



## Review Article

# Nanofluids and their role in enhancing automotive performance: A comprehensive review

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## ABSTRACT

This paper discusses the nanofluid integration in the contemporary automotive industry including its effect on engine cooling and lubrication, and fuel efficiency. As there are increasing demands of energy efficient and environmentally friendly cars, nanofluids have gained much attention due to their superior thermal conductivity, heat transfer efficiency, and tribological properties. To evaluate the performance of nanofluid in the automotive systems, the study used a thorough review methodology where it examined both experimental and computational results of the literature available in the study. The findings showed that the addition of CuO and ZnO nanoparticles in fuel and Al<sub>2</sub>O<sub>3</sub> and ZnO in lubricants increased thermal efficiency by 17.62% and decreased specific fuel consumption by 14.98%. Emissions of carbon monoxide (CO) and nitrogen oxide (NO<sub>x</sub>) went down by 20.04% and 10.25% respectively, and CO<sub>2</sub> emissions rose by 29.16%, which is indicative of a more complete combustion. Moreover, the lubricants made of nanofluids demonstrated a 0.484% enhancement in viscosity stability and hence are able to perform better under different conditions. Although it has these benefits, other issues like nanoparticles agglomeration, high production, and compatibility issues with the existing automotive parts continue to hinder its wide usage. The originality of this work is the comprehensive evaluation of nanofluids in various subsystems of automobiles as compared to earlier studies which have mainly targeted individual subsystems like the heat transfer. This study will offer a systematic approach to the optimization of nanofluids formulations to maximize efficiency, minimize emissions, and make the automotive industry sustainable by assessing the progress, limitations, and future research directions. The future work needs to be directed toward the enhancement of nanofluid stability, economical manufacturing approaches, and the lifecycle analysis to implement it on large scales. These results make nanofluids an innovative technology in the next-generation automotive engineering.

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## INTRODUCTION

The automotive industry across the world is in constant flux due to the need to have better performance, fuel efficiency and sustainability. With the increasing complexity of vehicles, the necessity to find new ways of streamlining thermal regulation, lubrication, and fuel use has increased [1]. A potential direction in this respect is the utilization of nanofluids; specifically engineered suspensions, in which nanoparticles are suspended in conventional fluids such as water, ethylene glycol, and lubricating oils [2]. These nanofluids have high thermal conductivity, heat transfer, and lubrication characteristics relative to their underlying fluids, thus they are very desirable in the automobile industry as shown in Figure 1. As the issue of climate change is increasing, and strict emission standards are enforced, together with the desire to build more energy efficient cars, nanofluids have become a source of interest by the industry experts and researchers alike. Their capability to increase cooling capacity of radiators, engine lubrication and even fuel efficiency provides a promising future in the automotive engineering [3].

Nanofluids are normally made up of nanoparticles of metals and metal oxides, carbon-based substances such as graphene suspended in base fluids. The nanoparticles, because of high surface area and high thermal properties, significantly enhance the heat transfer properties of the fluid [4, 5]. Traditional coolants such as water and ethylene glycol are popular in automotive thermal management systems, but their thermal conductivity is constrained, meaning that they do not cool optimally. Nonetheless, with the

emergence of nanofluids, significant advances in convective heat transfer have been realized which allow more effective cooling systems to be implemented avoiding overheating of engines, loss of energy, and even increase in the life of automotive parts. Research shows that a slight amount of nanoparticles in coolants can result in significant gains in thermal conductivity, which results in a smaller radiator size and weight, which in turn is a factor in vehicle fuel efficiency and performance [6, 7].

Other than thermal management, nanofluids have also exhibited significant potential in enhancing the efficiency of lubrication. Engine oils are also necessary to reduce friction and wear among moving parts to ensure that the engine is long lasting and efficient. However, traditional lubricants possess intrinsic disadvantages regarding the capability to reduce wear and provide the best viscosity at severe operational conditions [8]. Tribological properties of lubricants have been claimed to be improved by incorporation of nanoparticles, e.g. copper, aluminum oxide or carbon nanotubes. Such nano-enhanced lubricants offer excellent anti-wear properties, enhanced load carrying capacity and reduced coefficients of friction in comparison to traditional lubricants. This leads to lesser mechanical wear, high efficiency, and longer service of the engines and thus nanofluid-based lubricants are a promising innovation in automotive industry [9, 10].

The other new field in which nanofluids have shown potential advantages is in the fuel enhancement. The use of nanoparticles in traditional fuel types such as gasoline and diesel to enhance combustion efficiency, fuel economy,



**Figure 1.** Applications of nanofluid in automobiles.

and emission properties has been studied. Some nanoparticles are catalysts that increase the oxidation of the fuel and result in a more complete combustion [11]. This subsequently minimizes the production of harmful ejection like CO, NO<sub>x</sub> and PM hence making transportation cleaner and more sustainable. Moreover, nanofluid based fuel additives have been found to improve the calorific value of fuels, which allow improved engine performance consuming less fuel. Such developments are in tandem with the global quest towards more environmentally friendly technologies and tough environmental laws that are being enforced to minimize car emissions [12].

Nanofluids have some promising benefits, but there are a number of issues that hinder their wide use in the automotive industry. Stability is also still a significant issue, as nanoparticles tend to form aggregates thus interfering with uniformity and

prolonged efficiency of nanofluids [13]. Also, the synthesis and dispersion methods of nanoparticles are expensive and therefore difficult economically to implement at large scale. Safety concerns especially on the environmental and health effects of exposure to nanoparticles should also be well researched before mass commercialization [14]. Nevertheless, there are current research efforts to tackle these issues by coming up with more stable nanofluids, low-cost production techniques and eco-friendly nanoparticle preparations. A simple flow chart to represent the stepwise procedure is shown in Figure 2.

Earlier published review articles related to the application of nanofluids in automotives, along with their objectives, are presented in Table 1 [15-23], and the number of articles published on the utilization of nanofluids in automotives, as per the Scopus database, is illustrated in Figure 3.



Figure 2. Flow chart to represent stepwise procedure.

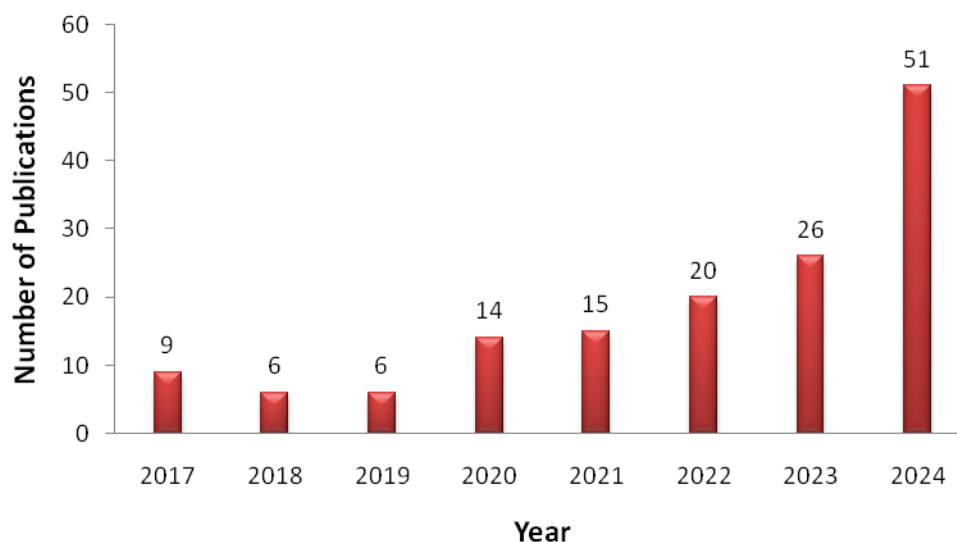


Figure 3. Number of research articles published related to the application of nanofluid in automobiles as per the Scopus database.

**Table 1.** Earlier published review articles related to application of nanofluid in automotives with their objectives

| Ref. No.   | Theme of Review                    | Review Objective                                                                                                                                      |
|------------|------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| [15], 2010 | Future Automobiles                 | In assessing the use of nanofluid in cars, it is important to note that it can be used to enhance efficiency, performance, and sustainability.        |
| [16], 2013 | Coolant in automobile radiator     | To review nanofluid applications in automobile radiators, highlighting benefits, challenges and future prospects.                                     |
| [17], 2015 | Vehicle engine cooling system      | To review nanofluid applications in vehicle engine cooling systems, evaluating performance, experimental finding, and optimization challenges.        |
| [18], 2016 | Application in automobile radiator | To review nanofluid thermal properties using ANN modelling and analyze automotive radiator applications.                                              |
| [19], 2019 | Automobile cooling system          | In order to revise the use of nanofluid in heat transfer, analyzing the vehicle cooling and performance.                                              |
| [20], 2021 | Automotive applications            | To review nanofluid applications in automotive system, analyzing efficiency, material impact and environmental concerns.                              |
| [21], 2022 | Automobile radiator cooling        | To examine thermal properties of hybrid nanofluid, stability and heat transfer in automobiles.                                                        |
| [22], 2023 | Automotive applications            | To assess nanofluid use in automobiles, to outline the advantages, limitations, and prospects of research.                                            |
| [23], 2023 | Coolant in IC engines              | In order to discuss nanofluids as the cooling of IC engines, the analysis of performance, methods of preparation, and the most suitable formulations. |

Current literature proves that nanofluids have increased heat transfer, low friction, and lubrication capabilities. Research indicates that they are better in thermal conductivity, stability compared with traditional fluids, making them one of the potential choices in automotive applications. Nevertheless, issues associated with sedimentation, agglomeration and compatibility with the automotive systems are under-investigated and require additional studies. Although much of the research has been done on nanofluids and their thermal characteristics, their particular contribution in improving automotive performance is not fully exploited. The majority of the research works are dedicated to the application of nanofluid in heat transfer systems, whereas the influence of nanofluid on engine cooling, lubrication, fuel efficiency, and emissions remains poorly studied. Also, the lack of standardized testing procedures and inconsistency in experimental data make it difficult to implement in practice. There is also not much research on the interplay of nanofluid composition, stability, and long-term effects on automotive components. The critical examination that summarizes the current research, research gaps, and the way forward is needed to develop the use of nanofluids in the automotive sector.

In order to fill this gap, there is a need to conduct an extensive review of findings on the use of nanofluids in automotive systems. This involves the evaluation of their thermal conductivity, viscosity, tribological and stability during the operations. It is important to know their long-term impacts on engine and component performance in real world implementation. The performances should be set into benchmarks with rigorous experimental studies, computational simulations, and life-cycle cost analyses.

The purpose of this review is to critically examine how nanofluids are used in improving automotive performance in terms of their thermal, tribological, and fuel efficiency advantages. It critically reviews the recent developments, issues, and prospects of using nanofluids to cool engines, lubricate engines, and augment fuels. The novelty of this review lies in its holistic assessment of nanofluids in multiple automotive subsystems, integrating experimental findings, computational insights, and industrial perspectives. Unlike previous fragmented studies, this review provides a structured framework for optimizing nanofluid formulations, addressing stability issues, and facilitating their practical adoption in commercial automotive applications for improved efficiency and sustainability.

## FUNDAMENTALS OF NANOFLUID

Nanomaterials are substances with structural components at the nanoscale, usually between 1 and 100 nanometers. At the nanoscale, they demonstrate distinct physical properties compared to their bulk counterparts, driven by quantum effects, high surface-area-to-volume ratios, and enhanced reactivity [24]. The nanomaterials can be classified into the various types depicted in Figure 4 such as nanoparticles, nanorods, nanotubes, and nanocomposites with each having a unique property which can be used in a particular application. They are exceptionally strong, thermally conductive, electrically conductive, and catalysts, which are useful in a wide range of industries, including medicine, electronics, energy storage, and automotive engineering. Some typical nanomaterials are carbon based

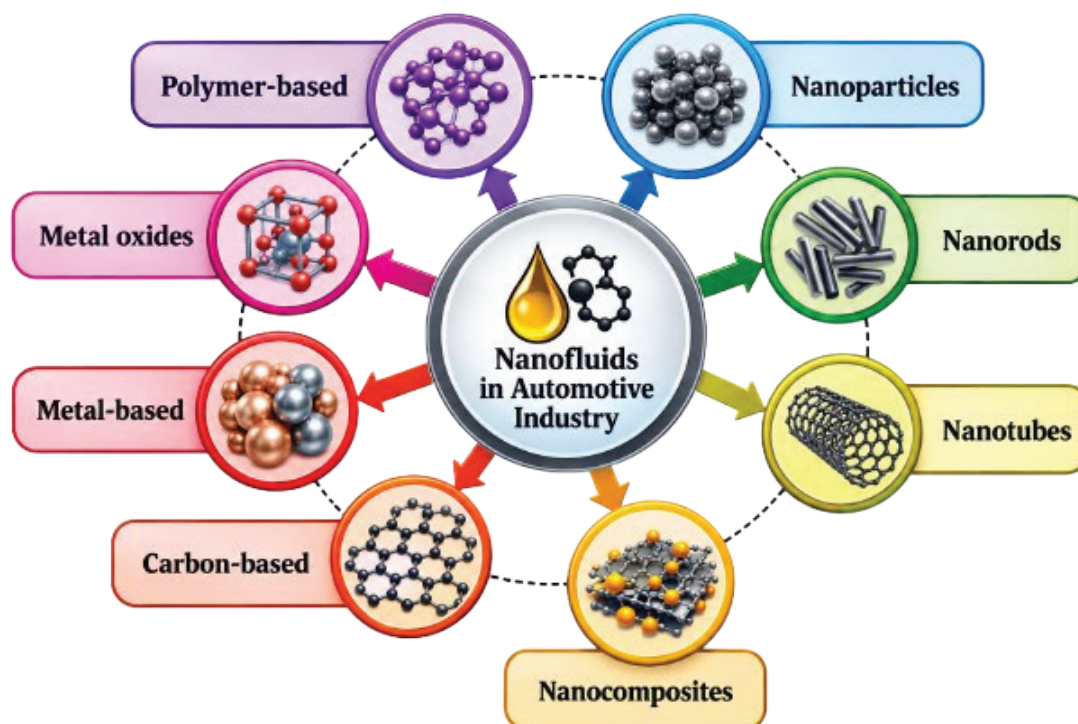


**Figure 4.** Different types of nanomaterials.

(carbon nanotubes, graphene), metal based (gold, silver, copper), metal oxides (titanium dioxide, aluminum oxide), and polymer based nanomaterials [25]. The sophisticated nature of such materials has been made possible through the engineering of such materials at the atomic scale, which leads to the creation of superior functional materials with better properties, which has contributed to innovations in energy-efficient systems, high-performance coating, and the lifetime of materials in different industries [26].

