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Review

Nanofluids for Advanced Applications: A Comprehensive Review on Preparation Methods, Properties, and Environmental Impact

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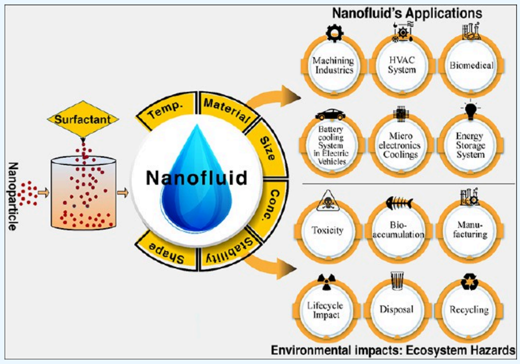
ABSTRACT: Nanofluids, an advanced class of heat transfer fluids, have gained significant attention due to their superior thermophysical properties, making them highly effective for various engineering applications. This review explores the impact of nanoparticle integration on the thermal conductivity, viscosity, and overall heat transfer performance of base fluids, highlighting improvements in systems, such as heat exchangers, electronics cooling, PV/T systems, CSP technologies, and geothermal heat recovery. Key mechanisms such as nanolayer formation, Brownian motion, and nanoparticle aggregation are discussed, with a focus on hybrid nanofluids that show enhanced thermal conductivity. The increase in viscosity poses a trade-off, necessitating careful control of the nanoparticle properties to optimize heat transfer while reducing energy consumption. Empirical data show up to a 123% increase in the convective heat transfer coefficients, demonstrating the tangible benefits of nanofluids in energy efficiency and system miniaturization. The review also considers the environmental impacts of nanofluid use, such as potential toxicity and the challenges of sustainable production and disposal. Future research directions include developing hybrid nanofluids with specific properties, integrating nanofluids with phase change materials, and exploring new nanomaterials such as metal chalcogenides to enhance the efficiency and sustainability of thermal management systems.



■ INTRODUCTION

Nanofluids are advanced colloidal systems made of nanoparticles, typically metal oxides or carbon-based materials dispersed in conventional base fluids like water, ethylene glycol, or oil. The addition of nanoparticles increases the thermal conductivity convective heat transfer rates and viscosity of the fluid due to their high surface area-to-volume ratio and enhanced thermal properties. This leads to improved thermophysical behavior, making nanofluids suitable for high-performance cooling systems, heat exchangers, and industrial thermal processes. Nanofluids offer a cutting-edge solution for thermal management and energy systems. The concept of nanofluids was introduced in 1995 in response to the growing industrial demand for more efficient heat transfer systems.[1] Nanofluids are specialized fluids that incorporate nanoparticles usually smaller than 100 nm dispersed within a base liquid such as ethylene glycol, water, or oil.[2] Dispersal of these nanoparticles within the base fluid creates a stable suspension that substantially enhances thermal properties compared to traditional liquids. This enhancement primarily results from the intensified random motion of nanoparticles, which induces greater turbulence within the fluid, minimizing thermal resistance and improving the overall heat transfer effectiveness. Given these characteristics, nanofluids have attracted significant interest for their possible application in several fields such as automobile radiators, heat exchangers, solar energy systems, and electronic cooling mechanisms.[3]

Previous research has shown that incorporating nanoparticles into mediums like water, mineral oil, or engine oil can significantly enhance these fluids' thermophysical and rheological properties. This enhancement is crucial for improving heat extraction capacity, which plays a crucial role in boosting heat transfer efficiency and reducing energy consumption central goals in current research. One promising strategy for enhancing heat transfer involves including materials with higher thermal conductivity with the base fluid. Over the years, researchers have focused on employing very small solid particles scattered in fluids to improve heat transfer efficiency.[4,5] Advancement of hybrid nanofluids, which blend different base fluids and nanoparticles, has led to their widespread application across industries such as machining,

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cooling systems, biomedical fields, and energy storage. Figure 1 highlights the broad applications of nanofluids. However,

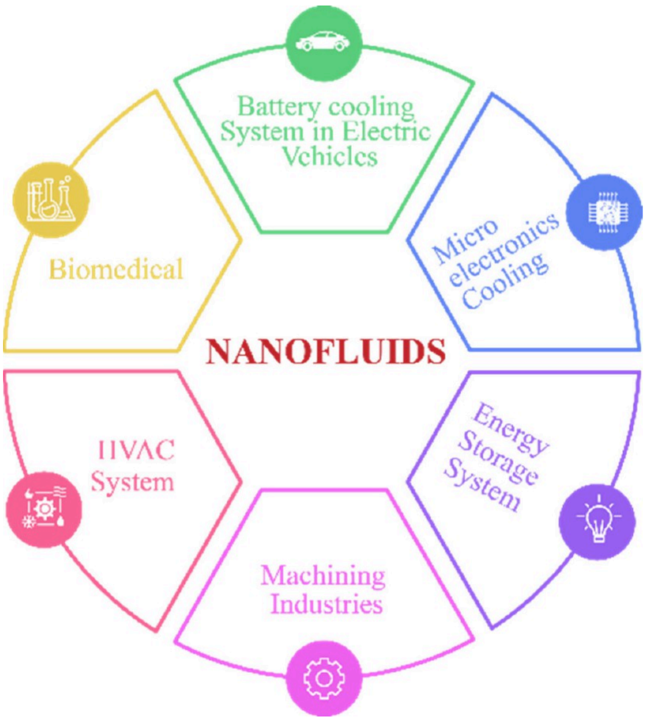

Figure 1. Application of nanofluids.

challenges associated with nanofluids include particle aggregation, clogging of flow channels, erosion of transmission devices, sedimentation, and pressure loss. Particle resettling can result in slurry formation, enhanced thermal resistance, and reduction in the fluid's heat transfer efficiency. Dong et al.[6] researched the conductivity of nanocopper particles and observed that adding copper nanoparticles at concentrations below 1% significantly improved the conductivity of ethylene glycol and oil. Subsequent studies explored the thermal conductivity of Al_2O_3 nanofluids mixed with ethylene glycol and water at various volume concentrations and temperatures.A 50:50 weight solution of water and ethylene glycol served as the base fluid. The results indicated that, under identical volume concentration and temperature conditions, the CuO nanofluid demonstrated superior thermal conductivity as compared to simple nanofluid.[7,8] The synthesis, application, and disposal of nanoparticles in manufacturing processes inevitably result in their release into the environment, including air, soil, and water systems. Therefore, it is essential to assess and mitigate any potential environmental impacts. A widespread understanding of the quantity, behavior, fate, and toxicity of engineered nanoparticles in natural aquatic environments is critical for evaluating their environmental health risks.

Recent research has broadened the scope of nanofluid analysis to include the analysis of hybrid nanofluids. Hybrid nanofluids combine two or more nanoparticles in a base fluid to offer superior thermal properties and heat transfer performance. These fluids provide enhanced stability and improved flow characteristics by leveraging the combined effects of different nanoparticles. The unique composition of hybrid nanofluids results in better control over the thermal conductivity and viscosity, making them effective in cooling and energy applications. They are designed to meet specific engineering demands in processes that require efficient heat transfer systems, thereby offering improved characteristics that surpass those of nanofluids, including a single type of nanoparticle. The main goal in developing HNFs is to optimize both rheological and thermal characteristics beyond the capabilities of conventional nanofluids. Compared with traditional nanofluids, HNFs are anticipated to demonstrate superior thermal conductivity. However, the body of experimental and numerical research on hybrid nanofluids remains limited.[9] Phase change materials play a critical role in the nanofluid field, with advancements being pivotal for the development of environmentally sustainable and efficient systems. Similarly, the integration of green solvents in battery metal recycling is essential, with organic acids identified as the most effective due to their high efficiency, cost-effectiveness, and scalability for industrial applications in sustainable recycling processes.[10,11] The current review clearly indicates that nanofluids show enhanced thermal conductivity, which generally improves with volumetric nanoparticle concentrations. This review highlights this emerging class of fluids, distinguishing them from traditional colloids, which, like nanofluids, have been in use for a considerably longer time.

Stable nanofluids with uniformly dispersed nanoparticles are essential for maintaining optimal viscosity in suspensions. When aggregation occurs due to van der Waals forces or Brownian motion, the viscosity of the nanofluid increases, which leads to reduced flowability and diminished heat transfer. Nanoparticle clustering obstructs fluid motion, increasing resistance and lowering thermal conductivity. Surface modifications such as surfactant addition or pH control enhance nanofluid stability by minimizing aggregation and maintaining low viscosity. Achieving the ideal balance between thermal conductivity and viscosity relies on improving stability, as shown in surfactant-enhanced nanofluids with controlled nanoparticle dispersion. Acquiring stable nanofluids is crucial for improving their thermal performance.[12] Ideal nanofluids should possess low viscosity, have high thermal conductivity, be cost-effective, and have good stability.[13] Improvement in heat transfer, which is linked to a nanofluid's thermophysical properties, largely depends on the nanofluid's distributive stability in the fluid.[14] Several features, considering the characteristics of both base fluids and nanoparticles, play an important part in this stability. For example, SiO_2-EG/DW nanofluids have demonstrated stability for up to 36 months. The nanofluid's stability is closely correlated to the types and concentration of surfactants used. Crucial micelle concentration is the absolute concentration of the surfactant at which the synthesis of polymers begins. Research indicates that a 1 CMC concentration of CTAB surfactant provides improved reinforcement and stability for Al_2O_3-water nanofluids in comparison to a 0.5 CMC concentration.[15] Al_2O_3-water nanofluids using CTAB demonstrate more than a 50% increase in stability duration compared with those including SDS surfactant. Studies comparing functionalized MWCN and SiO_2 nanofluids revealed that the inclusion of ink for a surfactant cause the graphene nanofluids to have a zeta potential of −51.4 mV.[16] However, a significant scale of nanoparticle aggregation can lead to increased viscosity and reduced nanofluid thermal conductivity. Nonuniform distribution and aggregation of nanoparticles may also cause flow obstruction and degrade the heat transfer performance of nanofluids.[17] Nanofluid stability is also closely linked to its electrical properties. A thicker

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Table 1. Summary of Recent Review Papers on Nanofluids

Author	Year	Main conclusions	ref.
García-Rincón et al.	2024	Nanofluid stability, enhanced by surfactants and preparation methods, is key for improving long-term thermal efficiency in solar collectors.	34
Islam et al.	2024	Enhance thermal conductivity by 27−84%, benefiting biomedical research, heat transfer, energy transportation, and cutting fluids using trihybrid nanofluid.	35
Yang et al.	2023	To improve nanofluid stability, emphasizing that optimal stability achieved at pH values between 4 and 9 and below 2% concentration is crucial for enhancing heat transfer efficiency.	36
Ma et al.	2022	Thin-layer or single-layer MXene nanofluids demonstrate enhanced stability, superior light absorption, and higher thermal conductivity in comparison with their multilayer counterparts, owing to their rich surface chemistry and high specific surface area.	37
Panchal et al.	2022	Surfactants such as SDBS, SDS, and PVP are highly compatible with metal oxide nanofluids, while GA, CTAB, and oleic acid are more appropriate for carbon-based nanofluids.	38
Said et al.	2022	Incorporating nanofluids into solar desalination systems boosts production of freshwater by approximately 30−40%. Al_2O_3 and SWCNT are the most suitable nanoparticles for achieving this enhancement. With chemical stabilization, nanofluids can maintain stability for up to 90 days.	39
Urmi et al.	2021	SiO_2 nanofluids can achieve a maximum stability time of up to 6 months.	40
Yildiz et al.	2021	Nanoparticles added to nano lubricants decrease friction losses, resulting in reduced energy consumption at low ratios. However, as the fraction ratios are bigger, there is a tendency for friction losses to grow, which detrimentally impact on the working of the system.	41
Sofiah et al.	2021	Vegetable oils are favored as alternatives to conventional heat transfer fluids because they are widely available, cost-effective, and biodegradable.	42

electrical double layer forms at the surface of the nanoparticles, preventing clustering and thus improving stability. The optimal pH values, which depend on factors like type of nanoparticles, volume fraction, fluid temperatures, and thermal properties, are critical for preventing aggregation.[18] For instance, a nanofluid's stability with SDBS and CTAB surfactants is usually reached at a pH of below 6.[19] Enhancing the nanofluid's thermal conductivity correlates with an enhancement in zeta potential values. The ideal pH range, which primes the highest thermal conductivity to the lowest viscosity, is between pH 4 and 9, making it suitable for practical applications where improved dispersion stability is required.

