Hybrid nanofluids for automotive cooling

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ABSTRACT Hybrid nanofluids (HNFs) consisting of multiple types of nanoparticles in base fluids, provide better thermal conductivity, stability, and rheological characteristics for automotive cooling systems. The current review is centered on the recent progress in the formulation of HNF which are oxide-carbon hybrids and bio-derived stabilizers like cellulose nanocrystals (CNCs). Besides, the main thermophysical parameters (thermal conductivity, viscosity, specific heat, and density) are studied in the context of particle morphology, concentration, and dispersion techniques. Ethylene glycol-water blends are still the most widely used base fluid because they provide a good combination of freeze protection and compatibility with materials. However, their low thermal conductivity requires enhancement through nanoparticles. Ultra-low loading hybrids (≤0.1 wt%) developed through surfactant-free ultrasonication or covalent functionalization are promising for the enhancement of thermal conductivity by double digits while maintaining minimal increase in viscosity. CNC-TiO_2 hybrids are still the sustainable options that provide renewable stabilization and chemical resistance, but they have not been completely validated in the automobile radiator loops. The review has pointed out the major issues regarding the lack of synthesis standardization, electrochemical safety, and lifecycle assessment. The future research should focus on large scale extraction of CNC, ligand-assisted assembly of oxide, and integrated system testing under real duty cycles to make the service-ready, environmentally friendly HNF coolants.

KEYWORDS: Hybrid nanofluids; Automotive coolings; Cellulose nanocrystals; Thermal conductivity; Ethylene glycol.
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Review Article

INTRODUCTION

The efficient management of thermal energy still is the main factor in determining the powertrain efficiency, emissions, durability, and packaging in the case of modern vehicles. The recent surveys of vehicle thermal management point out it as a cost-effective control for both normal and electrified platforms, with the auxiliary loads (such as fans, pumps, HVAC) taking up a not small part of the brake power in an average passenger car (Di Battista *et al.*, 2023). In the same way, modern engine thermal standards stress that increasing under-hood heat fluxes and tight emissions limits make it more critical to have coolant-side heat transfer and module-level optimization done well (Lakshminarayanan & Agarwal, 2022). In this situation, the radiator–coolant loop has been the weak point: traditional coolants like ethylene glycol (EG)/water mixtures have low thermal conductivity as their main drawback and, at the same time, they have viscosity penalties at high EG fractions that increase pumping power and reduce heat exchange coefficients (Ōzerïnç *et al.*, 2009). In the automotive radiators these thermophysical limitations result in either larger cores or increased airflow being required to keep the coolant-side ΔT and overall heat rejection (Mutuku, 2016) at the same level.

Nanofluids, which are colloidal mixtures of nanoscale (approximately 1–100 nm) solids in a liquid, were introduced as a method to overcome these limitations by enhancing effective thermal conductivity (k) and, under proper conditions, convective heat transfer coefficients (Ȯzerinç *et al.*, 2009). Enhancement has been attributed mechanistically to the existence of interfacial nanolayers, the mixing and clustering of particles induced by Brownian motion, although their relative contribution is dependent on the system (Rahman *et al.*, 2024). Studies related to automobiles have revealed that the temperature gradients can be steepened and the local Nusselt number increased as the radiating-like flows are created by the dispersing of oxide nanoparticles in either EG or water/EG (Mutuku, 2016). Practical incorporation, however, must consider the trade-offs: even at very low concentrations, nanoparticles can cause the viscosity (μ) to increase and in electrically active subsystems (e.g., fuel cell stacks) they can even raise the electrical conductivity significantly, which would lead to parasitic losses and safety issues (Islam *et al.*, 2017). Therefore, the "net benefit" of nanofluids is determined by securing conductivity gains at the lowest possible solid loading accompanied with the stability of dispersion and the μ within acceptable limits.