Nanofluid is a stable colloidal suspension of nanoparticles in a base fluid, such as  $H_2O$ , EG or oil. The addition of nanoparticles greatly improves the base fluid's thermal, rheological and tribological properties [27]. The nanofluids have high thermal conductivity, high heat transfer rates, low viscosity, and high stability as compared to the regular fluids. These properties render them very useful in heat dissipation, lubrication and energy transportation purposes [28]. Depending on the type and concentration of nanoparticles used, it is possible to create nanofluids that are optimized and tailored to meet specific properties desired in a given application, such as the cooling mechanisms in systems, lubrication of mechanical systems, and thermal management in high-performance electronic and automotive systems [29].

Nanofluids have become a revolutionary solution in the automobile sector, especially in the cooling of engines, lubrication and increase in fuel efficiency. Nanofluids are used in the cooling systems to enhance the performance of the radiator by improving the efficiency of the radiator to

dissipate heat, eliminate overheating, and reduce thermal management [30]. In lubrication applications, nanoparticle-based lubricants reduce friction and wear, enhancing engine longevity and fuel economy. Moreover, incorporating nanoparticles into fuels improves combustion efficiency, resulting in reduced emissions and enhanced fuel consumption. The integration of nanofluids in automotive components ensures enhanced performance, energy efficiency, and sustainability. However, issues like stability, cost-effectiveness, and integration with existing automotive systems must be resolved for widespread adoption [31].

#### Synthesis and Preparation Method of Nanofluid

Nanofluids synthesis and preparation are mainly done using two methods; the one-step method and the two-step method. The one step approach involves the synthesis and dispersion of nanoparticles in one step, and can be done by physical vapor deposition, laser ablation, or by chemical reduction. This method is less agglomeration and stability but is normally complicated and expensive [32]. The latter is more commonly employed, in which nanoparticles are initially prepared using physical or chemical methods like sol-gel, precipitation or hydrothermal and then dispersed in a base fluid. Dispersion techniques such as ultrasonication, magnetic stirring, and addition of surfactants are used to preserve homogeneity but particle aggregation and sedimentation are still a problem [33, 34]. Figure 5 shows the two-step procedure of the production of nanofluids.



Figure 5. Two-step method for nanofluid production.

The stability of nanofluids is affected by a number of factors as demonstrated in Figure 6, such as pH regulation, choice of surfactants and nanoparticle fictionalization. Stability of nanofluids is important in accuracy of measurements. Nanoparticles using agglomeration and sedimentation might change thermophysical characteristics, which results in changes in thermal conductivity and viscosity

values. In order to reduce these uncertainties, we dispersed the product appropriately through ultrasonication and stabilizing agents. Selection of base fluid, i.e.  $H_2O$ , EG or oils are dependent on purpose of use. Further techniques of stabilization, including electrostatic and steric stabilization, increase dispersion and longevity [35]. To measure thermal conductivity and viscosity, the precision of the measurements was

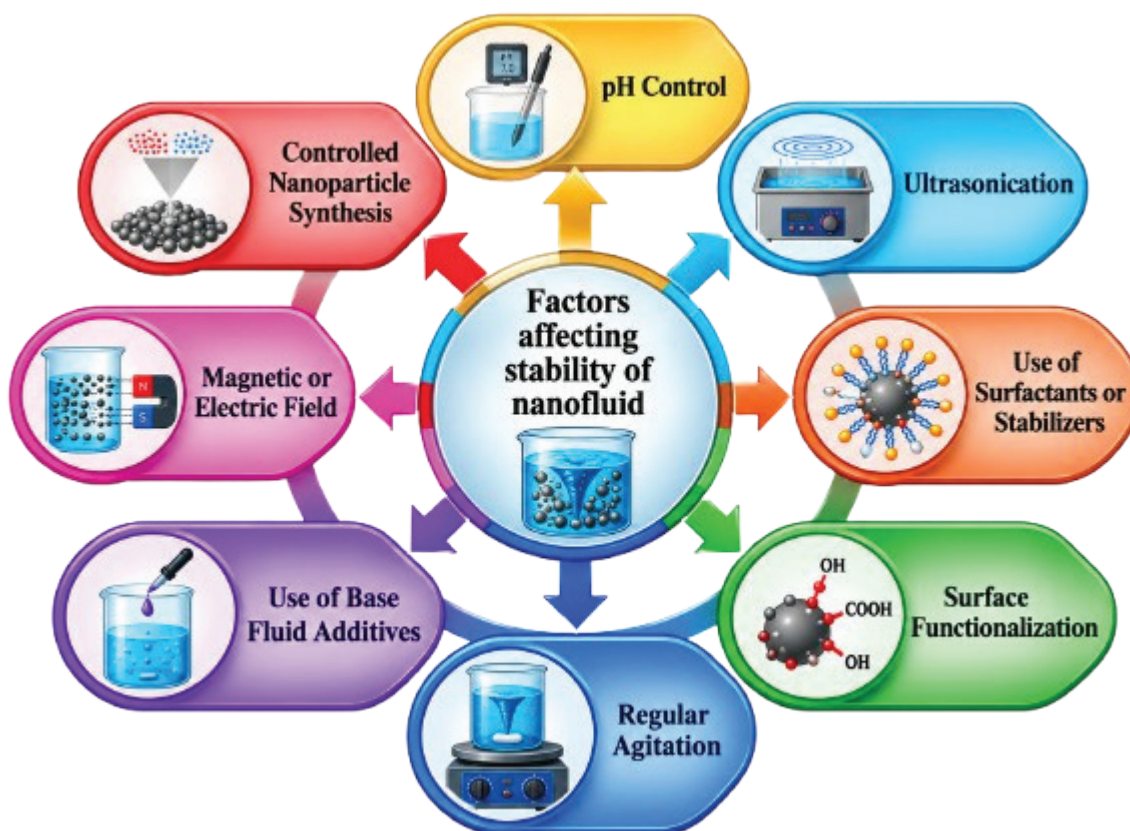


Figure 6. Factors affecting nanofluid stability.

guaranteed by employing high-precision instruments with respectable calibration standards. As an example, the thermal conductivity of the nanofluids was measured by a KD2 Pro thermal properties analyzer within an error of  $\pm 2\%$  whereas the viscosity was measured by a Brookfield viscometer at an error of  $\pm 1.5\%$  [36]. Purity of nanofluid is another important aspect that has a great impact on its thermal, rheological and tribological properties. Nanofluids with high purity are more stable, have improved heat transfer, and less sedimentation or agglomeration of nanoparticles. The purity of nanofluids depends on the quality of nanoparticles and the mother fluid. Nanoparticles may contain impurities, including remaining surfactants, unreacted precursors or unwanted by-products of the synthesis and these impurities can modify the behavior of the fluid and impact its performance in various applications, including automotive cooling, lubrication and fuel enhancement. To achieve high purity, various purification techniques such as centrifugation, filtration, and washing are employed to remove contaminants. Characterization tools like DLS, zeta potential measurement, and TEM are employed to verify the chemical composition and purity of nanofluids and also to improve its stability. The method of synthesis has a strong influence on the thermal conductivity, viscosity and overall functionality of nanofluids which are vital in heat transfer, biomedical and energy systems. The latest developments are on hybrid nanofluids where various nanoparticles are added to enhance functionality. The efficiency of nanofluids in the industrial and technological processes still requires optimization of synthesis methods and stabilization approaches [37].

### Thermal Properties of Nanofluid

The thermal characteristics of nanofluids are necessary for their effectiveness in heat transfer applications. Nanofluids demonstrate superior heat transfer properties relative to conventional fluids, owing to the exceptional conductive nature of nanoparticles and their efficient dispersion [38]. Factors such as nanoparticle concentration, size, shape, and base fluid type significantly influence thermal conductivity. Also, nanofluids exhibit enhanced convective heat transfer, since it has high Brownian movement and nanoparticle contact with the fluid [39]. The other major thermal characteristics are the specific heat capacity,

the viscosity, and thermal diffusivity which determine their performance in the cooling and energy system [40]. These properties should be optimized by appropriate synthesis and stabilization methods to be used in electronics cooling, automotive, aerospace, and renewable energy systems [41]. Table 2 demonstrates the effect of different nanofluid characteristics on an automotive engine performance.

### Thermal Conductivity

The improved heat transfer property of nanofluids is critical in better cooling of heat in automobiles, especially in the cooling system of the engine. Nanofluids are much more conductive to heat than conventional coolants like  $H_2O$  and EG [42]. The high levels of thermal conductivity are caused by the high thermal conductivity of nanoparticles, increased Brownian motion and enhanced micro-convection in the fluid. The thermal conductivity of nanofluids is influenced by different factors such as the type, size and shape of nanoparticles. Metals, such as Cu and Ag, and metal oxides, including  $Al_2O_3$  and  $TiO_2$  are the most common nanoparticles in that they are highly thermal conductive [43].

In cars, the increased efficiency of heat transfer is used to achieve the optimal engine temperatures, prevent overheating, and improve fuel efficiency. Nanofluids are used in radiators and cooling systems, which result in improved heat transfer and this, lowers thermal stresses on engine components and increases engine life [44]. Nonetheless, issues like change in viscosity, stability, and cost are to be tackled to have a workable implementation. Current studies are on hybrid nanofluids and improved methods of stabilization to enhance thermal effectiveness and long-term stability in automotive cooling systems [45]. It is possible to compute the thermal conductivity (TC) of a nanofluid (knf) using a variety of models, one of the most popular being the Maxwell-Garnett equation of the spherical nanoparticles, which is symbolized as Eq. 1 [46].

$$k_{nf} = k_f \frac{k_p + 2k_f + 2\phi(k_p - k_f)}{k_p + 2k_f - \phi(k_p - k_f)} \quad (1)$$

Other sophisticated models including the Hamilton-Crosser model, and experimental correlations take into

**Table 2.** Impact of various nanofluid properties on the performance of an automotive engine

| Nanofluid Properties      | Effect on Engine Performance                                    | Remarks                                        |
|---------------------------|-----------------------------------------------------------------|------------------------------------------------|
| Thermal Conductivity      | Increased thermal conductivity improves the heat dissipation.   | Engine cooling efficiency enhanced             |
| Viscosity                 | A rise in viscosity can influence the resistance of fluid flow. | Needs optimization for better lubrication      |
| Specific Heat Capacity    | Higher specific heat capacity improves heat absorption          | Enhances engine temperature regulation         |
| Density                   | Affects coolant flow and heat transfer performance              | Higher density fluids may impact pumping power |
| Stability                 | Stability in the long-term averts the problem of sedimentation. | Ensures consistent thermal performance         |
| Heat Transfer Coefficient | An increase in coefficient increases convective heat transfer.  | Improves the work of cooling systems.          |

account the impact of nanoparticle shape, brownian motion and clustering on thermal conductivity. These factors need to be optimised to maximise the heat transfer efficiency in automotive applications, where efficient engine cooling and minimised thermal stresses on components are required. The homotopic method demands a trade-off between raising the nanoparticle concentration to raise thermal conductivity and not taking it too high to cause an agglomeration or higher viscosity which may decrease flow efficiency.

### Viscosity

The viscosity of nanofluids is a critical parameter in their use in the automotive industry, especially in the cooling and lubrication systems. The viscosity defines the ease of flow of fluid, pumpability, and energy consumption in the cooling system of an engine. Nanofluids tend to have a slightly higher viscosity compared to the traditional coolant, because of the presence of nanoparticles, which may influence fluid flow and raise the power needs of the pumping system [47]. Nanofluids viscosity depends on many factors, including the concentration, size, shape, temperature, and the base fluid properties of nanoparticles. Greater nanoparticle concentrations typically cause increased viscosity, which can improve thermal conductivity but may also cause higher frictional losses and lower flow efficiency [48].

In the case of automotive use, it is important to strike the right balance between thermal conductivity and viscosity. Better thermal conductivity will enhance heat dissipation in radiators and engine parts, but excessive viscosity will cause a higher resistance in the cooling system and decrease efficiency. It has been found that the effects of viscosity are lower with the spherical nanoparticles than with the elongated or irregular-shaped nanoparticles [49]. Moreover, temperature is important since the viscosity of nanofluids tends to reduce with increase in temperature which is an advantage in high temperature car settings [50].

To guarantee the effective application of nanofluids in automotive cooling and lubrication, the stabilizing measures, including the addition of a surfactant, pH regulation and advanced dispersion strategies, are used. The methods assist in avoiding the agglomeration of nanoparticles that may further raise the viscosity and poor performance [51]. There is interest in hybrid nanofluids, a mixture of various nanoparticles, to maximize thermal and rheological characteristics to enhance engine efficiency. Comprehensively, the control of nanofluids viscosity is critical to the optimization of its nanofluids in automotive applications and thus improved heat transfer, less wear, and fuel economy whilst preserving its efficient flow properties in the engine cooling systems [52]. The homotopic method entails optimizing the concentration of nanoparticles and stabilization methods to obtain a viscosity that would enable the pumping with both efficiency in heat transfer and low energy expenditure pumping. In certain nanofluids (e.g.,  $\text{Al}_2\text{O}_3\text{-MWCNT/5W50}$ ), non-Newtonian behavior needs to be represented correctly to be able to predict its behavior at different shear rates.