Nanoparticle aggregation significantly affects the viscosity of nanofluids, as it is driven by thermodynamic properties and interaction forces. Due to Brownian motion, nanoparticles collide and form secondary particles, which can further merge into larger aggregates. As these aggregates grow, they increase the fluid's viscosity, leading to higher resistance to flow. Once the aggregation exceeds a certain size, sedimentation occurs, resulting in instability and degraded performance of the nanofluid due to elevated viscosity.[20] Nanoparticles exhibit a significant surface area, and as their dimensions are decreased to approximately 1 nm, a substantial sum of atoms becomes concentrated on the surface of the particle. Such a high concentration leads to inadequate atomic arrangement and increased surface energy, which promotes aggregation.[21] To address the instability resulting from the intense surface movement and interactions in nanoparticles, it is crucial to reduce the effects by reducing high surface energy and chemical movement present in nanoparticles. The stability of small-sized nanoparticles in suspension is mostly determined by van der Waals forces,[22] gravity forces,[23] and electrostatic forces. When electrostatic repulsion produced by an electrical double layer surrounding particles surpasses the van der Waals attraction among them, nanoparticles achieve uniform dispersion within the medium, resulting in a stable nanofluid.[24] Covalent and noncovalent functionalization of multiwalled carbon nanotubes in nanofluids demonstrates significant thermal conductivity enhancements and stability, with covalently modified nanotubes showing the best steadiness at around 7%.[25] Al_2O_3-GO hybrid nanofluids enhance thermal conductivity by up to 4.34% and reduce viscosity by 4.6% compared to mono nanofluids.[26] Cu-Al/Ar hybrid nanofluids enhance thermal conductivity up to 14.48% compared to Cu/Ar nanofluids, attributed to higher Brownian motion velocity and unit nanolayer density.[27] Hybrid nanofluids enhance thermal conductivity by up to 34.3% over Cu nanofluids, due to stronger Brownian motion and looser aggregation morphology.[28]

Nanofluids are prepared using two main techniques based on nanoparticle dispersion mechanisms to ensure optimal distribution and stability within the base fluid while maximizing thermal and rheological properties for improved heat transfer performance, a one-step method[29] and a two-step method.[30] Nanofluid stability is influenced by various factors, including the materials used, the nanofluid's temperature, and also the size, shape, and nanoparticle concentration. Higher particle density and larger particle sizes generally lead to a worse dispersion stability in nanofluids. The likelihood of nanoparticle collisions increases with higher volume fractions, leading to significant aggregation and reduced stability.[31] To enhance the nanofluid's stability, both physical and chemical approaches are employed. Physical methods involve reducing nanoparticle size primarily through ultrasonic oscillation and the agitation of nanofluids.[32] On the other hand, chemical methods include adjusting the liquid's pH and adding various surfactants to alter the nanoparticle's surface properties.[33] The strategies mentioned modify the surface characteristics of particles and disrupt the interactions among nanoparticles during the aggregation activity.

Thermal characteristics and nanofluid stability are critical yet inconsistently studied areas in current research, with significant gaps in understanding the impacts of variables such as surfactant separation, particle clustering, fluid temperature, and particle geometry on thermal conductivity. Further research is essential to optimize these parameters for an enhanced thermal performance. The biomedical field is increasingly using nanofluids for sensing and imaging, spurring rapid commercial development. However, this also raises concerns about the environmental impact of nanoparticle production, use, and disposal, highlighting the need for accurate predictions of nanoparticle behavior in natural environments. The realistic usage of nanofluids is heavily affected by the thermal conductivity, which is influenced by

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various factors. These factors include nanoparticle concentration, preparation techniques, use of surfactants, ultrasonic treatment, pH levels, surface modifications, and the presence of magnetic fields in ferromagnetic fluids. For hybrid nanofluids, their thermal conductivity particularly relies on the synergistic effects that arise from the interactions between the different types of nanoparticles. Addressing the challenges of nanoparticle aggregation and long-term stability through comprehensive research is crucial. This will facilitate the development of nanofluids as efficient heat transfer media and support their large-scale, energy-efficient applications in various industries. Recent work on nanofluids is detailed in Table 1.

2. PREPARATION OF NANOFLUIDS

Nanofluid preparation is a complex process that requires precise steps to optimize thermal conductivity by achieving uniform nanoparticle dispersion along with effective mixing techniques and stabilization under controlled environmental conditions to ensure consistent performance.[43] The two prevalent methods for NF preparation are the single-stage and two-stage processes, each with distinct advantages and limitations.[44] In both methods, the role of surfactants and stabilizers is crucial to preventing nanoparticle agglomeration and maintaining long-term stability. Surfactants function by adsorbing onto the surfaces of nanoparticles, reducing interparticle forces and promoting electrostatic or steric stabilization. This results in a higher surface charge, which prevents particle aggregation and ensures uniform dispersion within the base fluid. However, a significant challenge arises when nanofluids are exposed to high temperatures. Surfactants may degrade or desorb at elevated temperatures, diminishing their stabilizing effect and leading to nanoparticle agglomeration, which negatively impacts the thermal performance of the nanofluid. Surfactants are indispensable for improving nanofluid stability, and their use at high temperatures is critically evaluated to avoid performance degradation.

Figure 2 presents a detailed overview of various nanoparticle categories, surfactants used for stabilization, and corresponding nanofluid types. The careful selection of preparation method and surfactant is essential for tailoring nanofluids to specific applications, especially in systems requiring high thermal performance under extreme conditions.

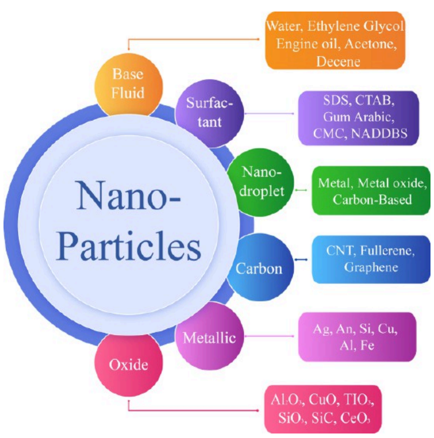

Figure 2. NPs, surfactants, and HNF types.

2.1. Single-Stage Preparation Process. The single-stage preparation method involves the simultaneous synthesis and dispersion of nanoparticles directly within the base fluid, resulting in a homogeneous suspension that improves the thermal properties of the nanofluid. This process is illustrated in Figure 4a. In the single-stage method, nanoparticles are directly synthesized in the base fluid via processes like ultrasonic dispersion or high-shear mixing, where key parameters include nanoparticle concentration (0.1−5%), fluid temperature (typically room temperature to 80 °C), and mixing time (30 min to several hours). The nanoparticles are either presynthesized or generated during the process, ensuring uniform dispersion. Surfactants or stabilizers may be added to enhance the stability and prevent agglomeration. The dispersion is performed under controlled conditions to ensure a stable and homogeneous nanofluid.[45] Table 2 provides examples of experimental studies involving nanofluids prepared via the single-stage method. One of the challenges associated with this method is the difficulty of separating nanoparticles from the base fluid to obtain dry particles, Nonetheless, the single-stage method offers advantages, including reduced nanoparticle agglomeration, enhanced stability of the fluid,[46] and the exclusion of intermediary processes like storage, drying, dispersion, transportation, sonication, and stirring.[47] The advantages and disadvantages of the one-step method are illustrated in Figure 3a. Other methods used for single-step nanofluid preparation include the polyol process, microwave irradiation, plasma discharge, physical vapor condensation, and the phase-transfer method.

2.2. Two-Stage Preparation Process. The two-stage preparation method is a widely utilized approach for nanofluid fabrication, where nanoparticles, nanofibers, or nanotubes are first synthesized as dry powders using various chemical or physical techniques. The two-step preparation method involves the separate synthesis and dispersion of nanoparticles into the base fluid. First, nanoparticles are synthesized through chemical or physical methods, typically in dry powder form, and then dispersed in the base fluid using ultrasonic or high-shear mixing. Key parameters include nanoparticle size (typically 10−100 nm), concentration (0.1−5%), fluid temperature (room temperature to 80 °C), and dispersion time (30 min to several hours). Surfactants or stabilizers are added to enhance stability and prevent aggregation, with the process carried out under controlled conditions to achieve uniform dispersion and prevent nanoparticle sedimentation (refer to Figure 4b). Such a method is straightforward and economical for large-scale nanofluid manufacture, particularly due to the industrial scalability of nano powder production and its direct application in the preparation procedure. A considerable weakness is the tendency of nanoparticles to aggregate during the drying, storage, and transportation phases, driven by solid van der Waals forces.[48] This aggregation can conduct sedimentation in nanofluids, causing issues such as settling, microchannel blockage, and reduced thermal conductivity. Figure 3b illustrates the advantages and disadvantages of the one-step method. The following problems could be mitigated by adding surfactants (avoiding high temperatures) to base fluid, which reduces size of nanoparticle clusters and results in a uniform colloidal suspension.[49,50] Table 2 exhibits experimental studies of the nanofluid preparation process.

2.3. Phase Transfer Procedure. In addition to these two processes, numerous alternative methods have been extensively discussed in the literature, each offering unique advantages for nanofluid preparation. These approaches contribute to improving the dispersion, stability, and thermal performance

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Table 2. Overview of Nanofluid Preparation Techniques and the Duration of Stability

Nanofluid	Particle size (nm)	Base fluid	Stabilization method	Stability duration (Zeta potential)	ref.
α-Al_2O_3, hBN	α-Al_2O_3 40, hBN 70	EG/DI water	1 to 4 h stirring and ultrasonication	30.8 mV	54
ZnO, GO	17	Distilled water	2−3 h stirring and ultrasonication	>49 days	55
SiO_2/Ag	Ag 15; SiO_2 20	water	Ultrasonication (750 W, 50 kHz)	>240 h	56
ZrO_2, SiC	ZrO_2 20, SiC 45−65	Distilled water	1 to 4 h	>17 days	57
			Stirring and ultrasonication		
Fe_3O_4	20	water	30 min ultrasonication, 30 min magnetic stirrer,	>21 days	58
Nanodiamond Fe_3O_4	21	Ethylene glycol water (20:80%, 40:60%, and 60:40%)	2 h ultrasonic bath	>72 h	59

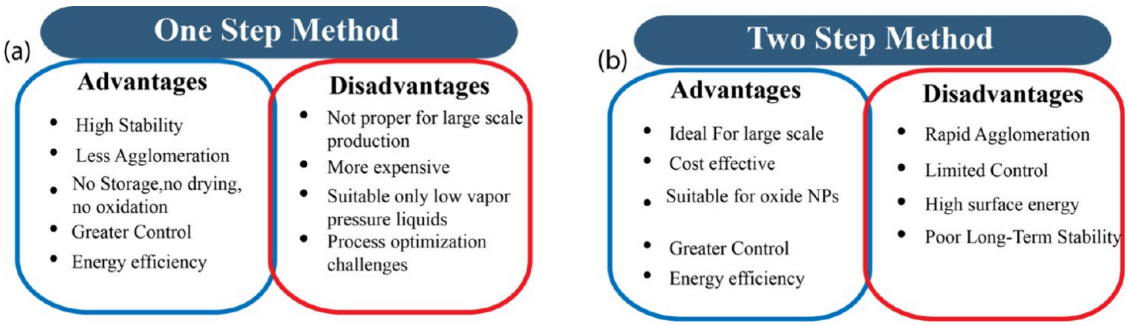

Figure 3. Advantages and disadvantages of (a) one-step method and (b) two-step method.