The idea of combining two or more types of nanoparticles in Hybrid Nanofluids (HNFs) has been the solution to the problem. HNFs, using semiconductor oxide subsystems (like high-k oxides with carbonaceous particles) are looking for synergistic enhancement of the effective heat transfer coefficient (keff) at lower total loading, improved rheology, and stability tailored to the application (Suneetha *et al.*, 2022; Scott *et al.*, 2022). The reports on critical evaluations concerning automotive radiators are that the HNFs that are properly formulated (like Al_2O_3/TiO_2; graphene/Al_2O_3/CNT etc.) can result in double-digit improvements in thermal performance metrics when concentration, inlet temperature and flow rate are optimized despite the durability and corrosion/fouling behavior in closed loops being still poorly characterized (Bargal *et al.*, 2025). Investigations on stability and their reviews have pointed that the longevity of dispersions depends mainly on surface chemistry and the method of formulation: surfactants or covalent functionalization could enhance zeta potential and reduce agglomeration but may also change μ, wettability, and interfacial heat transfer, therefore careful selection and dosage are required (Mane & Hemadri, 2022; Arora & Gupta, 2021). Even the application of common surfactants, which may seem to be a very simple option, has shown some complex effects: in the system of graphene oxide/water, for example, anionic SDS not only improved colloidal stability compared to CTAB and Triton X-100 but was also impotent against surfactant presence in terms of its universal increase of distribution thermal conductivity in all temperatures and concentrations (Keklikcioglu Cakmak, 2019).

A sustainability point of view becomes a must for the development of new coolants. It is no longer enough to consider only the performance of the materials; their selection, synthesis methods, and disposal routes should also contribute to reducing their toxicity and carbon footprint. Nanomaterials derived from biological sources in this respect—especially cellulose nanocrystals (CNCs) derived from crop waste—provide an eco-friendly, non-toxic base with variable surface chemistry for hybrid applications (Mateo *et al.*, 2021; Kamelnia *et al.*, 2025). The application of the circular economy to agro-waste-based nanoparticles has also unveiled green, low-energy synthesis routes and pointed out process/control toxicity as a major factor in the development of scalable, harmless additives (Flores Contreras *et al.*, 2024). Although they have been carried out outside the automotive industry, initial life cycle/cost studies suggest that if stability and compatibility are kept, HNFs can make cooling devices consume less energy and emit fewer gases over their entire service lives, thus supporting their environmental case when production and disposal are correctly managed (Cuce *et al.*, 2025).

In light of this, the current review has three objectives. Using foundational thermal property studies (Rahman *et al.*, 2024) and evaluations focused on automotive/radiators (Mutuku, 2016; Bargal *et al.*, 2025), we first summarize what is currently known about nanofluids and hybrid nanofluids for automotive cooling. Second, we find recurring gaps in formulation-structure-property relationships, particularly in the areas of electrical conductivity management in powertrains, corrosion/erosion compatibility, surfactant-free stabilization routes, viscosity–conductivity trade-offs at low loading, and dispersion stability under thermal/hydraulic cycling (Mane & Hemadri, 2022; Arora & Gupta, 2021; Islam *et al.*, 2017). Third, we list potential paths for environmentally friendly CNC–TiO_2 hybrid coolants: The combination of TiO_2's chemical stability and well-documented thermal/dispersion behavior in glycol–water matrices, along with CNCs' renewable, high-surface-area scaffolds with adjustable surface charge for colloidal stabilization, suggests a route to high keff at ultra-low φ with less dependence on persistent surfactants and better life cycle profiles (Suneetha *et al.*, 2022; Mateo *et al.*, 2021). This review aims to inform long-lasting, service-ready hybrid nanofluid formulations for next-generation automotive cooling by combining material selection with sustainability metrics (recyclability, embodied energy, and pressure drop) and system-level constraints (pumping power, electrochemical compatibility, and pump power).

NANOFLUIDS AND HYBRID NANOFLUIDS: CURRENT STATE

Effective thermal management is essential for durability, emissions reduction, and vehicle performance. Heat rejection efficiency is limited by the low thermal conductivity and high viscosity of conventional coolants, such as ethylene glycol (EG)/water mixtures (Di Battista *et al.*, 2023; Lakshminarayanan & Agarwal, 2022). Due to these restrictions, bigger radiators or more airflow are required (Mutuku, 2016).