### Specific Heat

Specific heat capacity of the nanofluids is a very important characteristic which determines their suitability in automotive cooling systems [53]. In the automobile industry, nanofluids with a high specific heat capacity can be used to optimize the quantities of heat absorption and dissipation, which then improves the cooling effects of the engine, and averts overheating. Specific heat of nanofluid depends on the nature, concentration and thermal characteristics of nanoparticles. In most cases, the specific heat of the nanofluid decreases slightly upon the addition of nanoparticles with high thermal conductivity when compared to the base fluid. Nevertheless, a perfect thermal conductivity to specific heat balance is critical to effective heat transfer [54]. Specific heat capacity of a nanofluid may be determined using the following formula:

$$C_{p,nf} = \frac{(1-\phi)\rho_f C_{p,f} + \phi\rho_p C_{p,p}}{\rho_{nf}} \quad (2)$$

In automotive use, a balanced specific heat capacity is important to give effective heat exchange in engine cooling, radiators, and lubricants to minimize thermal stress and improve fuel efficiency [55]. The attention of researchers is on hybrid nanofluids to enhance specific heat and thermal conductivity to enhance cooling performance without compromising stability and flow characteristics. The homotopic criteria entails the choice of nanoparticles that have high thermal conductivity but moderate density effects so that heat transfer is efficient without having to pump very high powers.

### Density

Nanofluids density is a vital factor that determines their effectiveness in the automotive industry especially in cooling and lubrication systems. Density influences the rate of mass flow of the fluid, the power needed to pump the fluid, and the overall heat transfer effectiveness [56]. When nanoparticles are introduced, the nanofluid usually becomes denser than the base fluid since nanoparticles are usually denser than the liquid coolant such as water or ethylene glycol. To achieve the optimal balance between density and viscosity is important to guarantee the efficient flow of the fluid without unnecessary energy consumption [57, 58]. The density of a nanofluid could be determined using the equation below:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_p \quad (3)$$

## NANOFLUID IN AUTOMOTIVE APPLICATIONS

Nanofluids are common in the car industry in engine cooling system, transmission fluids, lubricants and fuel additives. Their high heat dissipation qualities allow them to perform a better thermal control in radiators, preventing overheating and enhancing engine efficiency [59].

Nanoparticles in lubricants improve tribological characteristics, which lower wear and friction between moving components, thus improving engine durability and fuel efficiency. Furthermore, nanofluids as fuel additives enhance combustion efficiency, which lowers emissions and increases mileage. Nanoparticles aluminum oxide, copper oxide, and carbon nanotubes have been widely studied to maximize viscosity, stability and thermal performance [60]. Sustainability is also assisted by the adoption of nanofluids, which reduce the energy loss and emissions. As the automotive industry takes the challenge of fuel efficiency and strict emission regulations, nanofluids are also being considered as a way of transforming automotive cooling, lubrication, and fuel systems [61]. Despite the challenges of stability of nanoparticles and the cost involved, the current research effort is leading to progress in nanofluid development of nano-particles to be used in practical car

applications, which is a promising future of more efficient cars with better environmental impact. This part will offer a brief background of some of the recent developments in the application of nanofluids in the automotive sector.

### Role of Nanofluids in Automotive Radiator Cooling System

Nanofluids are important to the operation of the automotive radiator cooling system because it is used to enhance the efficiency of the cooling system through the conductivity of heat and thermal properties. The conventional coolant fluids including water and ethylene glycol are not effective in the management of the high thermal loads produced by the modern engines. Nanofluids have a high thermal conductivity, greater heat transfer, and are more stable by dispersing nanoparticles, such as aluminum oxide, copper oxide, or graphene in these base fluids. This results in increased efficiency of cooling and eliminates engine

**Table 3.** Role of nanofluids in automotive radiator cooling system

| Ref. No.   | Nanoparticle                                                                           | Base fluid           | Volume Fraction | Parameter Enhancement                                                                                     |
|------------|----------------------------------------------------------------------------------------|----------------------|-----------------|-----------------------------------------------------------------------------------------------------------|
| [62], 2011 | Al <sub>2</sub> O <sub>3</sub>                                                         | H <sub>2</sub> O     | 0.1% to 1%      | Increase heat transfer efficiency by up to 45%.                                                           |
| [63], 2014 | Al <sub>2</sub> O <sub>3</sub>                                                         | H <sub>2</sub> O     | 0.1% to 2%      | Heat transfer improved up to 14.79% at 1% concentration but deteriorated beyond that.                     |
| [64], 2014 | Al <sub>2</sub> O <sub>3</sub> , CNT                                                   | H <sub>2</sub> O     | 0.15% to 1%     | CNT/H <sub>2</sub> O nanofluid at 1% concentration increased heat transfer by 90.76%                      |
| [65], 2016 | TiO <sub>2</sub>                                                                       | EG- H <sub>2</sub> O | 0.1% to 0.5%    | A 0.5% concentration enhanced heat transfer by 35% relative to the base fluid.                            |
| [66], 2018 | Graphene-TiO <sub>2</sub>                                                              | EG- H <sub>2</sub> O | 0.01% to 1%     | 0.4% concentration increased heat transfer but caused 0.9825 g of material loss                           |
| [67], 2019 | Al <sub>2</sub> O <sub>3</sub> -TiO <sub>2</sub> , Al <sub>2</sub> O <sub>3</sub> -MgO | EG- H <sub>2</sub> O | 0.12% to 0.4%   | The 0.4% Mg-Al <sub>2</sub> O <sub>4</sub> nanofluid improved heat transfer efficiency by 33.18%          |
| [68], 2019 | Al <sub>2</sub> O <sub>3</sub> -TiO                                                    | EG- H <sub>2</sub> O | 0.05% to 0.3%   | A 0.3% Al <sub>2</sub> O <sub>3</sub> nanofluid improved thermal performance by 24.21%.                   |
| [69], 2019 | Co <sub>3</sub> O <sub>4</sub> and Al <sub>2</sub> O <sub>3</sub>                      | EG- H <sub>2</sub> O | 0.02% to 0.2%   | Co <sub>3</sub> O <sub>4</sub> nanofluid at 0.1% concentration improved heat transfer by 18.3%            |
| [70], 2020 | GO and GNR                                                                             | Pure water           | 0.01% to 0.02%  | At 0.02% concentration, GO improved overall heat transfer by 33.9%,                                       |
| [71], 2020 | ZnO                                                                                    | H <sub>2</sub> O     | 0% to 0.3%      | The 0.2% concentration enhanced overall heat transfer coefficient by 50%.                                 |
| [72], 2021 | Al <sub>2</sub> O <sub>3</sub> , SiO <sub>2</sub> , and TiO <sub>2</sub>               | H <sub>2</sub> O     | 0.2% and 0.4%   | TiO <sub>2</sub> at 0.4% achieved the highest exergy efficiency (35.67%), improving by 62.14% over water. |
| [73], 2021 | ZnO and AlN                                                                            | EG- H <sub>2</sub> O | 0.2% and 0.5%   | ZnO nanofluids at 0.5 wt% increased heat transfer by 57.7%.                                               |
| [74], 2022 | Al <sub>2</sub> O <sub>3</sub> -TiO <sub>2</sub> -SiO <sub>2</sub>                     | EG- H <sub>2</sub> O | 0.05% to 0.3%   | The 0.3% concentration improved the coolant-side heat transfer coefficient by 39.7%                       |
| [75], 2022 | MWCNT                                                                                  | EG- H <sub>2</sub> O | 0.025% to 0.1%  | At 0.1% concentration, the overall heat transfer coefficient improved by 4.4%.                            |
| [76], 2023 | GnP-MWCNT                                                                              | Coolant oil          | 0.05% to 0.5%   | At 0.5% concentration, the OHTC increased by 124%.                                                        |
| [77], 2023 | CuO, ZnO, and MgO                                                                      | H <sub>2</sub> O     | 0.5% to 3%      | CuO- H <sub>2</sub> O exhibited the highest thermal conductivity (1.084 W/mK).                            |
| [78], 2024 | MWCNT- Al <sub>2</sub> O <sub>3</sub> -                                                | H <sub>2</sub> O     | 0.5% to 2.3%    | Radiator effectiveness increased by 22.54% at a concentration of 2.3%.                                    |

overheating and enhances the overall efficiency of the vehicle. Nanofluids have a higher heat transfer rate through convection thus making radiators smaller and lighter, which helps in reducing vehicle weight and increasing the fuel economy. Also, the presence of nanofluids leads to less energy loss in the cooling system, which leads to improved engine performance and durability. They are also of interest in the application of electric vehicle batteries since efficient thermal management is essential to battery safety and efficiency. Nevertheless, nanoparticle stability and cost are some of the issues facing the use of nanoparticles, but ongoing research and development of nanofluid technology is leading to its use in the next generation automotive radiator systems. Table 3 summarises the role of nanofluids in improving cooling efficiency of automotive radiators.

Peyghambarzadeh et al. [62] experimentally compared forced convective heat transfer of  $\text{Al}_2\text{O}_3$ /water nanofluid with pure water in an automobile radiator. Nanofluid concentrations (0.1–1 vol. %) increased heat transfer efficiency by up to 45%. Higher flow rates improved cooling, while inlet temperature had minimal effects. Brownian motion contributed to enhanced heat transfer beyond conductivity improvements. Ali et al. [63] experimentally analyzed the effect of  $\text{Al}_2\text{O}_3$ /water nanofluid concentrations (0.1–2%) on a Toyota Yaris 2007 radiator. Figure 7 demonstrate the variation of coolant pumping power with load and concentration, showing an increase as concentration rises due to higher pressure loss at a fixed load, and a further increase as the load itself increases. Heat transfer improved up to 14.79% at 1% concentration but deteriorated beyond that. The coolant and air heat transfer coefficients increased by

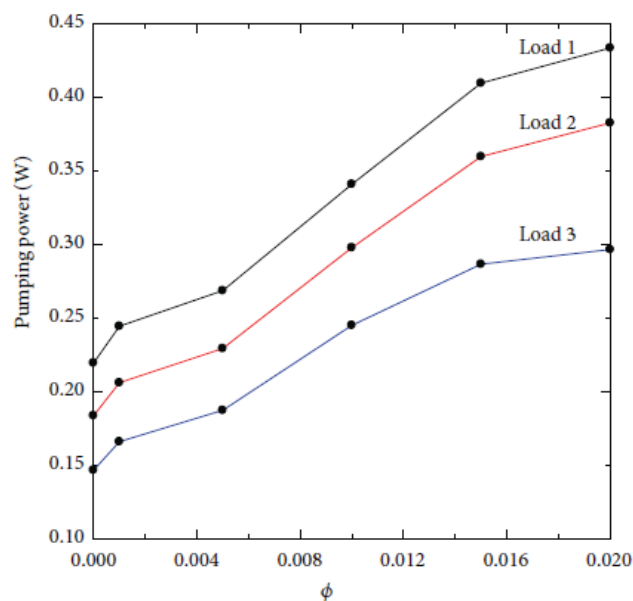


**Figure 7.** Variation of coolant pumping power with load and concentration [From Ali et al. [63], with permission from Hindawi].

14.72% and 14.45%, respectively. The optimum concentration was established by Reynolds and Nusselt numbers, and an increase in viscosity caused a decrease in performance at 1.52% viscosity.

Chougule and Shahu [64] experimentally compared  $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$  and  $\text{CNT}/\text{H}_2\text{O}$  nanofluids in an automobile radiator. The nanofluid  $\text{CNT}/\text{H}_2\text{O}$  (1% concentration) enhanced the heat transfer by 90.76% and  $\text{Al}_2\text{O}_3$ -water by 52.03%. Flow rates also enhanced Nusselt numbers to 76.55% and 44.18% improvement at 4 L/min in  $\text{CNT}$  and  $\text{Al}_2\text{O}_3$ , respectively. The thermal conductivity and performance of  $\text{CNT}/\text{H}_2\text{O}$  was better as it had a higher aspect ratio and a low thermal resistance. Sandhya et al. [65] experimentally evaluated  $\text{TiO}_2$  nanofluids (0.1–0.5%) in a 40:60 EG-  $\text{H}_2\text{O}$  mixture for automobile radiators. The schematic diagram of the test setup is shown in Figure 8. A 0.5% concentration increased heat transfer by 35% over the base fluid. At 45°C, a 45.4% enhancement in heat transfer coefficient was recorded. Flow rates increased performance, and little influence was on inlet temperature. Brownian motion also helped in enhancing heat transfer in addition to change in thermal conductivity.

Xian and Sidik [66] investigated the heat transfer and erosion-corrosion effects of a hybrid nanofluid (graphene nanoplatelets- $\text{TiO}_2$ ) in an automobile radiator. The 0.4% concentration increased heat transfer but caused 0.9825 g of material loss due to erosion. Corrosion effects were similar across all coolants. The ASTM D2809-09 standards categorized erosion-corrosion damage as low and it was possible that it could be applied in the future. Increased nanoparticle concentration intensified material loss. Arun kumar et al. [67] experimentally evaluated  $\text{Al}_2\text{O}_3$ - $\text{TiO}_2$  and  $\text{Al}_2\text{O}_3$ - $\text{MgO}$  nanofluids (0.12% and 0.4%) in a water-ethylene glycol mixture for car radiators. Compared to water, the 0.4%  $\text{Mg-Al}_2\text{O}_4$  nanofluid enhanced the heat transfer efficiency by 33.18%, and the 0.4%  $\text{Al}_2\text{TiO}_5$  nanofluid enhanced it by 27.9%. The higher concentration of nanoparticles and fluid velocity enhanced the heat transfer whereas ethylene glycol was used as an antifreeze solution, increasing the stability of the system. In their study, Said et al. [68] determined the performance of  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  nanofluids in a 50:50 mixture of distilled water and ethylene glycol as an automobile radiator. Figure 9 illustrates the change in thermal conductivity with temperature at various concentrations. A 0.3%  $\text{Al}_2\text{O}_3$  nanofluid improved thermal performance by 24.21%, while  $\text{TiO}_2$  at the same concentration increased it by 14.99%. The performance evaluation criterion (PEC) ranged from 1.03 to 1.31.  $\text{Al}_2\text{O}_3$  exhibited higher thermal conductivity, but  $\text{TiO}_2$  had better long-term stability. Elsaied [69] experimentally studied  $\text{Co}_3\text{O}_4$  and  $\text{Al}_2\text{O}_3$  nanofluids in EG- $\text{H}_2\text{O}$  mixture (0–20% EG) to use in vehicle radiators.  $\text{Co}_3\text{O}_4$  nanofluid (0.1% concentration) enhanced heat transfer by 18.3% and  $\text{Al}_2\text{O}_3$  by 16.7% increase. Higher Reynolds numbers enhanced heat transfer but reduced friction. EG reduced Nusselt number and increased pumping power.  $\text{Co}_3\text{O}_4$  outperformed  $\text{Al}_2\text{O}_3$  in thermal performance.