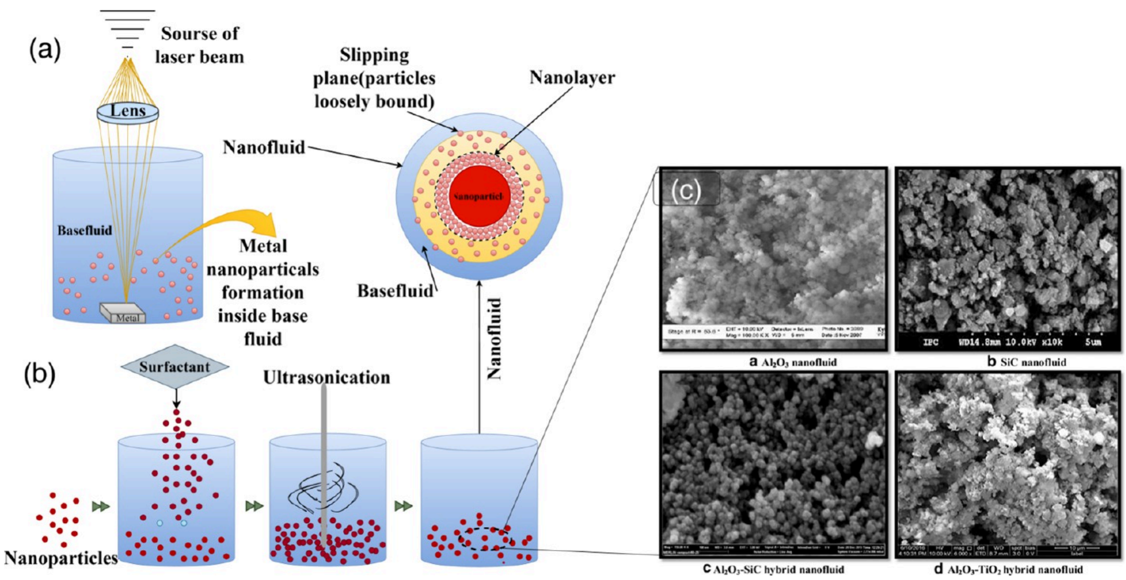

Figure 4. Preparation procedure of nanofluid comprising two methods: (a) the one-step approach and (b) the two-step method. (c) SEM images for the 0.1 wt % fraction of Al_2O_3 nanofluid, silicon carbide nanofluid, Al_2O_3-SiC hybrid nanofluid, and Al_2O_3-TiO_2 hybrid nanofluid.

of nanofluids across various applications. Similarly, kerosene-based Fe_3O_4 nanofluids can be produced through the phase transfer approach, maintaining consistent thermal conductivity over time; this is achieved by grafting oleic acid onto the Fe_3O_4 surface to make it kerosene compatible. Feng et al.[51] developed a multiphase intermittent spray cooling technique using Al_2O_3 nanofluids, revealing optimized heat transfer performance at 0.7% mass fraction, which can inform energy-efficient cooling systems for engineering vehicles. Zhang et al.[52] introduced a microfluidic approach for controllable synthesis of stable boehmite nanofluid, achieving enhanced boiling heat transfer performance for electronic cooling applications. For synthesizing copper nanoparticles, researchers developed a continuous flow microfluidic microreactor, allowing the microstructure and characteristics of nanofluids to be modified by adjusting variables such as flow rate, concentration, and additives. Wang et al.[53] reviewed methods for enhancing nanofluid stability, highlighting its influence on heat transfer efficiency and outlining challenges for future research and commercialization.

3. STUDY AND ANALYSIS OF NANOFLUID ON THERMAL CONDUCTIVITY

3.1. Thermal Conductivity. Thermal conductivity (k) is a key thermophysical property that quantifies a material's ability

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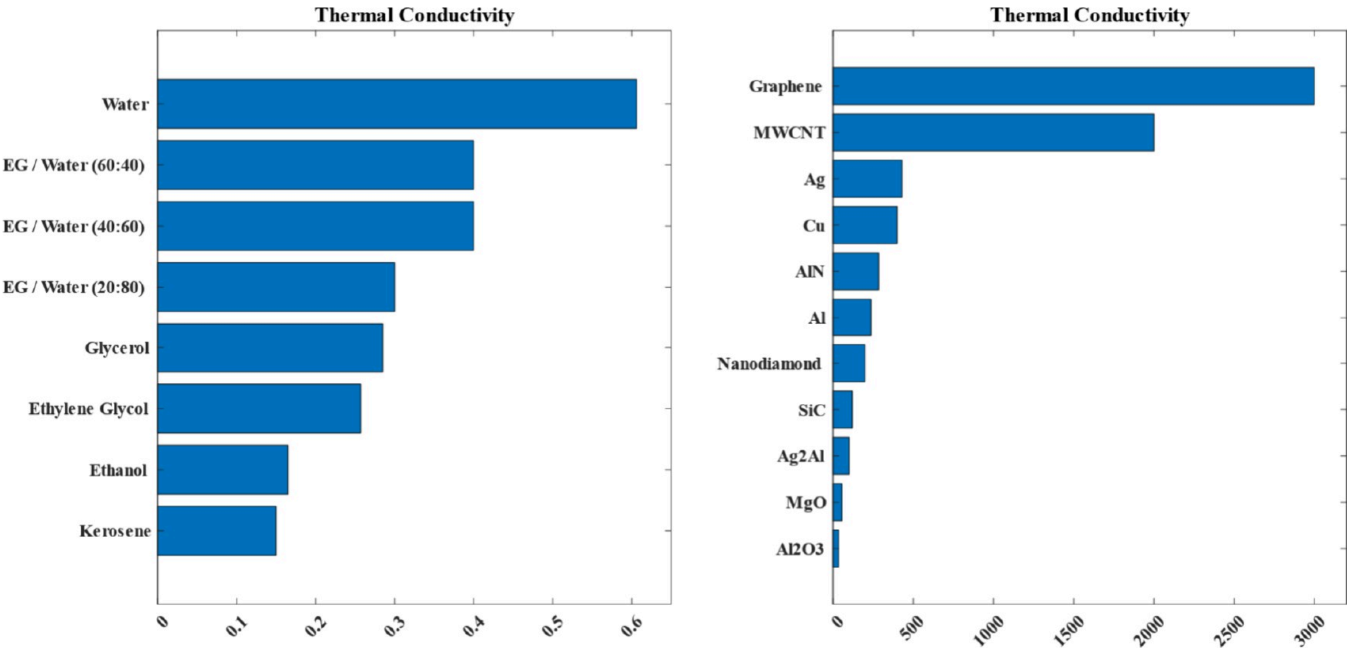

Figure 5. Analysis of the thermal conductivity of nanoparticles in base fluids.

to facilitate heat transfer. It is mathematically expressed to characterize the rate of heat conduction through a material, directly impacting its thermal performance across various engineering applications. This property is crucial in optimizing heat transfer efficiency in systems such as energy management, electronics cooling, and industrial heat exchangers.

$$k = \frac{Q/A}{\mathrm{d}T/\mathrm{d}x} \tag{1}$$

Here Q denotes heat flow across region A, whereas $\mathrm{d}T/\mathrm{d}x$ shows the change in temperature for a given distance $\mathrm{d}x$. Thermal conductivity, expressed in W/(mK), quantifies the amount of heat in watts that can be conducted through a material with a thickness of 1 m when it exhibits a temperature differential of 1 K across its two sides. Figure 5 depicts thermal conductivity values of the base fluid and several nanoparticles.

3.1.1. Mechanisms behind Enhanced Thermal Conductivity in Nanofluids. Amalgamation of nanoparticles into the conventional heat transmission of fluids frequently leads to a significant improvement in thermal conductivity, which cannot be fully elucidated or calculated by classical models. Although research is still being conducted, the precise mechanisms responsible for this improved thermal conductivity are not fully known and are a topic of contention among scientists. During the last 20 years, there has been extensive debate about the features that influence the improvement of a nanofluid's thermal conductivity. The improvement is widely acknowledged by researchers as being influenced by several processes identified in prior investigations. These mechanisms are typically condensed as follows:

- nanolayer creation occurring over the surface of nanoparticles
- nanoparticles undergoing Brownian motion
- mechanism of heat transfer in the nanofluid
- nanoparticle clustering or agglomeration

Thermal performance in nanofluids is influenced by several factors, including the nanoparticle type, concentration, size, and interparticle interactions. While mechanisms such as Brownian motion and heat transfer play a role, their significance diminishes at low nanoparticle concentrations or when particle sizes are in the nanometer range. The enhancement in thermal conductivity is primarily attributed to the formation of a nanoscale interfacial layer between nanoparticles and the base fluid, which serves as a thermal conduit.[60] Nanoparticle clustering or agglomeration further improves heat transfer by increasing the effective thermal contact between particles and the fluid. These mechanisms are extensively discussed in the literature, and additional explanation is unnecessary. The major challenge lies in developing a unified model that accounts for the interplay among these factors. Over the past decade, significant attention has been devoted to understanding the factors that contribute to thermal enhancement in nanofluids, with Brownian motion facilitating nanoparticle dispersion and enhancing particle—fluid interactions. Adsorption-induced stacking at the particle—fluid interface improves thermal contact, and thermophoresis accelerates heat transfer by driving nanoparticles toward cooler regions in a thermal gradient. These combined effects contribute to the superior thermal performance of nanofluids, and understanding their dynamics is crucial for optimizing their use in advanced thermal systems. Various mathematical models have been developed to substantiate these mechanisms, often compared to empirical data for validation.

3.1.2. Theoretical Models for Thermal Conductivity of Nanofluids. Heat transfer abilities of a solid/fluid mixture could be enhanced by combining a solid material with maximum thermal conductivity and a fluid with minimum thermal conductivity. The technique of enhancing heat transmission by elevating thermal conductivity within colloids has been a topic of interest since the late 1800s; therefore, it is not a novel method. For determination of a nanofluid's thermal conductivity, several traditional models are commonly used. Maxwell initially created a theoretical model in 1881 that accurately connects the effects on thermal conductivity with

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variables like the size of a particle, the particle's thermal conductivity, and fluid as explained in eq 2.

$$\frac{k}{k_f} = \frac{k_p + 2k_f + 2\phi(k_p - k_f)}{k_p + 2k_f - 2\phi(k_p - k_f)} \quad (2)$$

Here in Maxwell's model, k_p indicates the particle's thermal conductivity, k_f represents the fluid's thermal conductivity, and ϕ represents the particle's volume fraction. The criteria for this model are that k_p is significantly more than k_f and ϕ is much less than 1. Such a model is suitable for spherical particles. Given the notable disparity in thermal conductivity between particles and fluid, together with the lower concentration of particles, the model predicts a direct association among thermal conductivity and particle concentration, as indicated by eq 3.

$$\frac{k}{k_f} \approx 1 + 3\phi \quad (3)$$

Maxwell's model considered fluid's thermal conductivity, particles, and particle concentration, but it did not take into consideration the shape and interactions of the particles. To consider these aspects, various models were constructed including those proposed by Jeffery, Davis, Hamilton-Crosser, and Lu-Lin. However, numerous investigations have demonstrated the improvement in thermal conductivity found in nanofluids frequently surpasses the expectations predicted by traditional models.[61]

In 1935, Bruggeman presented a model to investigate the relations among randomly dispersed particles. The Bruggeman model characterizes a fluid consisting of a binary mixture of homogeneous cylindrical particles. It could be described as follows:

$$\phi\left(\frac{k_p + k_{eff}}{k_p + 2k_{eff}}\right) + (1 - \phi)\left(\frac{k_p + k_{eff}}{k_p + 2k_{eff}}\right) = 0 \quad (4)$$

The Bruggeman model is effective for spherical particles and does not impose restrictions on the particle concentration. For low concentrations, its results align with those of the Maxwell model. However, at higher concentrations, the Maxwell model often fails to accurately reflect experimental findings. In contrast, the Hamilton−Crosser model, introduced in 1962, addresses solid−liquid mixtures with nonspherical particles. To account for the impact of particle morphology, this formulation includes a shape factor denoted as n. When the ratio of thermal conductivity between the solid state and the fluid phase exceeds 100 ($k_p/k_f > 100$), the thermal conductivity can be expressed using the following equation:

$$k_{eff} = \left(\frac{k_p + (n - 1)k_b - (n - 1)(k_b + k_p)\phi}{k_p + (n - 1)k_b + (k_b + k_p)\phi}\right)k_p \quad (5)$$

This model containing variable n denotes the empirical shape component and is calculated as $n = 3/\psi$, where ψ represents the sphericity of the particle. Sphericity represented by ψ is defined as the ratio of the surface area of a sphere with the same volume as the particle to the actual surface area of the particle. In the last 20 years, there has been a significant amount of research dedicated to creating models that could forecast a nanofluid's thermal conductivity. These models consider several aspects and are then compared to the experimental data. Here, we will focus on only a small number of noteworthy models that have been constructed for nanofluids.