To improve convective heat transfer and thermal conductivity, nanofluids—suspensions of nanoscale solids in base fluids—were introduced (Ozerinç *et al.*, 2010). According to automotive research, temperature gradients and Nusselt numbers are enhanced by oxide nanoparticles dissolved in EG or water/EG mixtures (Mutuku, 2016). However, integration is difficult due to increased electrical conductivity and viscosity at low nanoparticle concentrations, particularly in electrified subsystems (Islam *et al.*, 2017).

Hybrid nanofluids (HNFs), which combine multiple nanoparticle types, offer synergistic improvements in thermal conductivity, stability, and rheology. By pairing high-conductivity oxides with carbonaceous materials, HNFs achieve better performance at lower loadings (Suneetha *et al.*, 2022; Scott *et al.*, 2022). Studies report double-digit gains in radiator heat transfer metrics with optimized HNF formulations (Bargal *et al.*, 2025).

Stability remains a key concern. Dispersion longevity depends on surface chemistry and formulation methods, including surfactants and covalent functionalization. These approaches can suppress agglomeration but may affect viscosity and interfacial heat transfer. Sustainable alternatives like cellulose nanocrystals (CNCs) derived from agricultural waste are emerging as renewable stabilizers, offering tunable surface properties without relying on synthetic surfactants.

Hybrid Nanofluids

Co-dispersions of two or more types of nanoparticles, known as hybrid nanofluids (HNFs), have become sophisticated heat-transfer media that are intended to get around the drawbacks of single-component nanofluids. HNFs seek to achieve synergistic improvements in thermal conductivity (Keff), rheology, and dispersion stability at lower total solids loading by combining complementary phases like high-conductivity oxides (e.g., AlO_3, TiO_2) with carbonaceous particles (e.g., graphene, CNT) (Suneetha *et al.*, 2022; Scott *et al.*, 2022).

Optimized HNF formulations have shown double-digit gains in thermal performance metrics, such as radiator efficiency and heat-transfer coefficients, in automotive cooling applications (Bargal *et al.*, 2025). These benefits are ascribed to heterogeneous networks that preserve acceptable viscosity (μ) and stability under thermal/hydraulic cycling while promoting heat conduction through solid–

solid contacts, interfacial nanolayers, and percolation clusters. However, achieving these benefits requires precise control of particle–particle and particle–fluid interactions. Strategies such as surface functionalization, pH adjustment, and ultrasonication are commonly employed but introduce complexity and cost. Moreover, the behavior of HNFs cannot be linearly extrapolated from mono-nanofluids due to emergent phenomena like hetero-aggregation and interfacial structuring.

Stability remains a critical challenge. Surfactants and covalent functionalization can enhance zeta potential and suppress agglomeration but may also affect viscosity and interfacial heat transfer (Mane & Hemadri, 2022; Arora & Gupta, 2021). For example, SDS improved colloidal stability in graphene oxide/water systems compared to CTAB and Triton X-100, though thermal conductivity effects varied (Keklikcioglu Cakmak, 2019).

The importance of sustainability considerations is growing. For hybrid formulations, bio-derived cellulose nanocrystals (CNCs) made from agricultural waste provide low-toxicity, renewable platforms with adjustable surface chemistry (Mateo *et al.*, 2021; Kamelnia *et al.*, 2025). According to life cycle studies, if stability and compatibility are preserved, HNFs with CNCs can lower energy use and emissions over the course of service lifetimes (Cuce *et al.*, 2025). While CNCs enable surfactant-reduced stability at ultra-low loadings, the k improvements are delivered largely by TiO_2/Al_2O_3/graphene/CNT components.

Present research on HNFs and nanofluids for automotive cooling is summarized in this review, which also highlights foundational studies (Ozerinç *et al.*, 2010; Rahman *et al.*, 2024) and identifies gaps in formulation–structure–property relationships. The development of surfactant-free stabilization pathways compatible with electrified powertrains, managing viscosity–conductivity trade-offs, and preserving dispersion stability under cycling are important challenges (Islam *et al.*, 2017).