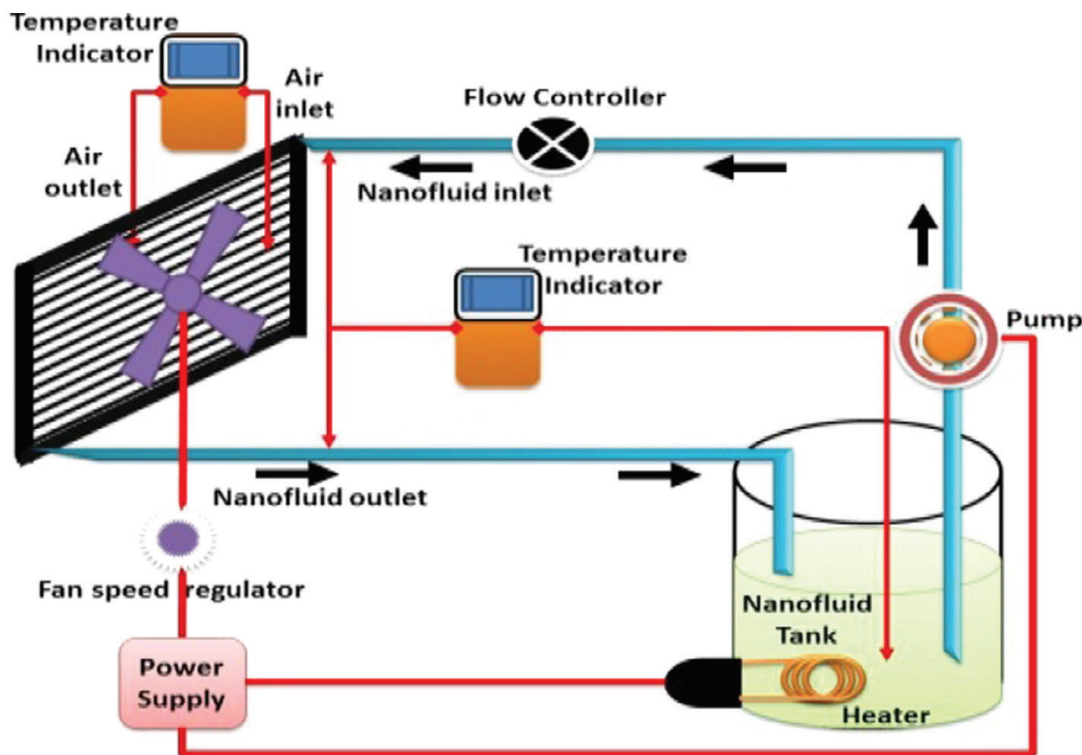


Figure 8. Schematic diagram of the test setup [From Sandhya et al. [65], with permission from Elsevier].

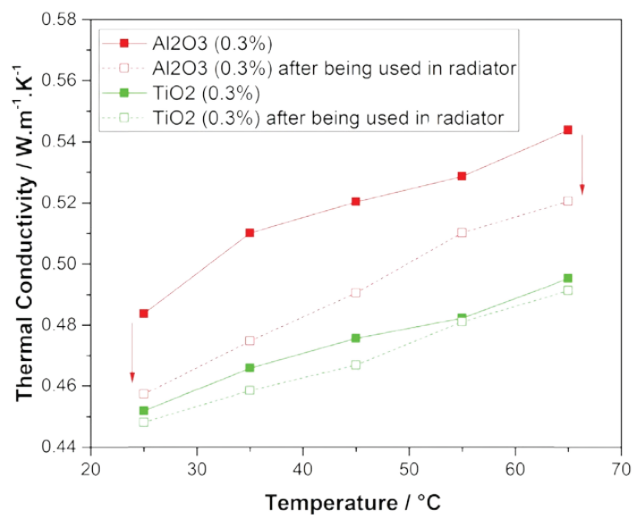


Figure 9. Change in thermal conductivity with temperature at various concentrations [From Said et al. [68], with permission from Elsevier].

Kılınç et al. [70] experimentally evaluated the cooling performance of GO and GNR nanofluids in a vehicle radiator. GO and GNR increased the overall heat transfer by 33.9% and 31.6%, respectively, at a concentration of 0.02%. The average enhancements for GO and GNR were 26.08% and 20.64%, respectively. Higher nanoparticle

concentrations improved cooling efficiency, with minimal sedimentation and pressure drop issues compared to metal oxide nanofluids. Qasim et al. [71] experimentally analyzed ZnO/H<sub>2</sub>O nanofluids (0–0.3%) in a Suzuki Mehran radiator under laminar flow (Re 186–1127). The 0.2% concentration enhanced heat transfer by 41%, overall heat transfer coefficient by 50% and Nusselt number by 31%. There was an increase in pressure drop and friction factor by 47% and 46%, respectively. Increased concentrations (0.3%) decreased performance because of the high viscosity and density which limited the efficiency increase. Erkan et al. [72] evaluated the exergy performance of Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub> and TiO<sub>2</sub> nanofluids (0.2% and 0.4%) in a diesel engine radiator. Figure 10 presents the dependence of exergetic efficiency on various nanocoolants. TiO<sub>2</sub> at 0.4% had the greatest exergy efficiency (35.67%), which was 62.14% higher than water. Al<sub>2</sub>O<sub>3</sub> decreased exhaust temperature by 59 K, whereby TiO<sub>2</sub> had the minimum exergy destruction (18.516 kW). Nanofluids were found to be more efficient and less emitting than the traditional coolants. Bargal et al. [73] experimentally tested the use of ZnO and AlN nanofluids in 50:50 H<sub>2</sub>O-EG mixtures as PEMFC cooling. ZnO nanofluids of 0.2 wt% and 0.5 wt% enhanced the heat transfer by 24.3% and 57.7% respectively, whereas AlN did it by 15.3% and 30.7%. An increase in nanoparticle concentration enhanced the radiator performance and general heat transfer. ZnO nanofluids were recommended for superior thermal performance in automotive PEMFC engines.

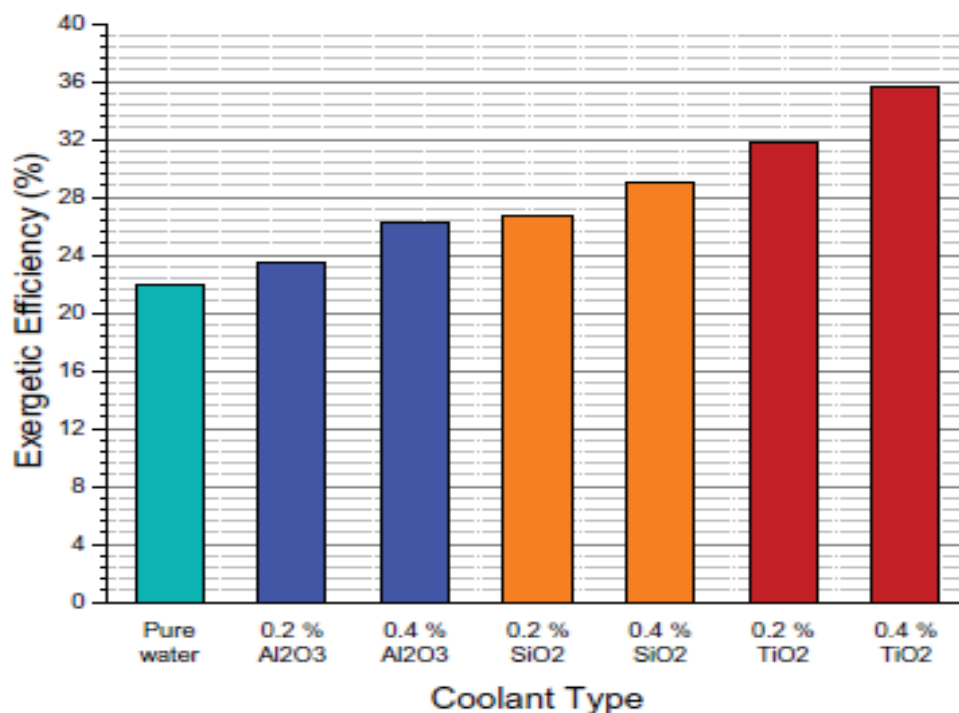


**Figure 10.** Variation of exergetic efficiency with different nanocoolant [From Erkan et al. [72], with permission from Springer Nature].

Ramadhan et al. [74] experimentally analyzed Al<sub>2</sub>O<sub>3</sub>-TiO<sub>2</sub>-SiO<sub>2</sub> tri-hybrid nanofluids (0.05–0.3%) in a water/ethylene glycol (60:40) mixture for automotive radiators. The 0.3% concentration enhanced the coolant-side heat transfer coefficient by 39.7%, while the air-side enhancement reached 23.8% at 0.05%. Higher Reynolds numbers increased overall heat transfer by 18.3%. Pressure drop and pumping power rose with concentration, indicating increased viscosity effects. Contreras and Filho [75] experimentally evaluated the heat transfer performance of MWCNT nanofluids in a 50:50 H<sub>2</sub>O-EG mixture for automotive radiators. The heat transfer rate was enhanced by 4.6% and total heat transfer coefficient was enhanced by 4.4% at a concentration of 0.1%. Increased temperature (105°C) decreased performance because of aggregation of nanoparticles. The stability analysis indicated that stability was 90% after three days, and this influenced the long-term stability. Kumar et al. [76] experimentally investigated a carbon-based hybrid nanofluid (GnP-MWCNT/coolant oil) in an automobile radiator. At 0.5% concentration, thermal conductivity improved by 59%, and the OHTC increased by 124%. The CHTC showed a 73.44% rise at 70°C. However, pressure drop increased by 23.72%. The nanofluid was stable over 21 days, indicating that it can be used as a substitute coolant. Khan [77] researched the CuO, ZnO and MgO nanofluids (0.5–3%) in a car radiator using H<sub>2</sub>O as base fluid. CuO- H<sub>2</sub>O had the best thermal conductivity (1.084 W/mK) which increased the transfer of heat by 48.76% at

3% concentration. ZnO-water and MgO-water enhanced the heat transfer by 46.49% and 43.66% respectively. CuO-water enhanced Reynolds number by 8.11% whereas friction factor reduced by 2.29%. Pumping power increased with concentration but remained feasible for automotive applications. Hassaan et al. [78] experimentally analyzed MWCNT–Al<sub>2</sub>O<sub>3</sub>/water hybrid nanofluid in a 2005 Honda Civic radiator. The heat transfer rate was enhanced by 33%, and Nusselt number by 23.7% at 2.3% concentration, with a 22.54% increase in the radiator efficiency. The pressure drop and friction factor were raised by 24 and 24.3 percent respectively. The hybrid nanofluid was found to be superior in terms of thermal performance, hence making it a feasible substitute to the distilled water in cooling automobiles.

Rana et al. [79] investigated the thermal enhancement in car coolant by utilizing hybrid nanoparticles (TiC-Al<sub>2</sub>O<sub>3</sub>) in ethylene glycol. It used the finite element method in the performance of the Carreau-Yasuda hybrid nanofluid in a boundary layer flow. The hybrid nanofluid had a high thermal efficiency as compared to a normal nanofluid. The important results were improved velocity profiles as we increased, high wall shear stresses (e.g., 0.5967 at We = 0.2 with hybrid and 0.4732 with regular nanofluid), and increased rate of heat transfer (e.g., Nusselt number 8.1499 vs. 5.1004) as the strength of the magnetic field was increased. Destructive chemical reactions boosted mass transfer rates, unlike generative reactions, highlighting potential energy efficiency improvements in automotive systems.

### Integration of Nanofluids in Automotive Fuel System

Introduction of nanofluids into car fuel systems is a promising technique of enhancing the efficiency and performance of engines. Dissolved nanoparticles  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ , and CNTs in traditional fuels improve thermal conductivity, combustion efficiency, and lubrication properties. These improvements result in improved atomization of fuels, engine deposits, and decreased emissions [80]. Also, nanofluids help in cooling down heat in fuel injection and cooling systems, thus avoiding overheating. It has been demonstrated that nanofluid-based fuels are capable of enhancing BTE by as much as 8 percent and decreasing SFC. The innovation opens the path to more efficient and eco-friendly automotive technologies [81]. The integration of nanofluid in automotive fuel system is summarized in Table 4.

Mehta et al. [82] examined nanofuels which were prepared by dispersing A1, F1, and B1 nanoparticles in diesel. These fuels exhibited a 7% reduction in SFC, with increased BTE (A1: 9%, F1: 4%, B1: 2%) and exhaust gas temperature (A1: 9%, F1: 7%, B1: 5%). CO emissions dropped by 25–40%, and hydrocarbons decreased by 8% (A1) and 4% (F1), while NOx emissions slightly increased. Sarvestany et al. [83] analyzed the effect of  $\text{Fe}_3\text{O}_4$  magnetic nanofluid on the engine performance and emissions of the diesel engine. The variation of BSFC with load is shown in Figure 11. A

0.4% nanoparticle concentration improved combustion, while 0.8% increased BSFC by 34%. NOx and  $\text{SO}_2$  emissions decreased by 56–67% and 14–20%, respectively, but CO emissions and smoke opacity rose by up to 125%. The research identified the prospects of using magnetic nanoparticles in the modification of fuels to be efficient and to control emissions.