During the initial phases of nanofluid research, multiple models were suggested that considered factors such as size of nanoparticles and the influence of nanolayers. Yu and Choi made modifications to the Maxwell model to consider the influence of nanolayer upon thermal conductivity. The solid particle's thermal conductivity k_p was substituted with a revised thermal conductivity of significant particles k_{pe}, utilizing the efficient medium theory (Schwartz 1995).

$$k_{pe} = \left(\frac{2(1 - \gamma) + (1 + \beta)^3(1 + 2\gamma)\gamma}{-(1 - \gamma) + (1 + \beta)^3(1 + 2\gamma)}\right)k_p \quad (6)$$

In this equation, $\gamma = k$ layers$/k_p$ refers to the expression of ratio of thermal conductivity between a particle and nanolayer, while $\beta = 1 + h/r$ denotes percentage of nanolayer thickness along the particle size to original particle dimension. The formula developed by Yu and Choi for nanofluid's efficient thermal conductivity can be represented as

$$k_{eff} = \left(\frac{k_{pe} + 2k_b + 2(1 - \beta)^3(k_{pe} - k_b)\phi}{k_{pe} + 2k_b - (1 - \beta)^3(k_{pe} - k_b)\phi}\right)k_p \quad (7)$$

Subsequent advancements lead to the advancement of a comprehensive model that incorporates both dynamic and static mechanisms of nanoparticles, including factors such as nanolayer formation, Brownian motion, interactions, concentration, and particle size. The resulting model is explained in the given term:

$$k_{eff\text{-}nf} = \left\{k_f\left(\frac{\phi_p\omega(k_p - \omega k_f)[2\gamma_1^3 - \gamma^3 + 1] + (k_p + 2\omega k_f)\gamma_1^3[\phi_p\gamma^3(\omega - 1) + 1]}{\gamma_1^3(k_p + 2\omega k_f) - (k_p - \omega k_f)\phi_p[\gamma_1^3 + \gamma^3 - 1]}\right)\right\} + \left\{\phi_p^2\gamma^6 k_f\left(3\Lambda^2 + \frac{3\Lambda^2}{4} + \frac{9\Lambda^3 k_{cp} + 2k_f}{16.2k_{cp} + 3k_f} + \frac{3\Lambda^2}{2^6} + \cdots\right)\right\} + \left\{\frac{1}{2}\rho_{cp}c_{p\text{-}cp}d_s\left[\sqrt{\frac{3K_bT(1 - 1.5\gamma^3\phi_p)}{2\pi\rho_{cp}\gamma^3 r_p^3}} + \frac{G_T}{6\pi\eta\gamma r_p d_s}\right]\right\} \quad (8)$$

The second part of the model describes the connections between pairs of semispherical particles in static suspension. Furthermore, the third part considers the impact of particle Brownian motion in suspension as well as the surface chemistry of the particles and interactions between particles. The processing of thermal conductivity (k) of the nanolayer is not feasible by either experimental or theoretical methods.

3.2. Methods for Measuring Thermal Conductivity. In recent years, scientists have devised multiple methods to quantify the nanofluid's thermal conductivity. Techniques used in the study are the thermal constant analyzer (TCA)

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technique and transient hot wire (THW) methodology derived from the temperature oscillation technique, transient plane source theory, 3ω method, and steady-state parallel-plate methods. Out of these strategies, the THW and TCA techniques are the most utilized.[62]

During a standard transient hot wire experiment, a nanofluid sample is subjected to an extremely thin metal wire, typically composed of platinum or rhodium. An unchanging current is given to the wire, increasing its temperature. Consequently, the temperature of the adjacent nanofluid increases because of the loss of heat. The wire, functioning as both a temperature sensor and a heat source, measures and records the temperature changes over a period. Conversely, the thermal constant analyzer technique employs a plane-like probe constructed of conductive foil sited in a round pattern, utilizing the transient plane source hypothesis. In the TPS technique, the probe functions as both the thermometer and the heat source, like the metal wire in the THW method. Thermal conductivity is governed by analyzing the variation in electrical resistance of the probe, as it responds to changes in temperature over a period. The THW and TCA procedures have the advantage of effectively eliminating errors resulting from natural convection in thermal conductivity measurements, therefore ensuring the trustworthiness of experimental data.

Further techniques for measuring thermal conductivity included but were not restricted to the Guarded Parallel-Plate method,[63] comparative interferometric method,[64] 3ω method,[65] thermal-lensing method,[66] light flash technique,[67] etc. embraced for measuring thermal conductivity. Although each of these methods has its advantages and limitations, it is recommended that researchers use multiple techniques to confirm recycling and the precision of experimental outcomes. Since the following techniques are well-established, they are not described in this research. A comparative uncertainty analysis of these methods for measuring nanofluid's thermal conductivity is available in the literature. Accurate measurements, especially at varying temperatures, require special care and expertise. Figure 6 provides a schematic overview of the process for preparing nanofluids and measuring their thermal conductivity.

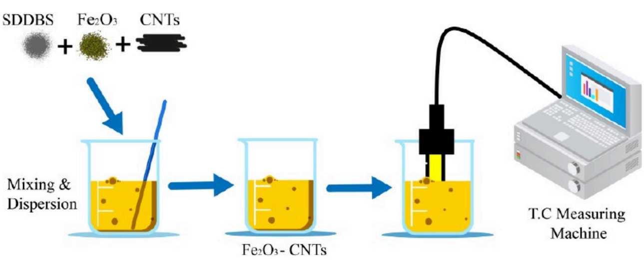

Figure 6. Schematic diagram illustrating the preparation of nanofluids and measurement of their thermal conductivity.

3.3. Parameters Impact the Thermal Conductivity.

Unusual improvement in a nanofluid's thermal conductivity has garnered significant interest from researchers. Consequently, numerous experiments have been performed to explore the working mechanisms behind this irregular thermal conductivity enhancement. The studies aim to analyze properties of nanoparticles, base fluid features, dispersion or aggregate of nanoparticles among base fluid, and the variables that affect the aggregation, as demonstrated in Figure 7. Table 3 specifies an assessment of recent inspections on nanofluids and the various elements that impact their thermal conductivity.

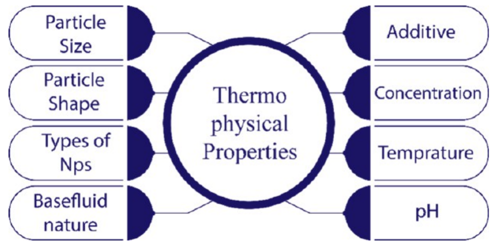

Figure 7. Thermophysical properties impacting factors.

3.3.1. Impact of Nanoparticle Size and Shape. Nanoparticle size, shape, and distribution critically influence the thermophysical properties of nanofluids. Figure 8 represents different shapes of nanoparticles, along with shape factors. Smaller nanoparticles enhance thermal conductivity due to increased surface area and improved particle interactions, but also elevate viscosity. Spherical nanoparticles facilitate better dispersion and higher thermal conductivity, while nanorods offer superior specific heat and conductivity, particularly in the solid phase. Proper nanoparticle dispersion ensures uniform enhancement, whereas aggregation leads to performance degradation. The combined effects of these parameters govern nanofluid heat transfer efficiency. Nithiyanantham et al.[68] examined the influence of Al_2O_3 nanoparticle size and shape on nanofluid properties, finding that Al_2O_3-NPs enhance thermal conductivity and reduce viscosity in the liquid phase while Al_2O_3-NRs improve specific heat and conductivity in the solid phase. Paul et al.[69] observed that oil-based nanofluids exhibited enhanced thermal conductivity with higher concentrations of nanoadditives and demonstrated specific heat variations with temperature changes. Mohammadi et al.[70] suggested that the surface area ratio of the nanofluid is associated with its thermal conductivity. Maheshwary et al.[71] found thermal conductivity of nanofluids with five various forms and determined that cubic nanofluids had superior thermal conductivity compared to rod-shaped and spherical nanofluids, though they exhibited poorer stability.

3.3.2. Impact of Volume Fraction. The volume fraction of nanoparticles in a nanofluid enhances thermal conductivity through increased particle interactions but also raises viscosity due to higher flow resistance. Beyond a critical threshold, nanoparticle aggregation can reduce the performance and cause instability. Bianco et al.[73] investigated that enhancement in heat transfer improves by elevating volume fraction of nanoparticles. Yu et al.[74] showed the hybrid nanofluids display superior thermal conductivity as compared to Cu mono fluids, due to more effective Brownian motion and aggregation structures. However, this increase is not always linear. Once the volume fraction surpasses a particular threshold, the thermal conductivity has the potential to decline, gradually converging toward the base fluid's thermal conductivity.[75]

3.3.3. Impact of Temperature. Nanofluids exhibit enhanced thermal conductivity due to the Brownian motion of nanoparticles, which improves the heat transfer efficiency. However, higher nanoparticle concentrations can increase viscosity, potentially reducing flow and affecting temperature regulation in thermal systems. Numerous scholars have

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Table 3. Conclusion of the Factors Influencing the Nanofluid's Thermal Conductivity as Reported in Recent Studies: Key Parameters Affecting the Nanofluid's Thermal Conductivity

NP type and concentration	Nanoparticle shape and size	pH	Base fluid	Magnetic field	Temp.	Aggregates	Additives and stability	Summarized potential applications	ref.
×	×	×	×	–	–	–	–	–	93
×	×			–	×	–	–	–	94
×	×	×	×	–	×	–	×	–	95
×	×			–	×	–	–	–	96
×	×		×	–	×	–	–	–	97
×	×	×	×	–	×	–	×	–	98
×	×		×	–	–	–	×	–	99
×	×	×	×	×	×	×	×	×	Present work

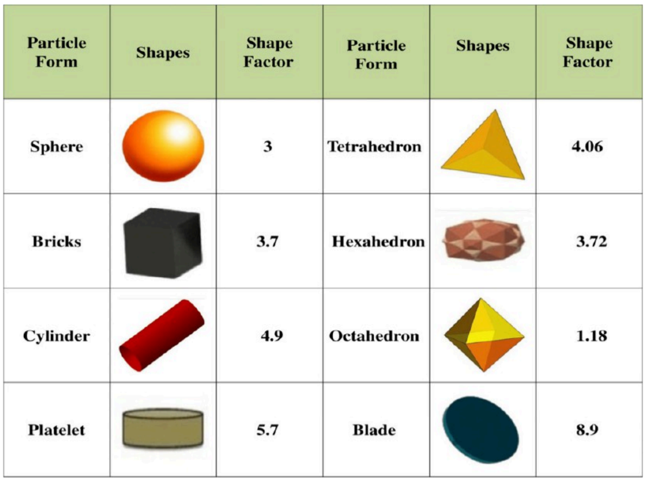

Figure 8. Shape of nanoparticles along with shape factor. Reproduced with the permission of Akbar,[72] copyright MDPI.

discovered the effect of temperature on the nanofluid's thermal conductivity. Dai et al.[76] stated that hybrid nanofluids with greater Cu concentrations enhance thermal conductivity by increasing nanolayer density and Brownian motion. Elevated temperatures significantly influence thermal conductivity, and the nanoparticle volume fraction also plays a crucial role in determining it..[77]

3.3.4. Impact of Aggregates. Nanoparticle aggregation in nanofluids leads to the formation of clusters, which disrupt the uniformity of the fluid's thermophysical properties, potentially decreasing thermal conductivity. The extent of aggregation is influenced by factors such as particle concentration, surface interactions, and fluid dynamics. Naylor et al.[78] developed a comparative interferometric method to precisely detect a nanofluid's thermal conductivity, finding that Al_2O_3-water nanofluids showed thermal conductivity comparable to that of deionized water within a 6% uncertainty range. Song et al.[79] suggested a prediction model indicating that nanoparticle aggregation enhances thermal conductivity, particularly with lower concentrations and smaller particle sizes, due to increased phonon mobility in the solid phase. Motevasel et al.[80] found that prediction models that did not account for particle aggregation had average deviations 2–6 times greater than those incorporating aggregation, underscoring the significant role of aggregation in thermal conductivity at low concentrations.

