, and minimizing potential environmental and health impacts. Advancements in large-scale nanoparticle synthesis, green surfactants, and continuous-flow dispersion systems may help bridge the gap between laboratory studies and commercial use. Further progress is also expected from data-driven modeling, machine learning assisted optimization of formulations, and multi-scale simulations that better capture temperature-dependent effects and real operating conditions. Together, these efforts will be critical for translating demonstrated laboratory benefits into durable, cost-effective automotive solutions.

9. Conclusion

Nanofluids have demonstrated remarkable potential in advancing automotive technologies through enhanced thermal management, improved energy efficiency, and reduced environmental impact. The incorporation of nanoparticles such as Al_2O_3, CuO, TiO_2, and carbon-based materials significantly improves the heat transfer capability of conventional fluids, making them effective in diverse applications including engine cooling, radiators, heat exchangers, and lubrication systems. Beyond thermal enhancement, nanofluids also contribute to reduced friction and wear, leading to lower fuel consumption, extended component lifespan, and decreased maintenance requirements. Moreover, when used as fuel additives, nanofluids improve combustion efficiency and emission characteristics, offering a sustainable pathway for cleaner engine performance. Despite these advantages, several technical and practical challenges continue to limit large-scale industrial adoption. The stability and dispersion of nanoparticles remain major concerns, as agglomeration and sedimentation can diminish long-term performance and increase flow resistance. Additionally, the cost and scalability of nanoparticle synthesis present economic barriers, particularly for hybrid and surface-functionalized nanofluids. Compatibility with existing cooling and lubrication systems, as well as potential issues related to corrosion and environmental toxicity, also require careful evaluation before commercialization. Looking ahead, future research should focus on developing eco-friendly, low-cost, and scalable synthesis methods, including green chemical and continuous-flow production techniques. The use of hybrid nanofluids combining metallic, ceramic, or carbon-based nanoparticles shows strong promise for optimizing both thermal and rheological behavior. In parallel, machine learning

and artificial intelligence tools can aid in predicting performance, optimizing formulations, and tailoring nanofluid properties for specific automotive conditions. In conclusion, nanofluids represent a transformative step toward the next generation of high-performance, energy-efficient, and environmentally responsible automotive systems. Continued interdisciplinary research integrating materials science, fluid mechanics, and computational modeling will be vital to realizing their full potential and ensuring reliable, large-scale implementation in the automotive industry.

Conflict of Interest

The researchers declare no conflict of interest.

Generative AI Statement

The authors declare that no generative artificial intelligence (Gen AI) was used in the creation of this manuscript.

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