Venkatesan and Kadiresh [84] conducted a study to examine the impact of an aqueous  $\text{CeO}_2$  nanofluid fuel additive on the efficiency and emissions of a diesel engine. Test fuels included diesel and biodiesel blends with 50cc/L of  $\text{CeO}_2$ . Results showed a 5.81% rise in BTE, a 6.25% decline in fuel consumption, a 31.48% decrease in hydrocarbon emissions, a 17% reduction in NOx, and a 10.5% lower smoke opacity compared to diesel. Sarvestani et al. [85] modeled specific fuel consumption and emissions of a diesel engine using  $\text{Fe}_3\text{O}_4$  nanoparticle-blended fuels at 0.4% and 0.8% concentrations. The outcome indicated that the consumption of fuel increased by 30% at 0.8% concentration. The emissions of NOx and  $\text{SO}_2$  were reduced by 67% and 20%, respectively, whereas CO emissions and smoke opacity grew by 50% and 231%, respectively. Regression models forecasted the outcome with 94%–98% accuracy. Ramanan and Yuvarajan [86] compared the emission of a diesel engine with RBOME mixed with 1% magnetite nanofluid. The findings indicated a decrease of 0.011% CO, 19 ppm HC, 93 ppm

**Table 4.** Summary of integration of nanofluid in automotive fuel system

| Ref. No.   | Nanoparticle                                       | Base fluid           | Engine        | Environmental Concern                                                                          |
|------------|----------------------------------------------------|----------------------|---------------|------------------------------------------------------------------------------------------------|
| [82], 2014 | Aluminum, iron, and boron                          | Diesel               | CI Engine     | CO emissions dropped by 25–40%.                                                                |
| [83], 2014 | $\text{Fe}_3\text{O}_4$ -magnetic                  | Diesel               | Diesel engine | NOx and $\text{SO}_2$ emissions decreased by 56–67% and 14–20%, respectively.                  |
| [84], 2014 | Cerium oxide                                       | Diesel and biodiesel | CI Engine     | 17% reduction in NOx and a 10.5% lower smoke opacity compared to diesel.                       |
| [85], 2016 | $\text{Fe}_3\text{O}_4$                            | Diesel               | CI Engine     | NOx and $\text{SO}_2$ emissions decreased by 67% and 20%, respectively.                        |
| [86], 2016 | Ferromagnetic                                      | RBOME                | CI Engine     | Reductions of 0.011% CO, 19 ppm HC, 93 ppm NOx, and 9% smoke opacity compared to RBOME         |
| [87], 2017 | $\text{Al}_2\text{O}_3$                            | $\text{H}_2\text{O}$ | Diesel engine | $\text{CO}_2$ emissions increased by 26%, and engine noise rose by 2.19% at 10% concentration. |
| [88], 2018 | $\text{TiO}_2$                                     | MOME                 | Diesel engine | $\text{TiO}_2$ reduced carbon monoxide by 13% and hydrocarbons by 4.2%.                        |
| [89], 2019 | $\text{TiO}_2$                                     | Diesel and biodiesel | Diesel engine | Reductions in ignition delay by 7%, hydrocarbon by 38%, and smoke emissions by 20%.            |
| [90], 2019 | $\text{Al}_2\text{O}_3$                            | Diesel               | CI Engine     | The D+50AN blend showed reductions in NOx by 15.6%.                                            |
| [91], 2021 | $\text{CeO}_2$                                     | Methanol             | Diesel engine | NOx emissions and smoke opacity were reduced by 70.9% and 90.3%, respectively.                 |
| [92], 2023 | ZnO                                                | Green fuel           | Diesel engine | NOx were reduced by 12.97% at maximum power output.                                            |
| [93], 2023 | $\text{Al}_2\text{O}_3$ , $\text{SiO}_2$ , and MgO | Tamarind seed oil    | CI Engine     | CO, UHC, NOx, and smoke emissions were substantially decreased.                                |

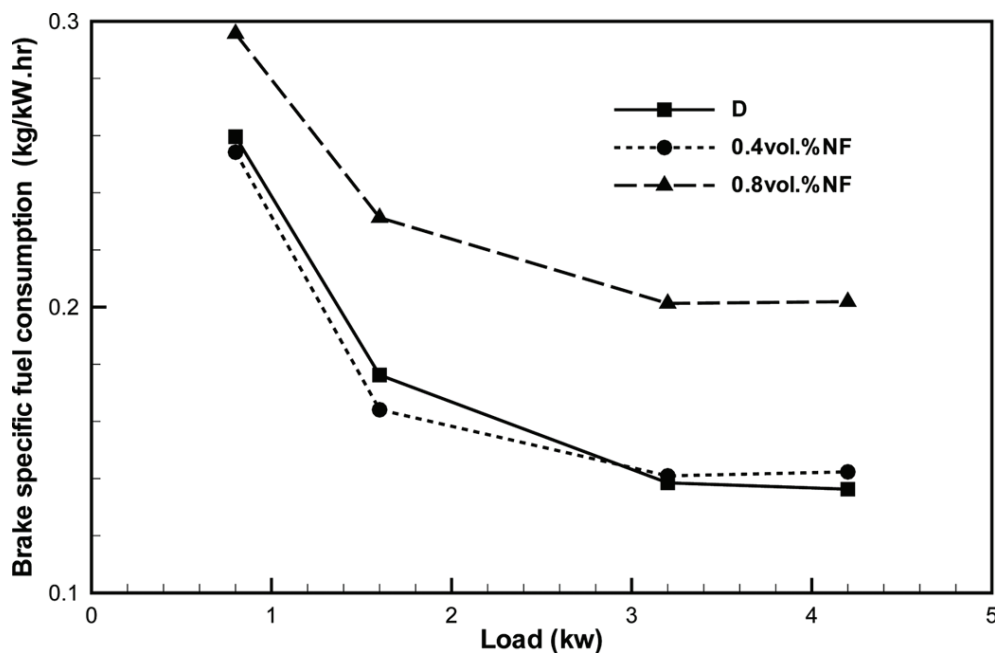


Figure 11. Variation of BSFC with load [From Sarvestany et al. [83], with permission from Taylor and Francis].

NO<sub>x</sub>, and 9% smoke-opacities over RBOME. The nanofluid enhanced combustion by lowering ignition delay and being an oxidation catalyst. Magnetic nanoparticles were collected from exhaust emissions for potential reuse. Chaichan et al. [87] investigated the effect of aqueous alumina nanofluid (1–10%) on diesel engine effectiveness and emissions. BTE

enhanced by 5.5%, and fuel consumption reduced by 3.94%. The variation of HC emission with engine speed is shown in Figure 12. CO, HC, NO<sub>x</sub>, and PM emissions decreased by 14.49%, 27.94%, 41.3%, and 37.64%, respectively. However, CO<sub>2</sub> emissions increased by 26%, and engine noise rose by 2.19% at 10% concentration.

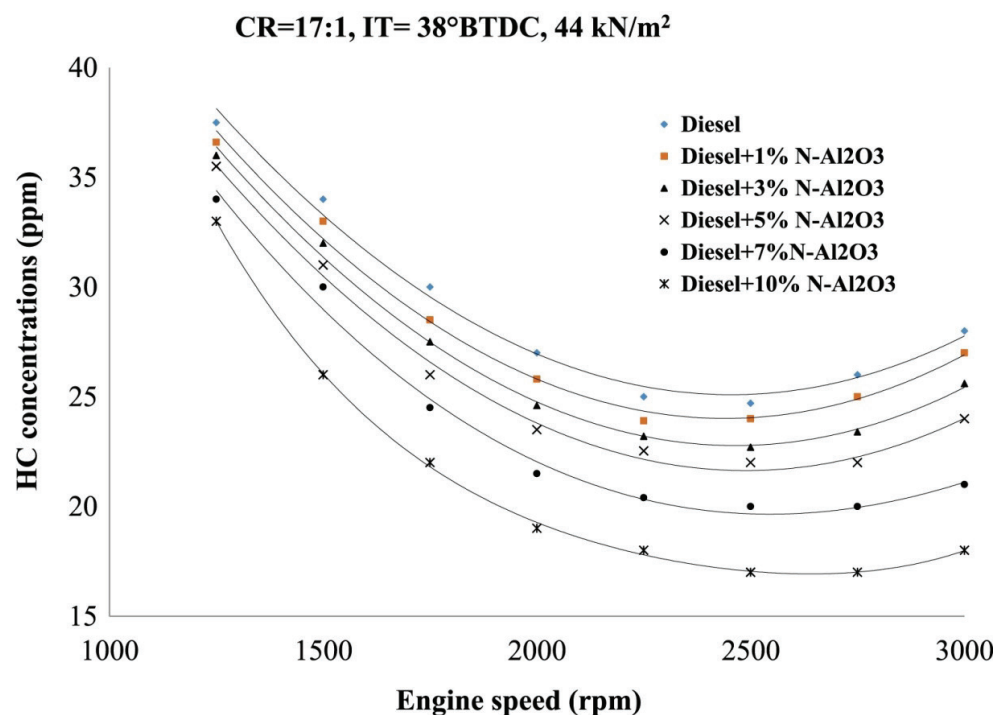


Figure 12. Variation of HC concentration with engine speed [From Chaichan et al. [87], with permission from Elsevier].

Yuvarajan et al. [88] examined the effect of  $\text{TiO}_2$  nanofluid on the emissions of a diesel engine using MOME biodiesel.  $\text{TiO}_2$  nanoparticles 50 nm were used at concentrations of 100 and 200 ppm. The findings indicated that  $\text{TiO}_2$  had a negative effect on carbon monoxide (by 13%), hydrocarbons (by 4.2%), and smoke emissions but a minor positive effect on  $\text{NO}_x$  emissions. The nanofluid increased the efficiency of combustion because of the increased oxidation and catalytic activity. Saxena et al. [89] optimized modified nanofluid (MNF) fuel blends with  $\text{TiO}_2$  nanoparticles in a diesel engine. The optimal conditions were  $\text{TiO}_2$  at 150 mg/L and 82.37% engine load. Under these conditions, BTE enhanced by 3.25%, BSFC reduced by 18.42%, and reductions in ignition delay (7%), hydrocarbon (38%), and smoke emissions (20%) were detected, accompanied by a slight rise in  $\text{NO}_x$  emissions. Venkatesan and Kadiresh [90] examined aqueous aluminum oxide nanofluid blends in a diesel engine to enhance performance and reduce emissions. The D+50AN blend showed the highest brake thermal efficiency improvement (5.9%) and reductions in  $\text{NO}_x$  (15.6%), smoke (22.34%), hydrocarbons (31.82%), and CO (13.79%) at maximum rated power. Further addition of the nanofluid to a level of more than 50cc resulted in poor performance and D+50AN was the best mixture to use in the diesel engine.

Pan et al. [91] examined the effect of cerium oxide ( $\text{CeO}_2$ ) nanoparticles in methanol based nanofluids on

combustion, performance and emissions of a dual-fuel diesel engine. Findings showed that BSEC had reduced by as much as 8.1, and BTE had also increased by 10.8. The emission test was employed to determine the reduction of HC and CO levels by 56.3 and 79.8%, and  $\text{NO}_x$  and smoke opacities by 70.9% and 90.3% respectively upon inclusion of ZnO nanofluid with diesel to study the green fuel blend [92] to improve combustion and engine performance. D + 50ZN blend gave the most favorable results with a 5.38 percent increase in brake thermal efficiency. Emissions of  $\text{NO}_x$  decreased by 12.97%. Sathish et al. [93] compared the performance of tamarind seed oil-based biodiesel mixed with  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ , and  $\text{MgO}$  nanoparticles in a CI engine. The variation of  $\text{NO}_x$  with load for different blend condition is shown in Figure 13. It was found that the D80TSOB20A mixture produced the greatest cylinder pressure (77 bar) and heat release rate (75 J/deg). Thermal efficiency of the brakes increased to 32% and CO and smoke emissions were greatly reduced as opposed to other blends.

#### Nanofluid as a Medium for Enhanced Shock Absorption

Nanofluids have also become a prospective shock absorbing media because of their high energy dissipation capacity, rheological tuning and dynamically responsive nature to impact loads. Diffusion of the nanoparticles in the base fluids modulates their viscosity, density and thermal conductivity, and thus the mechanical shock waves can

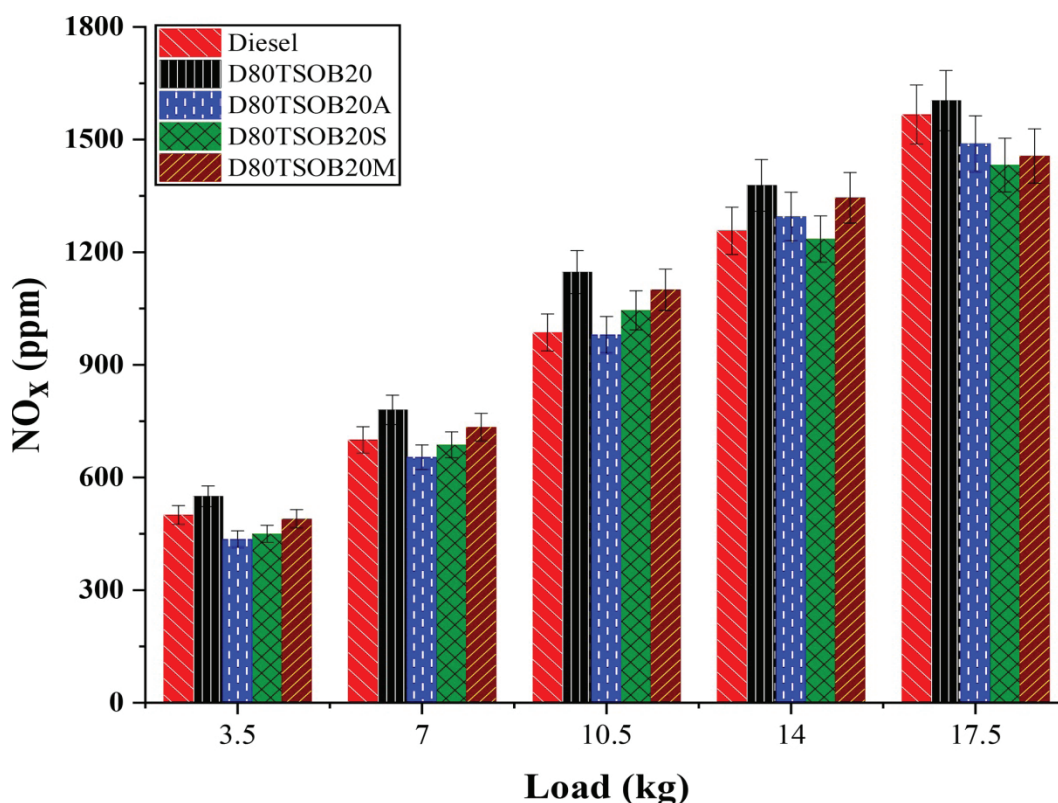


Figure 13.  $\text{NO}_x$  variations with load for various blends [From Sathish et al. [93], with permission from Elsevier].

be more effectively managed [94]. The characteristics of nanofluids render them extremely useful in impact resistance use, which is necessitated by automotive crash protection, protective clothing, aerospace structures, and military armoring systems. Nanofluids containing nanoparticles like silica, carbon nanotubes or metal oxides can show shear-thickening properties, in which viscosity rises with high strain rates, allowing rapid energy uptake at the impact point [95].