Base Fluids

The base fluid critically influences nanofluid performance by determining thermal conductivity (k), viscosity (μ), specific heat capacity (cp), and chemical compatibility. Water is widely used due to its high cp (~4.18 $kJ{\cdot}kg^{-1}{\cdot}K^{-1}$), low μ, and relatively high k (~0.6 $W{\cdot}m^{-1}{\cdot}K^{-1}$), enabling efficient convective heat transfer. However, its freezing point and corrosiveness limit standalone use in automotive systems (Rahman *et al.*, 2024). Oils are explored for niche applications requiring high boiling points or electrical insulation. However, their low k (~0.13–0.15 $W{\cdot}m^{-1}{\cdot}K^{-1}$) and high μ impose pumping penalties, limiting automotive use (Barai *et al.*, 2023).

With its high boiling points and freeze protection, ethylene glycol (EG) is the recommended antifreeze in automotive coolants. A 50:50 EG–water blend is appropriate for fuel-cell and internal combustion systems since it boils above 106°C and freezes close to -37°C. Research into EG-based nanofluids to restore thermal performance has been prompted by EG's lower k (~0.25 $W/m^{-1}{\cdot}K^{-1}$) and higher μ, which decrease heat transfer efficiency (Mutuku, 2016). In addition to increasing μ and electrical conductivity (σ), adding nanoparticles to EG–water mixtures can improve k. In electrified powertrains, for instance, TiO_2 nanofluids at 0.5 vol% increased σ by ~900% at 70 °C but improved k by ~10% (Islam *et al.*, 2017). Therefore, to balance thermal and electrochemical properties, ultra-low loading and surface functionalization are crucial.

EG–water blends remain the optimal choice for automotive nanofluids due to their balance of thermal performance, freeze protection, and material compatibility. Their widespread OEM adoption supports continued research into enhancing k and heat transfer coefficients (HTC) without redesigning system components (Lakshminarayanan & Agarwal, 2022; Di Battista *et al.*, 2023). To illustrate these improvements, Table 1 summarizes representative comparisons between single-component and hybrid nanofluids, using normalized metrics—thermal conductivity ratio (k/k_0) and viscosity ratio (μ/μ_0)—under reported conditions. All concentrations are expressed in wt%, and base fluid composition and temperature ranges are noted for clarity.

Table 1. Standardized comparison of single-component vs. hybrid nanofluids for automotive cooling.

Nanofluid type	Base fluid	Concen-tration (wt%)	Test conditions (t, flow)	K/k_0	M/μ_0	Performance metric	Reference
Al_2o_3 mono-nanofluid	Water	≤1.0	~25–60 °C, lab heat exchanger	1.10–1.20	↑ noticeable	HTC ↑ up to ~20%	Rahman *et al.* (2024)
Tio_2 mono-nanofluid	50:50 EG–Water	0.5	70 °C	1.10	↑ slight	Conductivity ↑; caution for EV stack	Islam *et al.* (2017)
Cuo mono-nanofluid	EG	~0.2	Boundary layer tests	–	–	Faster boundary temp decline	Mutuku (2016)
Cnt–gnp hybrid	EG; EG–Water (80:20)	0.5	~30–70 °C	1.13–1.16	Depending on surfactant	HTC ↑ 13–16%	Sanduru *et al.* (2024)
Al_2o_3/tio_2 hybrid	Water	0.1–0.5	Radiator tests, 60–90 °C	1.06–2.24	Manageable at low φ	Radiator HTC ↑ 6.3–124%	Bargal *et al.* (2025)
Mwcnt/tio_2 hybrid	EG	0.01	70 °C	1.17	Minimal change	Stable >4 weeks	Heshmatian *et al.* (2025)
Ternary hybrids (e.g., tio_2+$cofe_2o_4$+mgo)	Water	Model-based	MHD/radiation simulations	–	–	Nusselt number ↑	Yasmin *et al.* (2025)

EG-compatible hybrids that achieve ≥10% k gains at ≤0.1 wt% while maintaining stable dispersions over service intervals, controlling μ and σ, and guaranteeing materials compatibility with radiator alloys and elastomers present a near-term opportunity for automotive contexts where EG–water blends predominate. With the accumulation of experimental stability data sets (Sanduru *et al.*, 2024; Mane & Hemadri, 2022), the field is moving away from measuring individual properties and toward integrated system testing, which includes pump power, radiator loops, fouling/corrosion screening, and standardized reporting of critical parameters (particle size distribution, surface chemistry, dispersion protocol, and aging under thermal/hydraulic cycling).