3.3.5. Impact of pH. The pH of a nanofluid affects nanoparticle stability by altering surface charge and dispersion quality; extreme pH can cause agglomeration or corrosion impacting thermal and rheological properties. Cacua et al.[81] examined how pH value impact the nanofluid's thermal conductivity. They discovered that, within a specific range, thermal conductivity rises as the pH value rises. Furthermore, the zeta potential of nanoparticles is influenced by pH. Nanoparticle aggregation arises when the zeta potential surpasses the isoelectric point (IEP), resulting in negligible repulsive interactions among nanoparticles. This aggregation diminishes the stability of the liquid and, thus, decreases heat conductivity. Pandey et al.[82] reported that nanofluid thermal conductivity, measured using an ultrasonic interferometer and Bridgman's equation, increased with optimal values observed in a 50:50 water–ethylene glycol mixture.

3.3.6. Impact of Additives and Stability. Additives in nanofluids improve dispersion stability by modifying surface properties and preventing nanoparticle agglomeration, enhancing thermal conductivity. Their type and concentration affect the long-term stability by balancing viscosity and preventing sedimentation. Nese et al.[83] and Almitani et al.[84] processed cationic (CTAB), anionic (SLS, SDS), and nonionic (PS20, PVP) surfactants to study their effects on nanofluid thermal conductivity and stability. The results showed that surfactants improve stability and thermal conductivity, with anionic surfactants being the most effective and nonionic the least. Nanofluids ideally have uniformly distributed nanoparticles, but high surface energy causes aggregation, reducing stability and losing their beneficial properties.[85] Li et al.[86] discovered that the thermal conductivity of water-based alumina nanofluids improves as the volume fraction and temperature increase but declines when the sphericity falls. Li et al.[87] demonstrated that nonionic dispersants had a substantial positive effect on thermal conductivity and stability of BN-C_2H_4O nanofluid. Conversely, anionic and cationic dispersants have detrimental effects, leading to a decrease in thermal conductivity. Rasool et al.[88] analyzed the stability of radiative unsteady 2D flow of a magnetized hybrid nanofluid across a shrinking sheet, identifying dual solutions along only one stable branch over time, influenced by copper nanoparticle volume fraction and suction effects.

3.3.7. Impact of Magnetic Field. Magnetic fields influence nanofluid behavior by aligning magnetic nanoparticles, enhancing thermal conductivity and altering fluid flow characteristics; this interaction can lead to improved heat transfer and viscosity control in magnetic nanofluids. Saeed et al.[89] investigated heat transfer and MHD flow of ternary hybrid nanofluids along partial velocity slip and variable thermal conductivity on a stretching sheet, employing numerical methods to analyze the influence of magnetic fields and other key factors on flow and heat transfer presentation.

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Table 4. Summary of Enhancements in Nanofluid's Thermal Conductivity

Base fluid	Nanoparticle	Concentration	Temperature (°C)	Enhancement (%)	ref
Thermal oil	Al_2O_3-MWCNTs	0.12−1.5	25−50	45	100
Water	Al_2O_3	0.1−1.0	30	3	101
Deionized water	Al_2O_3	1−6	30	2.2	102
Water	Al_2O_3	0.01−1.0	20	9.1	103
Water	Ag - MWCNTs	0.04−0.16		47	104
Water	Fe_2O_3	01−4	30	19	105
Engine Oil	WO3-MWCNTs	0.6		19.85	106
Water	Fe_2O_3	0.1−0.4	30−80	23	107
Water	Fe_2O_3	0.003−0.007	45−55	19.51	108
Water	Sio_2	38	25−55	3	109
Water	TiO_2	0.25	20−60	12	110
Water	TiO_2	0−0.5	10−40	16	111
Deionized water	ZnO/DW	0.25−1	25	38	112
Deionized water	ZnO	0.25−1	25	5.8	113
Water	CNTs	0.5	20−45	36	114
EG	GO	0.05−0.25	50−60	36.72	115
Water	CGNPs	0.05−0.1	30	22.92	116
Water-EG	TiO_2-SiO_2	2−3	30	3	117
Water	Ni-ND	0.25, 0.3	20−60	29	118

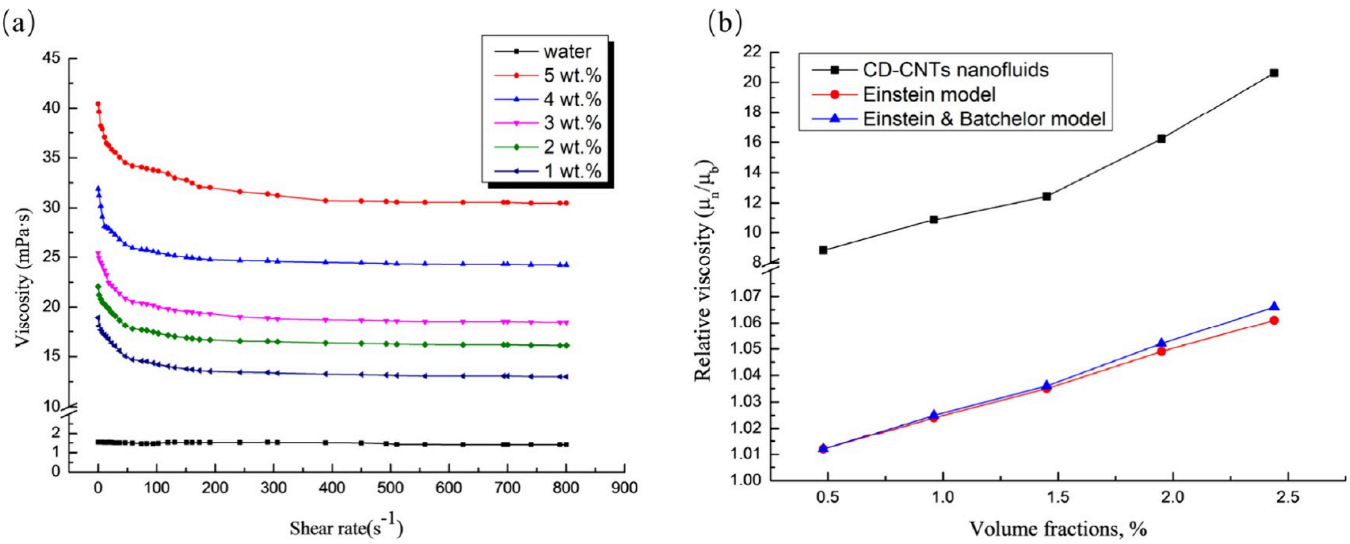

Figure 9. (a) Shear rate dependence of viscosity for different mass concentrations. (b) Relative viscosity of CD-CNTs nanofluids as a function of volume fraction. Reproduced with the permission of Li et al.[121] Copyright 2020 Elsevier Ltd.

Sangaraju et al.[90] reported that magnetic manganese oxide nanofluids show substantial increases in thermal conductivity of up to 52.4% when exposed to magnetic fields, with these enhancements accurately predicted by an ANFIS algorithm. Madhukesh et al.[91] studied the influence of magnetic effects and nanoparticle aggregation on thermal conductivity and flow in nanofluids over a porous Riga surface, revealing key insights for advanced cooling systems and engineering applications. Lund et al.[92] examined heat transfer behavior of a magnetized Casson hybrid nanofluid in a porous moving plane, highlighting the influence of the magnetic field, velocity ratio, and thermal radiation and uncovering nonunique branch solutions along with the Casson parameter's impact on skin friction.

Extensive research has explored the factors affecting the thermal conductivity, with various studies documenting the extent of their impact. The conclusion of these findings is presented in Table 4.

4. VISCOSITY

Nanofluids are suspensions of nanoparticles, typically smaller than 100 nm, dispersed in a base fluid such as ethylene glycol, water, or oil that significantly enhance thermal properties. Viscosity, a critical factor for nanofluid performance, affects the flow behavior, pressure drop, heat transfer efficiency, and pumping power. Viscosity increases with nanoparticle concentration in a nonlinear manner, with studies showing viscosity can rise by 45−90% at concentrations ranging from 2% to 5% by volume. The relationship between viscosity and nanoparticle concentration is complex and requires advanced models, as conventional models such as the Einstein equation are insufficient at higher concentrations, necessitating more accurate predictions from models such as the Krieger−Dougherty equation. Kishore et al.[119] conducted experiments on ternary nanofluids with altered mixing ratios and concentrations, achieving a 19% improvement in thermal conductivity for 0.5% volume, primarily due to graphene

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nanoplatelets. They used an ANN model with a regression accuracy of 0.99496 to predict both thermal conductivity and viscosity. Akande et al.[120] projected a dispersion factor to enhance the modeling of nanofluid viscosities dependent on nanoparticle volume fraction, which improved alignment with experimental data for TiO_2, γ-Al_2O_3, and SiO_2 nanofluids by accounting for particle geometry and chemical mixture. Li et al.[121] showed that carbon nanotubes modified with β-cyclodextrin can be used to create nanofluids with a high mass concentration. These nanofluids have excellent colloidal stability, improved thermal conductivity, and a modest increase in viscosity. Researchers achieved this through a scalable mechanical milling technique, as illustrated in Figure 9. Guerra et al.[122] determined that ultralow concentration boron nitride nanotube nanofluids (0.1−10 ppm) showed a non-Einsteinian viscosity decline of up to 29% in the presence of methane, with minimal temperature dependence. Selvarajoo et al.[123] explored the thermophysical characteristics of Al_2O_3 and graphene oxide nanofluids, finding that a 1% Al_2O_3-GO hybrid nanofluid enhanced thermal conductivity by up to 4.34% compared to mono nanofluids and achieved a viscosity reduction of up to 6.6%, with a new model predicting thermal conductivity and viscosity along errors of 6% to 4%, respectively. Raghav et al.[124] developed hexagonal boron nitride (hBN) nanolubricants in coconut oil, noting that viscosity elevated with nanoparticle concentration and declined with temperature, with significant increases in viscosity observed at elevated solid volumes and lower shear rates. Yalçın et al.[125] investigated the influence of several surfactants (cetrimonium bromide, gum arabic, and ammonium citrate) on dynamic viscosity of a 2% graphite nanofluid, finding that gum arabic significantly increased viscosity at lower temperatures, while ammonium citrate reduced stability, with high accuracy in regression equations for each surfactant.

The geometry of the nanoparticles significantly affects viscosity. Smaller nanoparticles generally increase viscosity more than larger ones due to their higher surface area-to-volume ratio, which leads to greater interactions with the base fluid. Nonspherical particles, such as rods or platelets, create more flow resistance due to their orientation and interaction dynamics. The base fluid's viscosity plays a key role, with nanofluids in more viscous fluids like ethylene glycol typically exhibiting higher viscosities compared to those in less viscous fluids like water. The interaction between nanoparticles and the base fluid's molecular structure further influences overall viscosity. Ruihao Zhang et al.[126] utilized molecular dynamics simulations to investigate the influence of nanoparticle morphology on viscosity and thermal conductivity of Cu/Au-argon nanofluids. The findings indicate that nanoparticles along higher surface-to-volume ratios exhibit enhanced thermal conductivity with specific results provided for columnar and spherical particles. Sadeghi et al.[127] studied Molecular Dynamics simulations within the Green−Kubo framework to evaluate Fe_2O_3-water nanofluid viscosity, revealing a positive correlation between nanoparticle volume fractions and viscosity, indicating that as volume of nanoparticles grows, viscosity also increases. Conversely, viscosity decreases with higher temperatures and smaller nanoparticle sizes while offering insights into nanofluid structural interactions (Figures 10 and 11). Yahyaee[128] examined the influence of various Al_2O_3 nanoparticle shapes upon a nanofluid's thermal behavior film on boiling in a vertical cylinder, revealing that blade-shaped nanoparticles notably improve thermal transport and

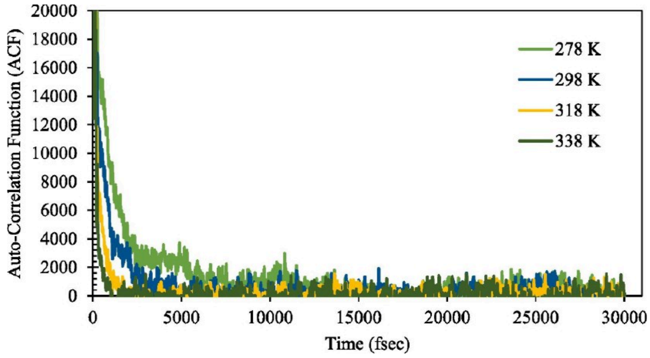

Figure 10. Autocorrelation function of shear stress at various temperatures for a specific volume fraction of a water-based nanofluid with iron oxide spheres. Reproduced with the permission of Samaneh.[127] Copyright 2023 Elsevier Ltd.