Nanofluids, when used in shock absorbers, can enhance shock absorber damping and stability in the automotive industry. Their capability to suppress vibrations and energy decays are also very effective in ride comfort and durability of suspension systems. In aerospace, nanofluid-based dampers reduce vibrations and shocks during takeoff, landing, and turbulence to increase the lifespan of components. In addition, nanofluids are considered in body armor and protective materials, and their dynamic stiffening effect can be more effective against high speed projectiles and blunt force trauma [96].

It has been shown that the shock absorption characteristics of nanofluids can be manipulated through the nanoparticle concentration, morphology and fluid composition. Nanofluids of high viscosity and optimal particle loading contain fewer sudden deformations and are therefore useful in energy absorption implementation [97]. Also, they have a high heat dissipation rate that causes structural

failure in sensitive components. The adaptability of nanofluids to different impact conditions is likely to be further enhanced in the future by the new formulations of nanofluid, such as smart and magnetorheological nanofluid. The injection of nanofluids into high-technology damping and shock-absorbing materials is a big move towards the creation of next-generation impact-resistant materials in the automotive, aerospace, and defense sectors [98].

Ali et al. [99] examined how hybrid nanofluids impacted the viscous damping of hydraulic oil in dashpots. The variation of damping coefficient with for hybrid nanofluid at different volume concentration is shown in Figure 14. It tested nanofluids with 1–5 vol% of fumed silica, precipitated silica, and MWCNTs. The MWCNT nanofluid (0S5C) at 5 vol percentage had the best damping enhancement, with a lowering of the settling time and overshoot. Shear thickening was verified by rheological tests in an increased concentration of MWCNT. The damping coefficient increased with MWCNTs but decreased with silica.

Pawar et al. [100] investigated the influence of CuO nanofluid on the viscosity and damping characteristics of shock absorber oil. Nano-lubricants with 0.25–1.5 wt% CuO increased viscosity, with 1 wt% showing a 20% rise at 25°C. The damping performance was increased 15% with RMS acceleration decreasing to 0.85 mm/s<sup>2</sup> at 400 rpm. Although viscosity and damping were improved, the transmissibility ratio did not vary significantly, which suggests

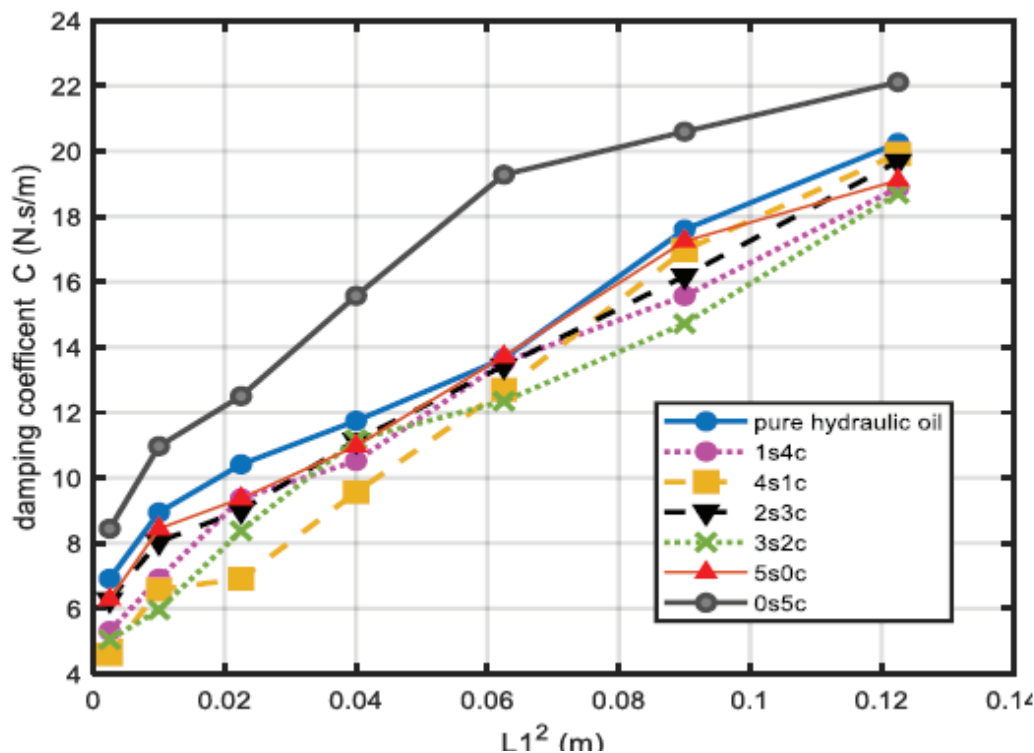


**Figure 14.** Variation of damping coefficient with for hybrid nanofluid at different volume concentration [From Ali et al. [99], with permission from Semarak Ilmu].

that shock absorber designs might require adjustments to achieve the maximum benefits of CuO.

### Revolutionizing Automotive Lubricants with Nanotechnology

Nanofluids have been seen as a potential engine lubricant because of their improved thermal and tribological characteristics. Nanofluids enhance viscosity, thermal conductivity and anti-wear properties by dispersing nanoparticles such as CuO, Al<sub>2</sub>O<sub>3</sub> or MoS<sub>2</sub> in base oils. These additives enhance the reduction in friction between the moving parts resulting in reduced energy loss and fuel efficiency [101–103]. Research has demonstrated that nanolubricants (a lubricant to which nanoparticles have been added to enhance thermal conductivity, reduce friction, minimize wear, and improve overall engine performance) can reduce engine wear by creating protective tribofilms, reducing the amount of metal-to-metal contact. They also have better heat dissipation capabilities that will ensure the engines run at optimal temperatures and minimize chances of overheating and extending the life of the engine [104]. Studies show that nanofluids are able to reduce the rate of oil degradation; hence, increasing the service life. Nevertheless, nanoparticles stability and dispersion methods, as well as filter blockage, are issues to be considered prior to the large scale application. With the increasing

automotive needs, nanofluid-based lubricants are also an option in enhancing the engine performance and efficiency [105]. Table 5 presents a summary of the use of nanofluid as an engine lubricant in automobiles.

Wu and Kao [106] investigated the impact of TiO<sub>2</sub> nanofluid as a lubricant additive in internal combustion engines. Engine tests indicated that with the application of TiO<sub>2</sub> in ethylene glycol, oil gelation was achieved after 10 hours but the problem was eliminated by applying paraffin oil. TiO<sub>2</sub> nanofluid decreased friction force and smaller particles (59 nm) were more effective. The research determined that particle size played a major role in reducing friction indicating that TiO<sub>2</sub> nanofluid was a promising lubricant. Etefaghi et al. [107] examined the impact of MWCNTs as an additive in SAE 20W50 engine oil. It was found that a 0.1 wt% of MWCNT concentration increased thermal conductivity by 13.2% and flash point by 6.7%. The concentration of 0.2 wt% resulted in a 13 percent rise in flash point, and viscosity was not affected at low concentrations. These results indicate that MWCNTs improve engine oil performance but do not substantially affect viscosity. Afrand et al. [108] examined the effects of temperature and concentration on the viscosity of SiO<sub>2</sub>-MWCNTs/SAE40 hybrid nanofluid for use in heat engines. The variation of viscosity with temperature at different volume concentration is shown in Figure 15. The

**Table 5.** Summary of the use of nanofluid as an engine lubricant in automobiles

| Ref. No.    | Nanofluid                                           | Engine Oil                | Concluding Remark                                                                                                    |
|-------------|-----------------------------------------------------|---------------------------|----------------------------------------------------------------------------------------------------------------------|
| [107], 2013 | MWCNT                                               | SAE 20W50                 | 0.1 wt% MWCNT concentration enhanced thermal conductivity by 13.2%.                                                  |
| [108], 2016 | SiO <sub>2</sub> -MWCNTs                            | SAE 40                    | 37.4% enhancement in viscosity at 1.0% volume fraction                                                               |
| [109], 2016 | Sc-Ag/GN                                            | 10W40                     | Sc-Ag/GN reduced friction coefficient by 30.4%                                                                       |
| [110], 2017 | Al <sub>2</sub> O <sub>3</sub> -MWCNT               | 5W50                      | Higher solid volume fractions (up to 1%) increased viscosity                                                         |
| [111], 2018 | Mg(OH) <sub>2</sub> /MWCNT                          | 5W50                      | Thermal conductivity improved by 13%–50%.                                                                            |
| [112], 2018 | MWCNT-ZnO                                           | 5W50                      | Viscosity decreased by over 7% at 0.05%–0.1% nanoparticle concentrations                                             |
| [113], 2019 | MWCNT-SiO <sub>2</sub>                              | 10W40                     | The highest viscosity increase (1.4×) occurred at 5°C with 1% concentration                                          |
| [114], 2019 | MWCNT-ZnO                                           | 5W50                      | Viscosity reduction of up to 9% at 0.05% solid volume fraction at 5°C minimized cold start damages                   |
| [116], 2020 | MWCNT-TiO <sub>2</sub>                              | SAE50                     | Viscosity decreased by 76% at 3999 s <sup>-1</sup> shear rate with a 1% concentration.                               |
| [117], 2021 | ZnO-TiO <sub>2</sub>                                | 5W30                      | Engine tests showed a 4.5% noise reduction.                                                                          |
| [118], 2021 | SiO <sub>2</sub> /soybean                           | Engine oil                | The viscosity decreased with increasing temperature, with a 55% reduction at 5°C for 1% volume fraction.             |
| [119], 2021 | Graphite                                            | SAE30                     | A 15.2% reduction in total fuel consumption and an 18% decrease in BSFC.                                             |
| [120], 2022 | MWCNT-Al <sub>2</sub> O <sub>3</sub>                | 5W50, 10W40               | The highest viscosity increase (+34.97%) was observed in 10W40.                                                      |
| [121], 2025 | CuO and ZnO, Al <sub>2</sub> O <sub>3</sub> and ZnO | Pure diesel and SAE 15W40 | CO and NO <sub>x</sub> emissions decreased by 20.04% and 10.25%, while CO <sub>2</sub> emissions increased by 29.16% |

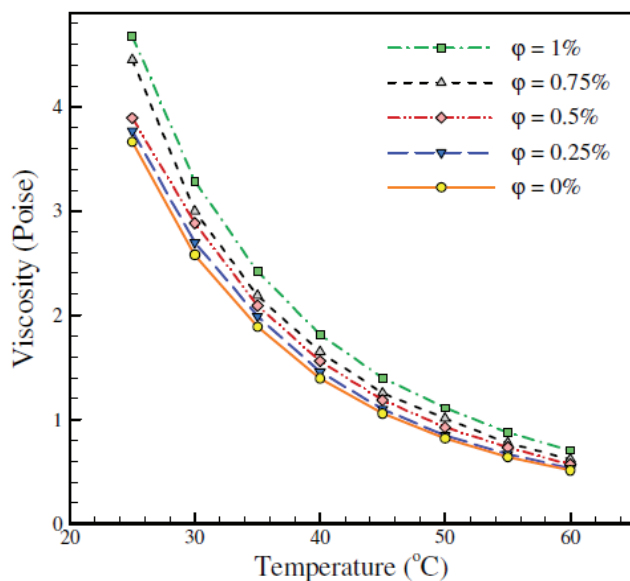


**Figure 15.** Viscosity variations with temperature at different volume concentrations [From Afrand et al. [108], with permission from Elsevier].

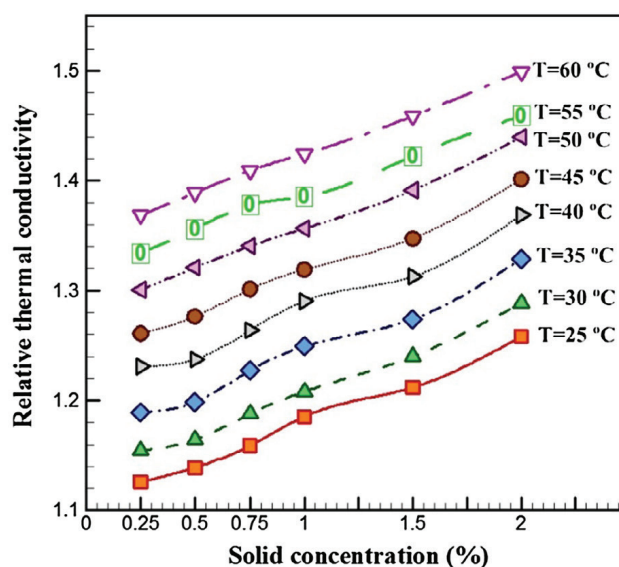


**Figure 16.** Variation of relative thermal conductivity with concentration at different temperature [From Asadi et al. [111], with permission from Elsevier].

findings indicated an increase in viscosity as nanoparticle concentration was increased with a maximum 37.4% increase at 1.0% volume fraction. However, viscosity decreased with increasing temperature from 25°C to 60°C.