SYNTHESIS AND STABILIZATION

The synthesis of nanofluids and hybrid nanofluids is essential for achieving optimal thermophysical properties and long-term stability. Two main methods are employed: the two-step method, where nanoparticles are first synthesized and then dispersed into the base fluid, and the one-step method, which combines synthesis and dispersion in a single process. While the one-step method offers better colloidal stability, the two-step method remains preferred for large-scale applications due to its flexibility and cost-effectiveness (Razzaq *et al.*, 2025).

Dispersion quality significantly affects thermal conductivity and flow behavior. Ultrasonication—especially probe-based—is widely used to break agglomerates and ensure uniform particle distribution. Probe ultrasonication provides higher energy density, resulting in smaller particle sizes and improved stability. Combining ultrasonication with pH control enhances zeta potential and reduces hydrodynamic diameter, improving colloidal stability (Sajid & Bicer, 2022). Combining ultrasonication with pH control enhances zeta potential and reduces hydrodynamic diameter, improving colloidal stability (Sajid & Bicer, 2022).

Surfactants facilitate dispersion as well. Nonionic surfactants provide steric hindrance, whereas ionic surfactants, such as CTAB and SLS, offer electrostatic stabilization. Their suitability for automotive coolants must be considered as foaming or thermal deterioration may compromise system dependability.

Surface functionalization and pH modification to boost electrostatic repulsion are two stability-enhancing techniques. Because of the interactions between heterogeneous particles, hybrid nanofluids typically exhibit greater stability than mono-nanofluids. However, they need specific stabilization procedures. Sustainable substitutes for synthetic surfactants are bio-based dispersants, like cellulose nanocrystals, which provide steric stabilization (Mane & Hemadri, 2022).

Thermophysical Properties

Particle size, shape, concentration (φ), and interfacial effects all affect hybrid nanofluids' thermal conductivity (k). Through increased interfacial area and Brownian motion, smaller particles (less than 50 nm) increase k; however, gains may be negated by excessive clustering or phonon scattering (Rahman *et al.*, 2024). Modified Maxwell models and experiments support the idea that high-aspect-ratio particles, such as carbon nanotubes (CNTs), form conductive networks that perform better than spherical inclusions (Elcioglu, 2025). Ultra-low loading hybrids are becoming more popular as increasing φ increases viscosity (μ) while simultaneously increasing k through percolation and nanolayer effects. For example, without surfactants, TiO_2/MWCNT in EG reached +16.7% k at 0.01 wt% and stayed stable for weeks (Heshmatian *et al.*, 2025).

Viscosity (μ) influences pressure drops and pumping power. In general, it decreases with temperature and increases with φ. System design becomes more difficult when non-Newtonian behavior is induced by anisotropic particles and surfactants. Trade-offs are demonstrated by hybrid systems: FeO_4+MWCNT in water produced +29% k but +50% μ at 0.3 vol%, whereas nanodiamond+FeO_4 in EG/water produced +14.6% k and +79% μ at 0.2 vol% (Mane & Hemadri, 2022). According to automotive research, the ideal convective performance is around 0.05 vol% (Aktas *et al.*, 2025). The choice of surfactants is important: anionic surfactants like SLS/SDS provide better balance, while CTAB increases μ while improving dispersion (Bayou *et al.*, 2025).

Specific heat (cp) and density (ϱ) shape transient thermal behavior. Typically, ϱ increases and cp decreases with φ, though exceptions exist due to nano-architecture effects. Electrical conductivity also rises with φ, posing risks in electrified systems—e.g., TiO_2 in EG–water increased conductivity by ≈900% at 0.5 vol% (Islam *et al.*, 2017). Thus, multi-objective design must balance k, μ, cp, and ϱ within system tolerances.