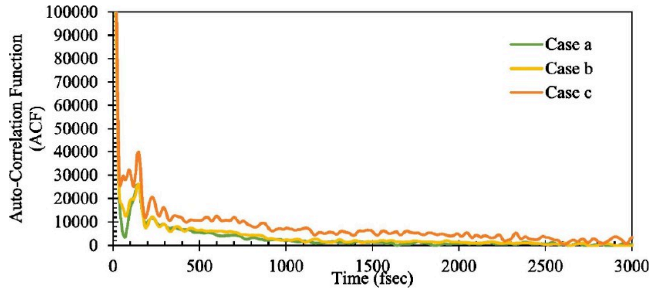

Figure 11. Shear stress autocorrelation function (SACF) for spherical Fe_2O_3 nanoparticles in water at varying volume/weight percentages. Reproduced with the permission of Samaneh.[127] Copyright 2023 Elsevier Ltd.

boiling heat transfer efficiency, particularly at maximum concentrations. Alahmadi et al.[129] explained the impact of cylindrical and spherical silver nanoparticles on heat transfer in silver-water nanofluid flow across a polished rotating disk, demonstrating that nanoparticle shape affects viscosity, skin friction, and the Nusselt number, providing insights for performing heat transfer systems. Yahyaee et al.[130] investigated the influence of nanoparticle diameter on film boiling in Al_2O_3-water nanofluids, revealing that smaller nanoparticles (5, 10 nm) improve thermal conductivity and heat transfer efficiency, while particles larger than 30 nm show reduced benefits. Mahitha et al.[131] analyzed the convective heat transfer of alumina nanofluids across an inclined plate, revealing decreased friction with increased inclination and superior temperature handling of alumina/engine oil nanofluids compared to other base fluids.

Temperature is a key factor affecting nanofluid viscosity, with viscosity generally decreasing as the temperature rises for both base fluids and nanofluids. However, the rate of decrease can vary depending on the nanoparticle's thermal properties. The thermal conductivity of nanoparticles influences the temperature-dependent viscosity change. Figure 12 shows the viscosity variations of different nanofluids as a function of the temperature. Nanoparticle aggregation can impact viscosity, with stable nanofluids exhibiting more predictable viscosity behavior. While surfactants and stabilizers are used to maintain dispersions, they can also influence viscosity. Ajeena et al.[133] determined dynamic viscosity for a ZrO_2/SiC hybrid nanofluid in distilled water, observing that viscosity decreases with temperature, achieving a maximum increase of 169.4% at

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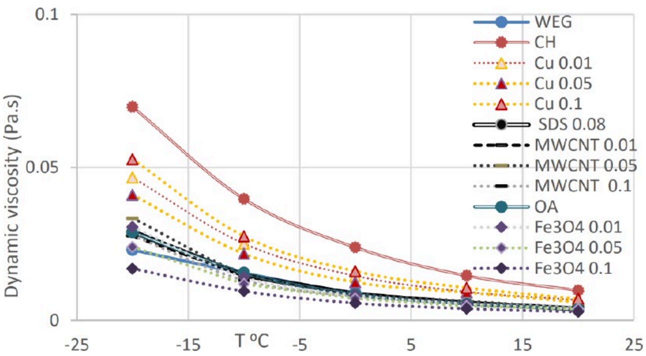

Figure 12. Viscosity of various nanofluids at different temperatures. Reproduced with the permission of Banisharif.[132] Copyright 2019 European Symposium on Nanofluids.

0.025% concentration, and developed a correlation with 98.92% accuracy for viscosity prediction. Akbar et al.[134] examined the peristaltic flow of a temperature-dependent CNT nanofluid in an irregular channel, finding that SWCNTs yield lower pressure gradients and higher axial velocities than MWCNTs, offering insights for improving medical drug delivery systems. ÇOlak[135] employed artificial neural networks to examine the effects of Arrhenius activation energy, partial slip, and temperature-dependent viscosity on the bioconvective flow of a non-Newtonian Maxwell nanofluid. The study achieved advanced accuracy in estimating outcomes and emphasized the potential of artificial intelligence for engineering analysis.

Numerous theoretical models and empirical relationships have been developed to estimate nanofluid viscosity, as summarized in Tables 5 and 6. Accurate viscosity measurements are typically conducted using capillary viscometers, rotational viscometers, and oscillatory rheometers. Capillary viscometers measure flow time through a narrow tube, rotational viscometers assess the torque required to rotate a spindle, and oscillatory rheometers provide detailed viscosity profiles under oscillatory shear stress. The viscosity of nanofluids is influenced by factors such as the nanoparticle concentration, geometry, base fluid characteristics, temperature, and stability. While theoretical models offer predictions, experimental validation is essential for optimizing their performance in thermal management applications.

5. NANOFLUID APPLICATION

5.1. Heat Exchangers. Nanofluids present an advanced alternative to conventional heat transfer fluids in heat exchangers, offering advantages in diverse applications involving electronics cooling, HVAC systems, large-scale manufacturing, energy systems, and engine cooling. Calviño et al.[146] investigated ZrO_2-based nanofluids for low-enthalpy geothermal systems, showing up to a 123% enhancement in convective heat transfer coefficients equating to base fluids. These findings highlight the enhanced nanofluid's thermophysical properties for heat exchanger application. Abbas et al.[147] examined thermal enhancement in engine oil with hybrid nanofluids in a porous cavity, finding that a higher Hartmann number and thermal radiation increase heat flux and decrease vortex size and temperature profile, which can apply to heat exchangers. The long-term stability of nanofluids is a key parameter that impacts thermal performance by ensuring uniform nanoparticle dispersion, which is essential for optimal thermal conductivity and heat transfer.[148] Instability, caused by agglomeration or sedimentation, reduces heat transfer efficiency and increases viscosity, impeding flow and lowering the convective heat transfer coefficient. This can lead to poor heat dissipation and reduced system efficiency. Thus, maintaining nanofluid stability is critical for sustaining enhanced thermal properties and performance over time.

Further research should address the corrosive, erosive, and fouling impacts of nanofluids in heat exchangers along with their performance at high temperatures. Current gaps include exploring high-temperature applications and less-studied characteristics, such as latent heat capacity and specific heat capacity. There is a need for additional experimental and numerical studies on nanofluids, particularly graphene-based dispersions, and their potential benefits in heat exchangers, including economic evaluations and potential heat transfer improvements. More research is also required on h-BN nanostructure-based nanofillers across different types of heat exchangers. Table 7 provides a concise overview of current empirical studies on nanofluids within various heat exchanger systems.

A comprehensive review highlights the advancements in nanofluids for heat transfer applications, focusing on nanoparticle synthesis, surface modifications, and experimental methodologies. Studies demonstrate that Ag NPs can enhance thermal conductivity by up to 30% over base fluids, improving

Table 5. Models for Nanofluid's Viscosity[a]

S. No	Model	Equation	Remarks
1	Einstein model	$\mu_r = \frac{\mu_{hf}}{\mu} = 1 + \eta\phi$	This applies when the nanoparticle volume fraction is less than 1% and no contact among the particles.
2	Batchelor model	$\mu_r = \frac{\mu_{hf}}{\mu} = 1 + \eta\phi + (\eta\phi)^2$	This model extends the Einstein model by considering nanoparticle Brownian motion and interactions among them.
3	Ward model	$\mu_r = \frac{\mu_{hf}}{\mu} = 1 + \eta\phi + (\eta\phi)^2 + (\eta\phi)^3$	Exponential model range of 35% for φ
4	Renewed Ward model	$\mu_r = \frac{\mu_{hf}}{\mu} = 1 + \eta\phi_e + (\eta\phi_e)^2 + (\eta\phi_e)^3$	The effect of liquid layering is considered to calculate φ.
5	Krieger−Dougherty equation (K-D model)	$\mu_r = \frac{\mu_{hf}}{\mu} = \left(1 - \frac{\phi}{\phi_m}\right)^{-[\eta]\phi_m}$	Monomial expansion is applied, and this model reduces to the Einstein equation; however, performing a binomial expansion will result in the Batchelor model.

[a]Reproduced with the permission of Chandrasekar.[136] Copyright Elsevier Ltd. The viscosity denoted by η has a value of 2.5 for hard spheres.

Table 6. Summary of Various Nanofluids and the Experimental Associations Identified in Different Studies, Consolidating the Key Findings

Correlations	Size (nm)	Vol %	NP	BF	ref.
$\frac{\mu_{nf}}{\mu_{bf}} = 0.955-0.00271T + 1.858 \times \phi/100 + \left(705 \times \frac{\phi}{100}\right)^{1.223}$	<100	0.01−0.1	Al_2O_3-CuO-TiO_2	Water	137
$\mu_{nf} = 75.87 + 5.03\beta + 77.84\theta - 4.06\gamma - 6.64\beta\theta + 0.2513\beta\gamma + 2.53\theta\gamma - 2.58\gamma^2 + 33.97\beta^2 + 5.22\gamma^2$	<100	0−1.5	$MG(OH)_2$	Base Oil	138
$\frac{\mu_{nf}}{\mu_{bf}} = 0.7096 + 3.84168\phi + 0.02256T - 24.284\phi^2 - 2.3839T^2 + 0.22802\phi T$	20, 45−65	0.025−0.1	ZrO_2/SiC	Distilled Water	139
$\mu_{nf} = -1.471 + 0.105/T + 1.515(1-\phi p) + 1.46(1-\phi p)^2 - 0.707(1-\phi p)^2/T^2 - 1.504(1-\phi p)^3 + 12(1-\phi p)/T^3 - 0.046/\gamma$	21	0−1	TiO_2	EG/Water	140
$\frac{\mu_{nf}}{\mu_{bf}} = 0.99761 + 0.26995 \times \varphi^{0.32737} - 0.03587 \times T^{0.89391} + 0.19267 \times \varphi^{0.32737} \times T^{0.89391}$	20	0.025−0.1	ZrO_2	Distilled Waer	141
$\frac{\mu_{nf}}{\mu_{bf}} = 1 + 413.97\phi$	45	8−16	Metal oxide	Water	142
$\mu_{nf} = a\exp(b(\varphi - 0.01146/0.01921)) + c\exp(d(\varphi - 0.01146/0.01921))$	50, 10−80, 10,	0.00125−0.05	Ag, Cu, TiO_2	Water	143
$\mu_{nf} = 233.2713\varphi^{0.8623}(1/t)^{0.8623} - 2.6698\varphi^{0.4821} + 0.9145$		0.005−0.02	Cu−Fe_2O_4−SiO_2	Water	144
$\frac{\mu_{nf}}{\mu_{bf}} = 0.9554 + 1.211\varphi\exp(\varphi) - 3.616\varphi^2 + 0.6647\varphi^3$		0.0625−1	MWCNT-CuO/SAE	Water	145

Nusselt numbers, reducing thermal resistance, and increasing thermal efficiency in systems such as heat pipes and exchangers. The optimal surface modification techniques and their effects on the heat transfer coefficients remain unresolved. This work addresses these gaps through advanced experimental setups and statistical analysis, emphasizing practical applications and performance metrics in nanofluid-based heat transfer systems. Table 8 consolidates critical studies focusing on nanofluid applications in heat transfer systems.