Meng et al. [109] prepared Sc-Ag/GN through super critical CO<sub>2</sub>, and the uniform silver nanoparticles (2-16 nm) on graphene sheets were obtained. Sc-Ag/GN, as an engine oil additive (0.06 - 0.10 wt. %), decreased the friction coefficient and wear scar diameter by 30.4 and 27.4 percent, respectively, compared to ZDDP, nano-Ag, and graphene oxide. The frictional film formed reduced the surface roughness, increasing lubricity. These results indicate industrial possibilities of Sc-Ag/GN in lubrication. Esfe et al. [110] investigated the rheological behavior of Al<sub>2</sub>O<sub>3</sub>-MWCNT/5W50 hybrid nano-lubricant. The readings of viscosity at 5-55°C and shear rate of 666.5-10,664 s<sup>-1</sup> showed non-Newtonian behaviour. The higher the concentration (up to 1%), the higher the viscosity and non-Newtonian effects and the lower the temperature. A new correlation, which was formed, attained a correlation coefficient of 0.9923 which effectively predicted the viscosity variations. The results justify the potential application of the hybrid nano-lubricant in engines. Asadi et al. [111] studied the heat transfer performance of Mg(OH)<sub>2</sub>/MWCNT-engine oil nano-lubricant. It showed Newtonian behavior in the entire temperatures tested (25°C-60°C) and volume fraction (0.25%-2%). The variation of relative thermal conductivity with varying concentration and different temperature is depicted in Figure 16. The dynamic viscosity increased with solid concentration but decreased with temperature, while thermal conductivity improved by 13%-50%.

Esfe et al. [112] examined the effect of MWCNT-ZnO (30%-70%) nanoparticles in 5W50 engine oil to improve lubrication. Viscosity decreased by over 7% at 0.05%-0.1% nanoparticle concentrations, reducing cold start damages. The nano-oil showed non-Newtonian behavior and higher viscosity index. ANN and RSM models predicted viscosity with R<sup>2</sup> values of 0.9999 and 0.9715, respectively. The nano-oil enhanced lubrication in low and high-temperature conditions. Rejvani et al. [113] investigated the rheological behaviour of MWCNT-SiO<sub>2</sub> (30-70)/10W40 nano-lubricant. It followed a non-Newtonian pseudo-plastic model. The viscosity was 35% higher than that of pure oil and dependent upon temperature and solid volume fraction. The maximum increase in viscosity (1.4×) was at 5C when the concentration was 1%. Esfe et al. [114] experimentally analyzed MWCNT-ZnO (20%-80%)/5W50 nano-engine oil for lubrication efficiency. A viscosity reduction of up to 9% at 0.05% solid volume fraction at 5°C minimized cold start damages. The nano-oil had non-Newtonian behaviour and reduced temperature dependence of viscosity. The results indicated its possible high-temperature lubrication and increased oil recovery possibilities.

Ramteke and Chelladurai [115] investigated the effects of hBN nanofluids on a diesel engine's tribological, performance, and emission characteristics. The 1 wt. % hBN nanofluid reduced piston ring wear, improved lubrication by forming a tribofilm, and increased brake power and thermal efficiency by 5.09% and 4.33%, respectively. Carbon monoxide and hydrocarbon emissions decreased by 46.15% and 55.95%, while NO<sub>x</sub> emissions increased by 40.03%. Esfe and Esfandeh [116] investigated the rheological behaviour of MWCNT-TiO<sub>2</sub> (40:60)/SAE50 hybrid

nanofluid at 25–50°C and 0–1% solid volume fractions. Results showed that viscosity decreased by 76% at 3999  $s^{-1}$  shear rate with a 1% concentration. The nanofluid was pseudoplastic and at concentrations less than 0.5%, the viscosity was low than that of the base fluid. Bharath and Selvan [117] investigated the rheological and heat transfer performance of ZnO–TiO<sub>2</sub> hybrid nanolubricant in a spark-ignition engine. Viscosity tests showed non-Newtonian behavior, with the hybrid nanolubricant having a higher viscosity index than conventional oil. The Maxwell–Garnetts model predicted a 5.7% increase in thermal conductivity at 0.1 wt%. Engine tests showed a 4.5% noise reduction and significant decreases in longitudinal (59%) and lateral (49%) vibrations at higher speeds.

Kharabati et al. [118] examined thermal and rheological characteristics of SiO<sub>2</sub>/soybean oil nano lubricant in internal combustion engines at 5° C to 40°C. Viscosity decreased with temperature, with a decrease of 55% at 5°C when the lubricant was 1% in volume. The maximum thermal conductivity (0.169 W/mK) was observed at 30 C and this is 12 percent higher than at base oil. Singh et al. [119] developed and tested graphitic nanoparticle-based nanolubricants for automotive applications. The variation of different performance parameter with load is shown in Figure 17. Nanographite-based nanolubricant showed a sevenfold improvement in wear resistance and a 13-fold reduction in friction. Engine tests revealed a 15.2% reduction in total fuel consumption, an 18% decrease in BSFC, a 22% rise in

BTE, a 28.23% boost in heat carried by the water jacket with reduced emissions. Esfe et al. [120] analyzed the efficiency of hybrid nano-lubricants under various experimental conditions. Experiments showed non-Newtonian and pseudo-plastic flow behavior. The highest viscosity increase (+34.97%) was in 10W40, while the highest decrease (-9.64%) was in 5W50. MWCNT-Al<sub>2</sub>O<sub>3</sub>/5W50 exhibited better viscosity control. Gosai et al. [121] examined the influence of nano-additives on diesel engine efficiency and emission characteristics. It concluded that using CuO and ZnO nanoparticles in fuel and Al<sub>2</sub>O<sub>3</sub> and ZnO in lubricants improved thermal efficiency by 17.62% and reduced SFC by 14.98%. The emissions of CO, NO<sub>x</sub> were reduced by 20.04% and 10.25% and CO<sub>2</sub> emissions enhanced by 29.16%, which means that it was fully burned.

## ENVIRONMENTAL CONCERN AND SUSTAINABILITY OF NANOFLUID PRODUCTION AND DISPOSAL

The recent development in nanofluids in automotive industry is mainly propelled by the fact that these fluids can be used to increase fuel efficiency, reduce emissions and enhance heat transfer in vehicles. Nonetheless, together with their technological advantages, the environmental issues that are related to the production, usage, and disposal of nanofluids should be evaluated critically in order to guarantee a sustainable adoption [122, 123].

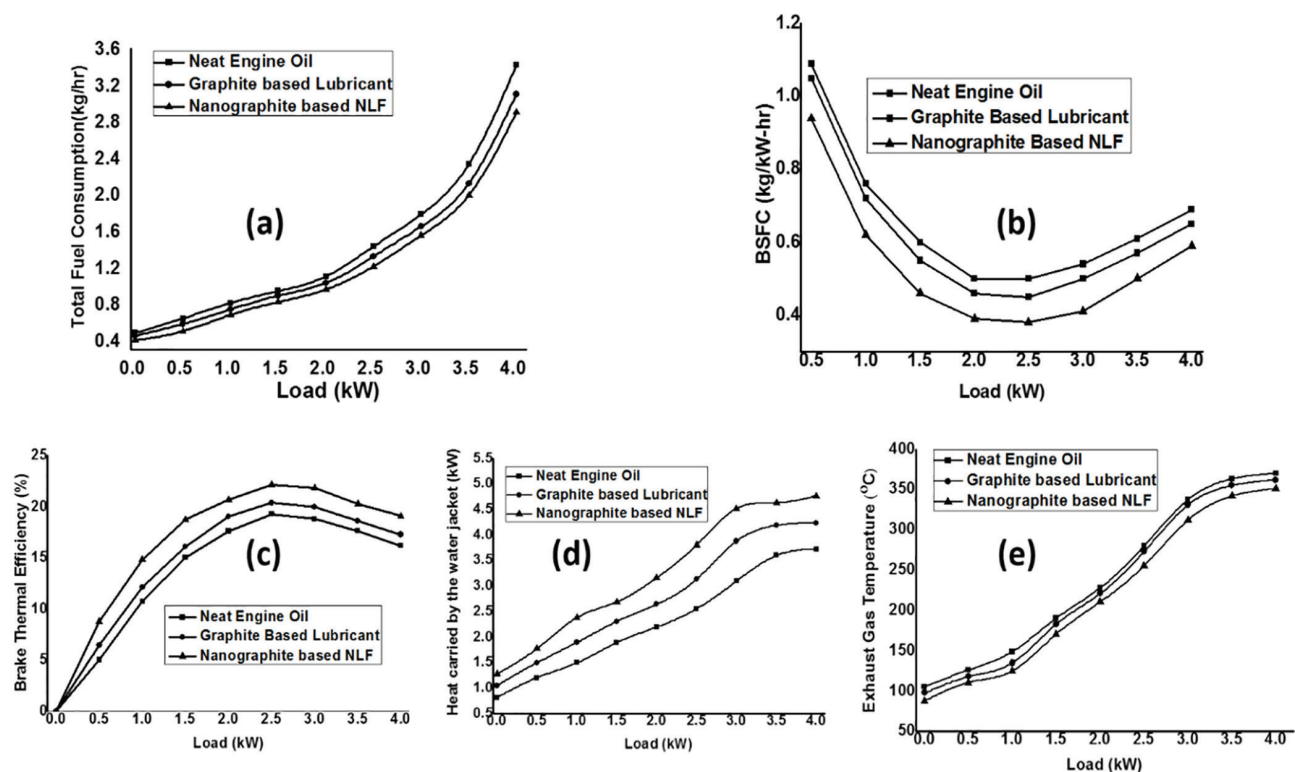


Figure 17. Variation of different performance parameter with load [From Singh et al. [119], with permission from Elsevier].

### Environmental Impact of Nanofluid Production

Nanofluid preparation is commonly associated with energy consuming procedures like chemical precipitation, sol-gel processing, and laser ablation, which add to carbon emissions and resource depletion. Also, certain production processes are based on dangerous chemicals, which cause possible environmental toxicity. It is also of concern that the energy requirement of synthesizing nanoparticles is very high and this is likely to impact the sustainability of mass production [124-125]. In order to alleviate these concerns, studies are concentrating on:

- Plant extracts and biocompatible solvents to synthesize using green methods to reduce hazardous waste.
- Energy efficient production methods that will minimize emissions and use of resources.
- Recycling and reuse of nanoparticles to improve sustainability and decrease reliance on raw materials.

### Nanofluid Usages and Potential Environmental Risk

Although nanofluids have great potential in improving the performance of vehicles, the long-term effects of the use of nanoparticle include the release of the nanoparticles into the environment. Potential risks include:

- Dispersal of airborne nanoparticles that can be harmful to health when inhaled.
- Water pollution, nanoparticles will be able to settle in aquatic environments, thus impacting on life in the sea.
- Pollution of soil, where stable nanoparticles change the microbiology and nutrient cycling.

In order to overcome these issues, strict protocols on nanofluid handling and storage must be put in place and formulations of environmentally friendly nanofluids which decompose harmlessly after application must also be prepared.

### Sustainable Disposal and Recycling Strategies

Disposal of used nanofluids is a serious environmental issue as when they are disposed of improperly, it may cause the build-up of nanoparticles in the ecosystem. Disposal and recycling are done using sustainable methods such as:

- Filtering and separation methods to reclaim nanoparticles in waste nanofluids, so that they can be reused in the industry.
- Environmentally-sustainable degradation, e.g., enzymatic degradation or photocatalytic degradation, to negatively degrade the nanoparticles prior to disposal.
- The regulatory systems to bring uniformity in disposal processes, with reduced risks to the environment.

The automotive industry can take advantage of the benefits of nanofluid by incorporating sustainability into nanofluid studies and application with minimal environmental trade-offs. The concerns will have to be addressed in order to embrace the use of nanofluids as a green technology in the next generation vehicles.

### Life Cycle Assessment of Nanofluid

In order to support the sustainability argument in favour of nanofluids in automotive industry, the need to measure

their environmental impacts by conducting lifecycle assessments (LCAs) and toxicity analyses is imperative. LCAs offer an all-inclusive assessment of the ecological footprint of nanofluids, starting with the extraction, synthesis, use, and disposal of the raw materials and toxicity tests determine possible ecological and human health hazards when nanoparticles are present. Nanofluid production LCAs indicate that nanoparticles, including  $\text{Al}_2\text{O}_3$ , CuO and carbon nanotubes (CNTs), are costly to produce, and can be an important contributor to the carbon footprint. In the usage stage, nanofluids also help to enhance environmental advantage by enhancing fuel efficiency and lowering emissions. The incorporation of CuO and ZnO nanoparticles in fuel and lubricants decreased specific fuel consumption by 14.98% and CO/NOx emissions by 20.04% and 10.25% [121]. These cuts are estimated to be 0.5-1.0 kg  $\text{CO}_2$ -eq/liter of fuel saved, which varies based on engine type and operation conditions. But, the disposal stage is problematic, because the nanoparticle recovery and recycling are not popular yet. LCAs demonstrate that inappropriate disposal of nanofluids may cause nanoparticles to be deposited in soils and water, making non-biodegradable nanoparticles such as CNTs to persist in the environment 10-20 years longer [126]. Recycling approaches (filtration and centrifugation) can reduce nanoparticle concentration in used nanofluids by up to 80% to recover the unused material, reducing the lifecycle  $\text{CO}_2$  by 50-60% and the lifecycle  $\text{CO}_2$  by 15-20% to reduce the use of virgin materials and mitigate the impacts of used nanofluids. The future research ought to be on designing closed-loop recycling systems to improve sustainability of nanofluid applications in automotive systems.