SUSTAINABILITY AND EMERGING TRENDS

Due to their high aspect ratio, high crystallinity, biodegradability, and rich surface hydroxyl chemistry, bio-derived cellulose nanocrystals (CNCs) are becoming popular as green stabilizers and functional additives for hybrid nanofluids. These properties combine to improve colloidal stability (both steric and electrostatic) and allow for interfacial tuning with inorganic phases (Trache *et al.*, 2020; García Betancourt & Osorio Aguilar, 2022). Length scale and crystallinity are now understood to be crucial to CNC surface reactivity and biological responses as safety-by-design takes center stage. This means that coolant formulations should favor moderate CNC lengths and controlled crystallinity to prevent undesired pro-inflammatory effects while maintaining dispersion advantages (Wang *et al.*, 2019). In this review, CNCs are positioned primarily as renewable stabilizers (steric/electrostatic), while thermal conductivity gains arise from the paired oxide or carbonaceous phases in the hybrid formulation.

Hybrid nanofluid studies provide evidence that CNCs can help reduce or eliminate surfactants and provide stability enhancement at ultra-low loadings. CNCs are a renewable stabilizer in carbon/oxide hybrids, as demonstrated by the stable dispersions of GNP–CNC hybrids in EG–water with temperature-dependent thermal conductivity datasets and high-fidelity ANN predictions (Hasan *et al.*, 2025; Rahman *et al.*, 2024). Bagasse-derived CNCs improve thermal stability and have reinforced elastomer matrices in materials that come into contact with coolants. These are helpful analogs for guaranteeing the compatibility and longevity of coolant-wetted components (Tohamy *et al.*, 2025). Table 2 shows some potential sources of biopolymers that have potential for hybrid nanofluids.

Table 2. Sources of biopolymers for hybrid nanofluids.

Biomass source	Extraction method (examples)	Key properties (aspect ratio, crystallinity, ζ)	Reference
Banana peel	One-pot microwave + mild H_2O_2 / H_2SO_4; Taguchi-optimized one-pot hydrolysis; alkali/bleach + acid	Crystallinity up to ≈ 85%; ζ ≈ −43 mV(20–209 nm); ζ ≈ −16.9 mV, crystallinity 21.46% under Taguchi; needle/spherical morphologies	Mohd Jamil *et al.* (2022); Zaini *et al.* (2024); Mishra *et al.* (2023)
Sugarcane bagasse	Ultrasonic-assisted sulfuric hydrolysis; esterification / silane coupling	Crystallinity ~70%; ζ ~−34 mV; enhanced thermal stability after surface modification	Tang *et al.* (2023)
Rice straw	Alkali–bleach–acid sequence; film formation tests	Thermal decomposition ~339 °C (native film); higher water susceptibility than bagasse films	Thongsomboon *et al.* (2023)

CNCs can be sustainably extracted from agricultural residues, aligning coolant innovation with waste valorization, with banana peel emerging as an abundant and viable feedstock. A one-pot microwave-assisted mild oxidative hydrolysis approach has been reported to yield CNCs with high crystallinity (≈85%) and a strongly negative zeta potential (≈–43 mV), indicative of excellent colloidal stability (Mohd Jamil *et al.*, 2022). In a related study, Taguchi-optimized one-pot hydrolysis produced CNCs with a particle size of approximately 152.6 nm, a zeta potential of ≈–16.9 mV, and controlled crystallinity, demonstrating the tunability of material properties through process optimization (Zaini *et al.*, 2024). Additionally, an alkali/bleaching pretreatment followed by acid hydrolysis achieved a CNC yield of ~29.9%, with particle sizes around 209 nm, a zeta potential of ≈–43 mV, and crystallinity of ~64%, confirming the robustness and reproducibility of banana-peel-derived CNC production across different chemical routes and laboratories (Mishra *et al.*, 2023).

Sugarcane bagasse is another high-volume residue: ultrasonic-assisted sulfuric hydrolysis produced CNCs with crystallinity ~70% and ζ ≈–34 mV; subsequent esterification/silane coupling improved thermal stability—valuable for EG-rich coolants (Tang *et al.*, 2023). Comparative valorization indicates bagasse generally shows higher thermal decomposition temperatures than rice straw—useful when selecting biopolymer sources for heat-exposed systems (Thongsomboon *et al.*, 2023). Broad agro-waste nanoparticle reviews conclude plant residues enable low-energy, low-cost routes to organic/inorganic nanomaterials, yet flag toxicity and process control as key scale-up challenges—caveats directly applicable to green hybrid nanofluids (Flores Contreras *et al.*, 2024).