5.2. Electronics Thermal Management. Graphene and CNT-based nanofluids offer exceptional heat transfer, making them ideal for thermal management in heat sinks, thermosyphons, heat pipes, and thermal interface materials. Their high thermal conductivity and unique structures improve convective heat transfer and reduce thermal resistance, enabling efficient cooling in high-performance devices. These nanofluids are also effective in cooling power electronics, batteries, and electric vehicles, addressing the increasing thermal demands of modern technologies. Sofiah et al.[164] highlighted the advancements in using nanofluids for thermal management in fuel cell technologies, emphasizing their role in enhancing energy efficiency, reducing system size, and promoting sustainable energy (Figure 13). Balaji et al.[165] demonstrated that operationalized graphene nanoplatelets in distilled water improved heat transfer coefficient by 71% and Nusselt number by 60% at 50 °C. Despite a slight pressure increase, the improved thermal properties of nanofluids outweighed this drawback. However, further research is needed on liquid blocks, double-layer heat sinks, the impact of inclination angles on heat pipes, thermosyphon boiling processes, and the integration of phase change materials to achieve a uniform temperature distribution. Additionally, biofriendly and green functionalization of nanostructures should be explored for sustainable cooling solutions. The following nanofluids are ideal products for electronic cooling applications.

Nanofluids significantly outperform conventional coolants due to their enhanced thermal conductivity and heat transfer capabilities, making them ideal for advanced thermal management applications. The incorporation of nanoparticles leads to increased heat transfer coefficients and a reduced thermal resistance. Metal oxide nanofluids, for instance, show up to 40% improvement in heat transfer, while carbon-based nanofluids can boost thermal conductivity by over 60%. Table 9 summarizes the heat transfer enhancements across various nanofluids, demonstrating notable improvements in Nusselt numbers and cooling efficiency in electronic automotive and industrial systems. These findings highlight the potential of nanofluids to revolutionize cooling technologies. Figure 14 outlines the distribution of nanoparticles used in research, reflecting their broad application in thermal management.

5.3. PV/T Systems. Nanofluids like carbon nanotubes and graphene significantly enhance the thermal effectiveness of PV/T systems, potentially increasing overall effectiveness by over 20% compared to traditional fluids. Their uniform dispersion in base fluids ensures better solar radiation absorption and a higher thermal conductivity. Hybrid formulations, combining Gr and CNTs, further improve thermal and electrical outputs by effectively managing solar radiation.

Wahab et al.[176] explored both passive and active cooling mediums to lower PV surface temperatures, a critical factor since higher ambient temperatures adversely affect PV cell heat transfer. The researchers utilized graphene and water at

Table 7. Current Empirical Investigations for the Utilization of Nanofluid in Heat Exchangers

Nanomaterial/Concentration	Base Fluid	Heat Exchanger Type	Main Findings	Remarks	ref.
MWCNTs at 0.2%, 0.4%, and 0.6% vol.	Solar glycol	Double Pipe, Shot Peened	An approximate 115% increment in heat transfer coefficient for volume fraction of 0.6% and mass flow rate (0.04 kg/s), and an approximate 30.6% increase in thermal conductivity at same volume fraction and temperatures ranging from 30 to 50 °C.	An increment of 1.56 times in pressure drops at a volume fraction (0.6%) and mass flow rate of (0.08 kg/s).	149
GO at 0.01% and 0.1% wt.	Water	Tube and shell	Enhancement of 8.7% and 18.9% in thermal conductivity at weight fractions of 0.01% and 0.1%, respectively, at temperatures of 25 and 40 °C.	A reduction of 22% and 109% in exergy dissipation was observed at 0.01 and 0.1 wt % under laminar flow conditions.	150
Gr–CuO at 0.5% vol. and Gr at 0.2% wt.	Water	Concentric tube	Enhancement of 9.6% in heat transfer coefficient.	Reduces 55% in total exergy loss.	151
	Water	Shell and tube	Increase in heat transfer coefficient of 29% at 0.2% wt.	Increase of 13.7% in thermal efficiency at 0.2% wt. concentration.	152
Gr at 0.02%, 0.055%, and 0.06% wt.	Water	Double	Increment of 51.1% on Re. of 425, with concentrations of 0.055 wt % and 0.06% wt.	At concentration of 0.06% wt, pressure drops, and pumping power were higher compared to other concentrations.	153

volume fractions from 0.05% to 0.15% with water nanofluids. The flow rates varied from 20 to 40 L/min. In addition, an exergy evaluation was conducted on several photovoltaic (PV) modules, considering the concentration of the flow rates and nanofluid. Figure 15 displays the experimental configuration used to investigate the four situations.

The experimental results led to the following conclusions:

- Gr nanoparticle's volume fraction increasing from 0.1% to 0.15% worsened system performance due to nanoparticle agglomeration and settling in distilled water, which restricted Brownian motion and reduced heat transfer capability.
- Higher flow rates in PV/PCM systems decreased exergy costs and entropy production, enhancing energy extraction.
- The sustainability index exhibited an upward trend as the flow rate rose, finally system with 0.10% Gr nanoparticles and PCM reached a maximum value of 1.17.
- This configuration also showcased the limited potential for further enhancement, emphasizing its exceptional efficiency.
- Electrical exergy asserted a higher impact on whole exergy performance compared to thermal exergy, mainly because the PV/PCM system produced less thermal energy.

To develop the effectiveness of large-scale photovoltaic cells, it is crucial to focus on optimizing the flow patterns, channel shape, and system maintenance. Channels that were constructed using a hexagonal honeycomb shape were able to reach a thermal efficiency of 87%. Carbon hybrid nanofluids demonstrated a 63% increase in heat transfer coefficient and 144% enhancement in Nusselt number. Hybrid nanofluids consisting of f-MWCNT/HEG/water showed a substantial improvement in heat transfer efficiency, along with a remarkable 289% increase observed at a concentration of 0.01 vol % and a Re. of 15500 when compared to the basic fluid. Comprehensive evaluations are essential to assess the impact of hybrid nanofluids on heat transfer properties, incorporating economic analyses that consider maintenance, warranties, and long-term system performance. The payback period should ideally be less than 14.5 years. Hybrid nanofluids, incorporating low-carbon and eco-friendly methods, can significantly improve the performance of PV/T systems, reduce operational costs, and decrease environmental impact. Further experimental studies are required for PV/T systems integrating phase change materials (PCMs) and innovative configurations, such as loop-pipe systems with nanofluids. Research should also focus on optimizing geometric and structural design, dynamic performance, and the use of biobased fluids. Additionally, prioritizing the development of eco-friendly synthesis methods, stabilization of formulations, and investigation of phase-change nanofluids for enhanced energy efficiency are crucial areas of future study. A comprehensive feasibility evaluation of PV/T systems utilizing nanofluids should be undertaken, encompassing economic, technological, and environmental considerations. Table 10 provides a concise overview of recent scientific investigations, both experimental and numerical, that have explored the utilization of nanofluid for the system of PV/T.

5.4. Concentrated Solar Power. Nanofluids containing graphene, carbon nanotubes, and metal chalcogenides

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Table 8. Summary of Key Literature on Nanofluid-Based Heat Transfer Enhancements[a]

Key Focus	Key Findings	Relevance to Study	ref.
Carbon/water nanofluid with baffles in double-pipe heat exchangers.	Nusselt number increased 35% with 0.3 vol % nanofluid and 12 triangular baffles at 40°	Emphasizes combining nanofluids with structural modifications for better heat transfer	155
Fe_3O_4 nanofluid with longitudinal strip inserts in U-bend exchanger.	Nusselt number increased 41.29% at 0.06% Fe_3O_4 concentration; friction factor increased 1.267 times.	Explores interplay of concentration and geometry for design optimization	156
Graphene oxide nanofluids in looped heat pipes for Li-ion batteries.	Graphene oxide improved thermal conductivity; best filling ratio was 65%.	Focuses on high-performance cooling in energy-dense systems	157
MgO-Al_2O_3 hybrid nanofluids in cylindrical heat pipes.	Hybrid nanofluids showed superior heat transfer performance; RSM optimization effective.	Supports optimization of hybrid nanofluids	158
Fe_3O_4/water nanofluids in double-pipe exchangers with wire inserts.	Nusselt number enhanced by 37.9%; effectiveness and NTU correlations proposed.	Validates Nusselt number enhancements for heat exchangers.	159
CuO nanofluids in twisted double-pipe exchangers for entropy reduction.	Entropy generation reduced by 11.8% at 3% CuO concentration; optimal twist pitch reduced thermal entropy by 24.2%.	Basis for efficiency evaluation in thermal systems.	160
Wetting characteristics of nanofluids in superhydrophilic heat pipes.	Wetting length increased 13%; nanoparticle size affected wetting and evaporation rates.	Explains surface interactions in heat pipes.	161
Gravity heat pipes with single and hybrid nanofluids.	Hybrid nanofluids improved efficiency by 7.3% over single nanofluids; best at 60° inclination.	Links inclination angle to fluid properties for better efficiency.	162
Water/graphene oxide nanofluid with twisted tape inserts in pipes.	Heat transfer coefficient 26% higher with graphene oxide nanofluid; reduced pressure drops.	Validates advanced nanomaterials for heat transfer improvement.	163

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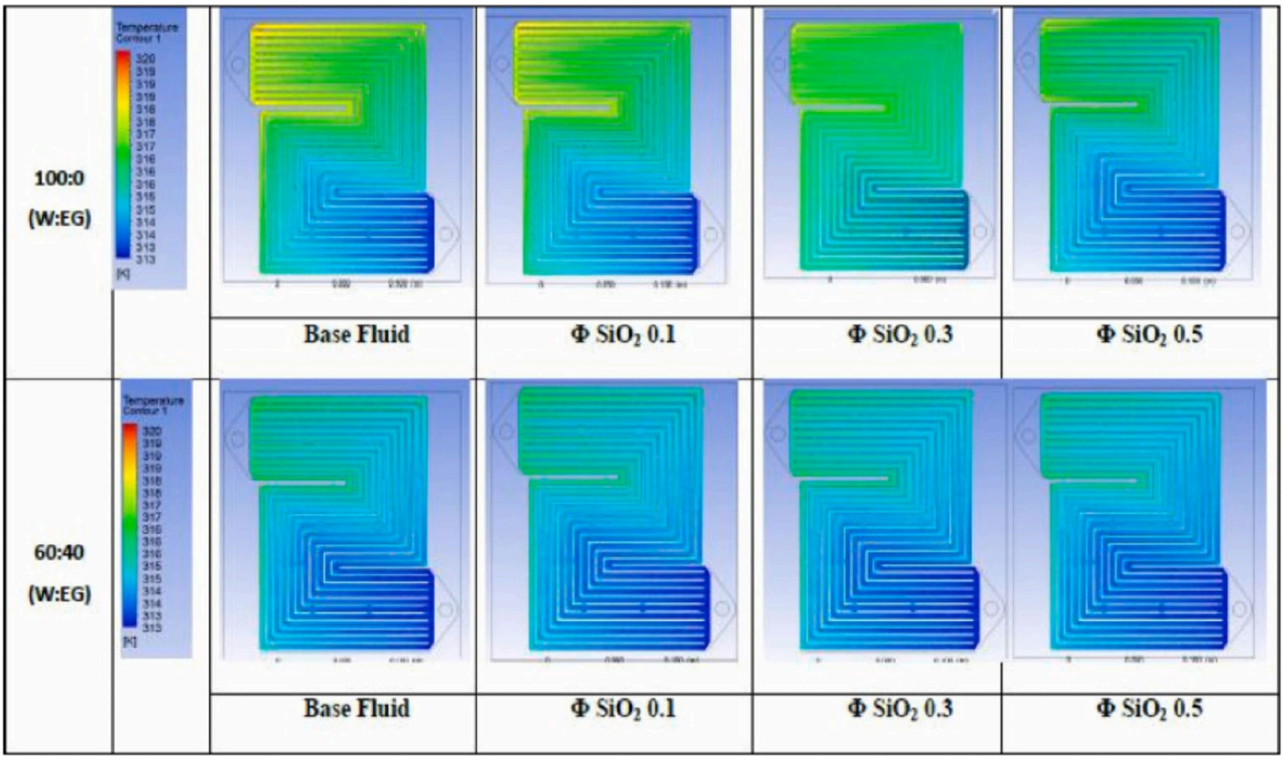

Figure 13. Temperature distribution for base fluids and silicon oxide nanocoolants. Reproduced with the permission of Vidhya.[156] Copyright 2024 Elsevier Ltd.

represent significant advancements in the Concentrated Solar Power (CSP) technology. These nanofluids offer enhanced long-standing and thermal stability, improved heat transfer rates, and higher thermal conductivity compared with conventional synthetic oils used in CSP systems. CSP technology, especially when utilizing parabolic trough collectors, benefits from the superior thermophysical properties of these enhanced heat transfer fluids. Within these types of structures, the heat transfer fluid flows through an absorber tube that is coated to enhance the immersion of solar energy. By integrating nanoparticles into base fluids, features like heat transfer coefficient and thermal conductivity are improved, reducing thermal resistance between fluid layers and boosting overall efficiency in CSP plants. Sedlackova et al.[181] observed the influences of silica dioxide nanofluids on corrosion and thermal properties in Solar Salt-based thermal energy storage systems, offering valuable insights for enhancing CSP efficiency.