### Roadmap for Standardization of Nanofluid Testing Protocols to Guide Industry Adaptation

It is essential to develop standardized testing procedures of nanofluids to hasten their introduction into industries. Figure 18 shows the roadmap of standardization of nanofluid testing protocols that should be used to accelerate adaptation of the industry. The roadmap starts with the development of a collaborative institution to include academia, industry, and regulatory organizations to set key performance indicators, including thermal conductivity, viscosity, stability, and the environmental impact. The first step must be to develop a standard nomenclature and classification of nanofluids to make nanofluids consistent in research and practice. Secondly, standardized methods of measurement such as equipment calibration procedures, sample preparation procedures, etc. have to be devised to deal with variability in existing testing procedures. Inter-laboratory validation will add to reliability and reproducibility. Simultaneously, the safety and toxicity tests must be combined to comply with the regulation requirements, which will help build confidence in the use of nanofluids. The roadmap focuses on progressive improvement, including feedback of pilot implementations in other industries

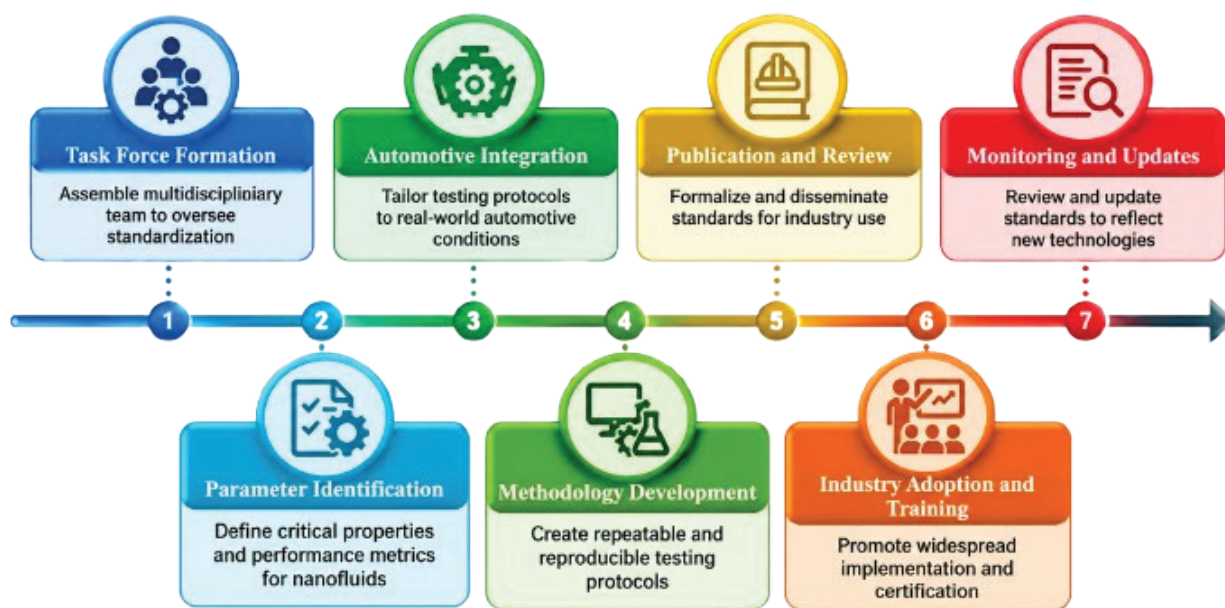


**Figure 18.** Roadmap for standardization of nanofluid testing protocols to guide industry adaptation.

such as energy, automotive and electronics. A standard, probably based on ISO or ASTM, which is globally accepted should be created by 2030, backed by open-access databases of nanofluid properties. The systematic methodology will curb the technical hindrances, lower expenses, and facilitate scaled, secure, and effective incorporation of nanofluids, impacting innovation and sustainability in sectors.

### CHALLENGES IN INTEGRATING NANOFLUID INTO MODERN AUTOMOTIVE TECHNOLOGIES AND ITS LIMITATIONS

The application of nanofluids in the contemporary automotive technology has a number of challenges and limitations. The long-term efficiency is decreased by stability problems, including agglomeration and sedimentation of nanoparticles. One of the key issues in the application of nanofluid is agglomeration. It arises because of Van der Waals forces and magnetic or electrostatic interactions between nanoparticles, and causes clustering which reduces thermal conductivity and even dispersion. In dynamic automotive conditions (vibration, changes in temperature), the effect of agglomeration risk is higher, which impairs the stability of nanofluids and leads to blockage in cooling or lubrication systems in automotive systems [13, 34]. The common countermeasures are: (1) pH modification to raise zeta potential that increases repulsive nanoparticles forces. Indicatively, ZnO/H<sub>2</sub>O nanofluids with a zeta potential of over 30 mV are stable up to 30 days [35]. (2) physical barrier formation (e.g., with surfactants, e.g., sodium dodecyl sulfate) to minimize the clustering of particles. Surfactants

can however break down at high temperatures (greater than 100 C) and cannot be used in engine environment [51]. (3) Using ultrasonic waves to disperse agglomerates but long-term ultrasonication (>2 hours) may destroy the structure of nanoparticles, decreasing thermal conductivity by as much as 5% [33].

Difficulties with commercialization are caused by high costs of manufacturing and complicated synthesis procedures. Even though nanofluids demonstrate improvements in performance (e.g., 17.62% thermal efficiency improvement, 14.98% SFC decrease), the performance is limited at industrial level. Cost considerations comprise: (1) Adding CuO and ZnO nanoparticles to fuel and lubricants enhances thermal efficiency by 17.62% and decreases specific fuel consumption by 14.98% [121]. Using a mid-size car (fuel consumption: 8 L/100 km) as an example, the fuel savings would amount to around 150-200 dollars/annually at a fuel price of 1.5/L, which would cover the costs of nanofluid in 1-2 years. (2) Nanolubricants lower engine wear due to tribofilms formation, low maintenance cost of up to 15% over 100,000 km [119]. Indicatively, graphitic nanolubricants lowered wear by seven times which could save up to \$500 on engine repairs [119]. (3) Fewer CO and NO<sub>x</sub> emissions (20.04% and 10.25% respectively [121]) meet strict emission regulations (e.g. Euro 7), which may save manufacturers money (vitality, fines) or allow tax subsidies.

It is unclear how it fits with engine materials and lubricants, and a great deal of research is needed. The issue of environmental and health implications on exposure to nanoparticles also makes adoption more cumbersome [127, 128]. Also, the absence of standardized testing procedures

**Table 6.** Challenges and limitations in integrating nanofluids into automotive technologies

| Aspect               | Challenges                                               | Limitations                                                       |
|----------------------|----------------------------------------------------------|-------------------------------------------------------------------|
| Stability            | Nanoparticles tend to agglomerate and settle over time.  | Long-term performance is uncertain due to instability.            |
| Cost                 | High manufacturing and synthesis costs.                  | Scaling up production remains economically unfeasible.            |
| Compatibility        | Unclear impact on engine materials and lubricants.       | Long-term wear effects on engine components are unknown.          |
| Testing & Validation | Lack of standardized testing protocols.                  | Performance inconsistencies across different studies.             |
| Dispersion           | Requires advanced dispersion techniques for homogeneity. | Variability in thermal conductivity affects efficiency.           |
| Safety & Regulations | Potential health and environmental risks.                | Limited data on nanoparticle exposure impact.                     |
| Viscosity Impact     | Higher viscosity can reduce fuel efficiency.             | Increased pumping power may lead to higher energy use.            |
| Scalability          | Difficult to maintain performance at commercial scale.   | Large-scale adoption is restricted due to performance variations. |
| Energy Demand        | High energy requirements for nanoparticle synthesis.     | Energy-intensive production raises sustainability concerns.       |

impedes reliability and performance validation. Such problems as higher viscosity with flow dynamics and inaccurate experimental data complicate the overall implementation. To ensure that nanofluids are a viable alternative in the auto industry, it is important to address these challenges. The challenges and limitations in integrating nanofluids into large scale automotive technologies are shown in Table 6.

## KEY APPLICATION OF THE FINDINGS

The research paper gives a detailed examination of the way nanofluids increase the functionality of different automotive subsystems such as engine cooling, lubrication, and fuel efficiency. The most important uses of the discovery are:

### Enhanced Engine Cooling

Nanofluids used in the cooling systems of automobiles enhance the ability to dissipate the heat in the engines, thus preventing overheating, leading to higher efficiency. The improved thermal conductivity of  $\text{Al}_2\text{O}_3$  and  $\text{TiO}_2$  nanofluids enables smaller and lighter radiators, which helps in reducing weight and fuel consumption of the vehicle.

### Improved Lubrication Performance

Lubricants that are made of nanofluid decrease engine wear and friction thus increasing the engine life and also fuel economy. The addition of  $\text{CuO}$  and  $\text{ZnO}$  nanoparticles to lubricants demonstrated decreased wear rates with increased stability in viscosity, which provides increased performance in lubricants in different operating conditions.

### Fuel Efficiency and Emission Reduction

The inclusion of nanoparticles like  $\text{CeO}_2$  and  $\text{Al}_2\text{O}_3$  in fuel enhances the efficiency of the combustion process, resulting in less fuel consumption and less emission. In particular, the levels of  $\text{CO}$  and  $\text{NO}_x$  emissions were reduced by 20.04 and 10.25 percent, respectively, and  $\text{CO}_2$

emissions grew, which proves the increase in the level of total combustion.

### Potential Use in Hybrid and Electric Vehicle

Nanofluids have a high thermal conductivity and can find great use in the future in electric vehicle (EV) battery thermal management systems, where effective heat dissipation is needed to ensure battery safety and longevity.

## CONCLUSION

Nanofluids have been found to have huge potential in enhancing the performance of automobiles especially in the field of lubrication and fuel efficiency. Adding nanoparticles to engine oil and fuel, scientists have found out improvements in thermal conductivity, viscosity, and tribological characteristics. Studies showed that nanolubricants reduced friction and wear, resulting in improved engine durability. Also, the fuel nano-additives led to a higher combustion efficiency and consequently, a higher brake thermal efficiency and reduced specific fuel consumption.

There was also an emissions analysis of the combustion that showed that carbon monoxide ( $\text{CO}$ ) and nitrogen oxides ( $\text{NO}_x$ ) were reduced because the combustion was improved, and carbon dioxide ( $\text{CO}_2$ ) emissions had slightly increased, which showed that the fuel being used was used fully. Nanofluids had a non-Newtonian nature of viscosity and were dependent on concentration and temperature, which affected their performance in various operating conditions. Combination of materials such as  $\text{CuO}$ ,  $\text{ZnO}$ ,  $\text{Al}_2\text{O}_3$  and  $\text{hBN}$  in fuel and lubricants was promising in terms of optimization of engine performance. The key findings derived from this review article are as follows:

1. Nanofluids significantly enhance the thermal and lubrication properties of automotive systems.
2. The addition of nanoparticles in fuels and lubricants improves engine performance and fuel efficiency.

3. Nanoparticles also decrease wear and friction, resulting into improved longevity and reliability of engine parts.
4. Nanofluids have better heat transfer characteristics, which help to cool engines.
5. Application of nanofluids leads to reduction of emission of harmful gases like CO, NO<sub>x</sub> and HC.
6. Nanofluids promote full combustion, which enhances the thermal efficiency of the brake.
7. Nanoparticles stability and dispersion in base fluids are still a challenge, which needs further studies.
8. Scalability and cost-effectiveness of nanofluid applications in automobile industry should be assessed.

Generally, the use of nanofluids in cars has demonstrated a trade-off between performance enhancement and reduction in environmental impact. The next research should aim at ensuring maximum benefits and minimum potential disadvantages are achieved by optimizing the concentration and stability of nanoparticles so that the advantages can be maximized but the disadvantages can be minimized like high viscosity with a higher concentration of nanoparticles. The present research verifies that nanofluids could become an effective method of making automotive engines more efficient and sustainable.

### Future Research Direction

The studies on the use of nanofluids in the automotive industry are scarce. Therefore, extensive studies are needed to accurately determine their behavior in automotive applications. The following research areas are some of the major areas that can be studied in future:

1. The focus of research should be on preventing the agglomeration and sedimentation of nanoparticles to increase stability of nanoparticles in automotive applications over periods of time.
2. It is essential to develop cost-effective synthesis and dispersion methods to ensure a large scale commercial viability.
3. More research is needed to determine the toxicity and ecological effects of exposure to nanofluid.
4. The aim of the investigations should be to maximize both the heat transfer and flow properties in the real-world automotive environment.
5. The long-term impacts of nanofluids on engine materials and lubricant formulations should be understood.
6. Prediction of nanofluids performance in the automotive systems can be enhanced by the combination of simulations and experimental data.
7. To have a sustainable adoption, a thorough examination of the life-cycle cost, recyclability, and environmental footprint of nanofluids is necessary.

### NOMENCLATURE

|            |                                                   |
|------------|---------------------------------------------------|
| $C_{p,nf}$ | Specific heat capacity of the nanofluid (J/kg·K)  |
| $C_{p,f}$  | Specific heat capacity of the base fluid (J/kg·K) |

|             |                                                      |
|-------------|------------------------------------------------------|
| $C_{p,p}$   | Specific heat capacity of the nanoparticles (J/kg·K) |
| $k_{nf}$    | Thermal conductivity of the nanofluid (W/m·K)        |
| $k_f$       | Thermal conductivity of the base fluid (W/m·K)       |
| $k_p$       | Thermal conductivity of the nanoparticles (W/m·K)    |
| $\rho_f$    | Density of the base fluid (kg/m <sup>3</sup> )       |
| $\rho_p$    | Density of the nanoparticles (kg/m <sup>3</sup> )    |
| $\rho_{nf}$ | Density of the nanofluid (kg/m <sup>3</sup> )        |
| $\phi$      | Volume fraction of nanoparticles                     |

### Abbreviations

|                 |                                      |
|-----------------|--------------------------------------|
| BSFC            | Brake specific fuel consumption      |
| BSEC            | Brake specific energy consumption    |
| BTE             | Brake thermal efficiency             |
| CI              | Compression ignition                 |
| CHTC            | Convective heat transfer coefficient |
| CO              | Carbon monoxide                      |
| DLS             | Dynamic light scattering             |
| EG              | Ethylene glycol                      |
| GO              | Graphene oxide                       |
| GNR             | Graphene nanoribbon                  |
| HC              | Hydrocarbons                         |
| hBN             | Hexagonal boron nitride              |
| MWCNT           | Multiwalled carbon nanotubes         |
| MOME            | Mustard oil methyl ester             |
| NO <sub>x</sub> | Nitrogen oxides                      |
| OHTC            | Overall heat transfer coefficient    |
| PEMFC           | Proton exchange membrane fuel cell   |
| PM              | Particulate matters                  |
| RBOME           | Rice bran oil methyl ester           |
| SFC             | Specific fuel consumption            |
| TEM             | Transmission electron microscopy     |
| UHC             | Unburned hydrocarbons                |
| ZDDP            | Zinc dialkyl dithiophosphate         |

### AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

### DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the manuscript.

### CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

### ETHICS

There are no ethical issues with the publication of this manuscript.

## STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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