From the perspective of the circular economy, converting bagasse and banana peels into CNCs creates value-added supply chains in areas with high agricultural outputs while lowering landfill loads and preventing emissions from open burning (Hossam & Fahim, 2023; Râpă *et al.*, 2024). Before claiming sustainability in service, coolant qualification protocols (dielectric, corrosion/erosion, fouling, and stability under thermal/hydraulic cycling) are necessary, according to circular economy meta-analyses that point out governance and standardization gaps (Teixeira, 2025; Purushothaman *et al.*, 2025). Green nanofluid frameworks for nanofluids track life-cycle toxicity, resource intensity, and end-of-life impacts while recommending biogenic nanoparticles and bio-derived dispersants (Cardoso *et al.*, 2025; Razzaq *et al.*, 2025).

Materials compatibility and durability in automotive cooling loops

The integration of hybrid nanofluids (HNFs) into ICE cooling systems must balance materials compatibility with long-term serviceability. Nanoparticles in EG–water blends can increase electrical conductivity which can rise galvanic risk for aluminum components. TiO_2 nanofluids in 50:50 EG–water have shown ~900% σ rise at 0.5 vol% and 70 °C (Islam *et al.*, 2017). Maintaining coolant chemistry within ASTM D3306 limits is important to control corrosion and inhibitor instability.

At high flow velocities, solids can cause erosion of pump impellers and seals. Also, sediments may obstruct radiator fins or heater cores. SAE J1034 (coolant concentrate, EG type) references ASTM D2809 for cavitation erosion corrosion of aluminum pumps which offers pertinent screening for HNFs. Ultra-low loadings (≤0.1 wt%) and surfactant-free dispersion have demonstrated double-digit k gains with over four weeks of stability in EG matrices. Consequently, it reduces the fouling risk while preserving rheology (Heshmatian *et al.*, 2025). Radiator level gains reported for oxide/oxide and carbon hybrids (e.g., Al_2O_3/TiO_2) should be interpreted as HTC improvements under specified conditions (Bargal *et al.*, 2025).

Because fouling and sludge accrue under thermal/hydraulic cycling, maintenance protocols should couple SAE/ASTM screening with drive-cycle-based transients (e.g., FTP-75, WLTC) to emulate on-road conditions. CNC-assisted steric stabilization and careful pH control can reduce surfactant reliance while supporting cleanability (Mateo *et al.*, 2021; Mane & Hemadri, 2022)

Techno-Economic Feasibility and Scalability Considerations

Economic viability is a critical factor for transitioning hybrid nanofluids (HNFs) from laboratory formulations to automotive service. Conventional glycol-based coolants typically cost between $2–$4 per liter. Preliminary estimates for CNC–TiO_2 hybrids however suggest material costs of $20–$50 per liter at laboratory scale. (Cardoso *et al.*, 2025).

Large-scale CNC extraction from agro-waste can reduce costs significantly. Taguchi-optimized one-pot hydrolysis routes report yields of ~30% with low energy input (Zaini *et al.*, 2024). However, techno-economic analyses (TEA) indicate that achieving cost parity with conventional coolants requires economies of scale and integration with existing biorefinery infrastructure (Cardoso *et al.*, 2025). Nanoparticle synthesis costs especially TiO_2 and carbonaceous additives remain a bottleneck unless it was sourced from industrial by-products or is optimized for low-temperature processes (Mateo *et al.*, 2021).

OEM scalability also depends on supply chain readiness and compliance with ASTM and SAE standards. Lifecycle considerations such as recyclability and reduced pumping power can offset initial expenses by lowering operational energy consumption and emissions over service life (Cuce *et al*., 2025). Future research should incorporate TEA frameworks alongside life cycle assessments (LCA) to benchmark CNC–TiO_2 hybrids against other incumbent coolants (Cardoso *et al*., 2025).

CRITICAL ANALYSIS AND FUTURE DIRECTION

Despite promising results for TiO_2-based and carbonaceous hybrids at ultra-low loadings, systematic studies on CNC–TiO_2 hybrids in EG–water coolants remain scarce. CNCs offer renewable stabilization and TiO_2 provides chemical robustness, yet their combined use is largely limited to proof-of-concept work rather than validated automotive systems (Rahman *et al*., 2024; Heshmatian *et al*., 2025). This gap precludes benchmarking against established hybrids for radiator applications (Bargal *et al*., 2025).

Generalization is further constrained by methodological variability. In glycol-rich media, dispersion is impacted by the significant effects of CNC extraction routes (e.g., microwave oxidative vs. alkali-bleach-acid) and post-functionalization strategies on crystallinity, aspect ratio, and zeta potential (Mohd Jamil *et al*., 2022; Tang *et al*., 2023). Cross-study comparability is hampered by inconsistent reporting of φ, particle size, and k/μ measurement protocols (Manimaran *et al*., 2025). There is an urgent need for a minimum information standard.

It is still technically difficult to achieve steric or electrostatic stabilization without being overly viscous. Surfactants enhance stability but frequently raise μ and introduce foaming risks; even a small increase in φ can cause μ to rise sharply (Mane & Hemadri, 2022). These problems are lessened by CNCs, but their length scale and crystallinity need to be adjusted to balance electrochemical safety, rheology, and k gains (Wang *et al*., 2019; Hasan *et al*., 2025).

Device-level validation is lacking. Reported thermal performance gains (6.3–124%) focus on oxide–oxide or carbon hybrids; CNC-containing coolants have not been tested in strip-fin or louvered-fin radiators under realistic duty cycles (Aktas *et al*., 2025). Durability under thermal/hydraulic cycling, fouling, and corrosion remains uncharacterized. Sustainability assessments are similarly immature: while agro-waste CNCs promise circular economy benefits, LCA and TEA for coolant-ready hybrids are absent (Cardoso *et al*., 2025; Teixeira, 2025).

In order to maximize zeta potential and wettability while reducing environmental impact, future research should focus on low-acid, one-pot CNC extraction (such as microwave-assisted hydrolysis) with benign surface modifications. Percolative heat-transfer networks at ≤0.1 weight percent could be made possible by ligand-assisted TiO_2 assembly on CNC scaffolds, limiting μ rise to single digits (Heshmatian *et al*., 2025). According to Islam *et al*. (2017), OEM-standard EG-water loops require comparative testing for k(φ,T), μ(φ,T), σ(T), cp/ϱ, pump power, Δp, and electrochemical safety. It is crucial to have standardized procedures for surfactant-free concentrates, quality characteristics (DLS size/PDI, zeta potential), and reclaim/recycle tactics. Finally, CCD/RSM campaigns in conjunction with CFD and ML surrogates ought to map multi-response surfaces for k–μ–σ and direct radiator-level optimization under variable duty cycles (Aktas *et al*., 2025; Hasan *et al*., 2025). Beyond CNC–TiO_2, oxide–carbon hybrids (e.g., Al_2O_3–graphene, SiO_2–CNT) and magnetic systems (e.g., Fe_3O_4-based) show strong thermal potentials but often trade increased viscosity or electrochemical complexity for performance.

Electrical conductivity is an important parameter for nanofluids in automotive cooling loops. Emerging EV platforms have imposed additional constraints including stringent dielectric strength and low ionic contamination to prevent short circuits in battery modules. ASTM D3306 and SAE

J1034 standards for glycol-based coolants do not fully address these requirements. The ionic leaching from nanoparticles or surfactants can compromise insulation in the vehicles cooling loops. Thus, making ultra-low loading and surfactant-free stabilization is important for future EV-compatible formulations. These considerations show the need for multi-objective design strategies. The strategies should balance thermal conductivity, viscosity, and electrochemical safety across diverse automotive architectures (Islam *et al.*, 2017; Mane & Hemadri, 2022).

CONCLUSION

This review highlights that hybrid nanofluids can deliver double-digit thermal gains at ultra-low loadings, yet their translation to service hinges on stability, rheology, and electrochemical safety. CNCs offer a renewable, tunable platform for stabilizing hybrids and reducing reliance on persistent surfactants; TiO_2 contributes chemical stability and coolant familiarity. However, CNC–TiO_2 remains under-explored specifically for automotive EG–water systems, and standardized protocols for synthesis, characterization, and reporting are urgently needed. Robust radiator-loop validations are rare, and life-cycle/cost evidence is still missing.

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