Metallic and metallic oxide nanoparticles are noted for their high thermal conductivity, while transition metal nanoparticles with their two-dimensional laminar structures offer significant in-plane thermal conductivity and reduced out-of-plane thermal losses. This makes them particularly effective for enhancing nanofluids used in solar thermal collectors. Recent

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Table 9. Comparison of Heat Transfer Enhancement of Different Types of Nanofluid Coolants from Reviewed Studies

Type of Nanoparticles	Nanoparticles	Base Fluids	Results	ref.
Metal oxide	TiO_2	H_2O	TiO_2 nanoparticles did not alter the spray characteristics substantially	167
Metal oxide	Al_2O_3	H_2O	Performance index of improved by 14.7% and 28.3%	168
Metal oxide	TiO_2	H_2O	26%, 44%, and 62% raises in Nusselt numbers	169
Metal oxide	TiO_2	ethylene glycol	Heat transfer coefficient improved by 12.5%	170
Metal oxide	CuO	H_2O	Convective heat transfer coefficient did noy surpass that of the gallium	171
Metal oxide	ZnO	H_2O	Heat transfer coefficient improved by 25.6−38.3%	172
Metal	Ag	H_2O	Overall heat transfer coefficient improved by 16.79%	173
Carbon materials	Multiwalled carbon nanotube (MWCNT)	H_2O	MWCNT can enhance the thermal conductivity coefficient up to 68%	174
Carbon materials	Multiwalled carbon nanotube/graphene nanoplate	H_2O	MWCNT improved relative thermal conductivity by 11.42−22.67%	175

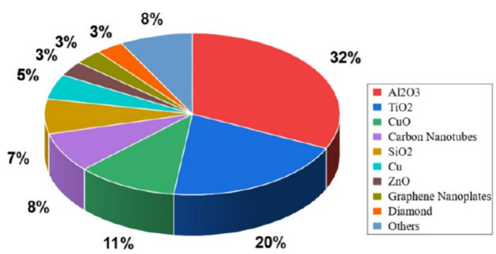

Figure 14. Percentage of researchers using specified nanoparticles in their research work. Reproduced with the permission of Sun.[166] Copyright 2024 MDPI.

research underscores the benefit of two-dimensional nanofluids in improving the effectiveness of Concentrated Solar Power (CSP) systems as shown in Figure 16. The large surface area of these nanomaterials, along with techniques like liquid phase exfoliation, contributes to their enhanced long-term stability and performance.[182]

Martinez-Merino et al.[184] synthesized WS2 nanosheets in eutectic mixture of diphenyl oxide and biphenyl, reporting 37.3% increment in thermal conductivity and 22.1% improvement in heat transfer coefficient. Aguilar et al.[185] explored graphene oxide nanofluids and noted improvements in thermal conductivity, specific heat, and heat transfer coefficient. Researchers prepared graphene oxide nanofluids by dispersing GO in a eutectic mixture of biphenyl and diphenyl oxide using liquid phase exfoliation with surfactants such as Triton X-100 and PEG-200. Triton X-100 provided the most effective exfoliation, resulting in the highest number of stable nanostructures. The Triton X-100-based nanofluids showed notable improvements: 6.6% in specific heat, 45.5% in thermal conductivity, and 29.7% in the heat transfer coefficient. These nanofluids also exhibited nearly complete sunlight attenuation between 20 and 3.5 mm, with stronger sunlight absorption at higher GO concentrations, indicating their potential for through-absorption solar collectors. Geng et al.[186] developed a CTF/EG at PW composite PCM with 10 times higher thermal conductivity than pure PW, low leakage, and 86.9% photothermal efficiency, making it ideal for solar energy storage.

Molten salt nanofluids offer enhanced thermal conductivity but face significant stability challenges at high temperatures due to nanoparticle agglomeration, sedimentation, and degradation of stabilizers. Achieving stable dispersion is a critical issue as the thermal instability of surfactants at elevated temperatures leads to the breakdown of their molecular structure, reducing their ability to absorb nanoparticles and form stable interfaces. This degradation results in agglomeration and sedimentation of nanoparticles, diminishing thermal conductivity, and impairing heat transfer performance. Additionally, nanoparticle doping can influence the corrosivity of molten salts, further compromising the long-term integrity of systems such as Concentrated Solar Power (CSP). Therefore, ensuring the stability and reliability of molten salt nanofluids remains a key challenge for their effective use in high-temperature applications. Fernández et al.[187] developed a polymeric nanoparticle-based coating for steel in Solar Salt,

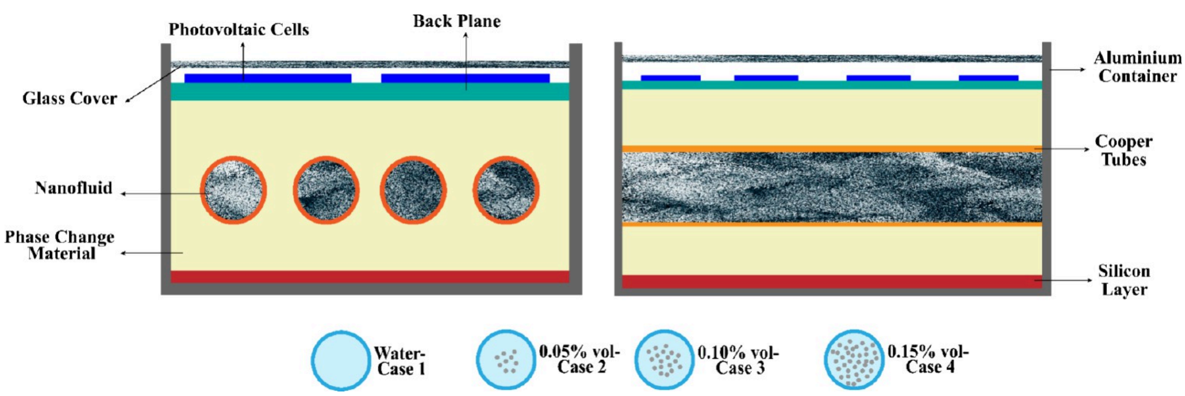

Figure 15. Schematic representation of PV/T system configuration under 4 distinct conditions. Reproduced with the permission of Wahab.[176] Copyright 2020 Elsevier Ltd.

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Table 10. Current Studies for the Application of Nanofluid in Photovoltaic/Thermal Systems

Nanomaterial/ Concentration	Base Fluid	Main Findings	Remarks	ref.
rGO-Ag from 0.0005% to 0.05% wt.	Water	The PV/T hybrid solar system, which utilized rGO−water/Ag nanofluids, demonstrated thermal efficiency ranging from 24% - 30%.	Improved efficiency was noted at concentrations lower than 0.02355% weight relative to a PV system that lacked optical filtration.	177
Gr at 0.05%, 0.15% vol. and RT 35HC PCM	Water	PV temperature was reduced by 23.9 °C, 16.1 °C, and 11.9 °C in the water-based PV/T/PCM system, nanofluid-based PV/T/PCM system, and PV/PCM system. Furthermore, the thermal efficacy for hybrid PV/T/PCM system exhibited a 17.5% increase in comparison with the water-based hybrid PV/T/PCM system, resulting in a general efficacy enhancement of 12%.	A significant increase in electrical effectiveness of 23.9%, 22.7%, and 9.1% was reported when evaluated to the established PV system.	178
MXene at 0.2% wt.	Water	At concentration of 0.2% wt. and flow velocity of 40 kg/h, there was a noticeable increase of around 21.4% of heat transfer coefficient.	A decline of 10% in the PV surface temperature was noticed in comparison to using water alone.	179
0.3% vol of Gr	Water	Energy efficiencies of the PV/T and PV systems enhanced by 23% and 13%, correspondingly.	An estimated reduction of 20 °C in temperature panel was noted when volume percentage was 0.3% and flow rate 0.085 kg/s.	180

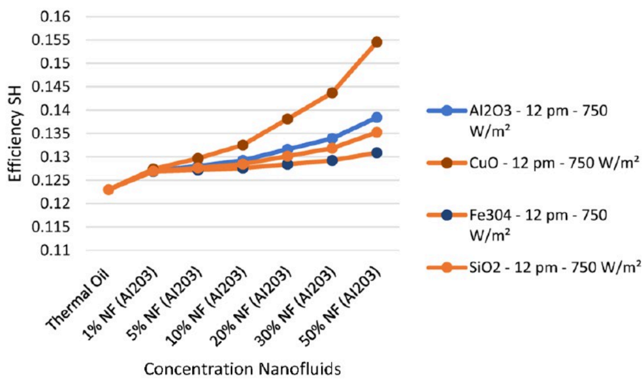

Figure 16. Efficiency of CSP systems with various nanofluids at different concentrations. Reproduced with the permission of Sami.[183] Copyright 2019 MDPI.

reducing corrosion by 33% in coated stainless steel and improving the homogeneity of the corrosion layer. Nithiyanantham et al.[188] observed that incorporating Al_2O_3 and SiO_2 nanoparticles into an $NaNO_3$-KNO_3 eutectic salt effectively reduced carbon steel corrosion rates by up to 300%. Camacho et al.[189] demonstrated that SiO_2 and Al_2O_3 nanoparticles diffuse into carbon steel at 390 °C, mitigating corrosion in molten salt nanofluids via high-temperature treatment and diffusion mechanisms. Leonardi et al.[190] presented a model and simulations to explain specific heat variations in nanoparticle-suspended ionic nanomaterials, identifying factors for enhancing thermal performance in energy applications. Yan et al.[191] created extremely thin layers of hexagonal boron nitride (h-BN) and mixed them into a liquid base made of molten salt (solar salt, $NaNO_3$-KNO_3 in a 60:40 molar ratio). Their nanofluids showed a 76.8% enhancement in thermal conductivity and a 12.8% enhancement in specific heat associated with the base solar salt. The degree of supercooling declined from 12.2 to 4.7 °C, enhancing heat transfer capability and reducing costs and equipment dimensions. This makes h-BN molten salt nanofluids a promising option for CSP applications by preventing phase separation and piping blockage. Table 11 provides a summary of recent publications on the usage of nanofluid and other hybrid nanofluid in CSP systems.

There is a substantial absence of study in the field of metal chalcogenide nanofluids, specifically about base fluids such as eutectic mixes of diphenyl oxide and biphenyl, that are extensively used in Concentrated Solar Power systems. Experimental investigations are needed for tungsten disulfide and molybdenum disulfide in their nanowire and nanosheet forms, which are known for their exceptional stability. Molecular-level numerical simulations could offer crucial insights into the relations among metal chalcogenide nanofluids and base fluid molecules within solar thermal energy collectors. Additional research should focus on leveraging nanofluids to enhance the thermal efficiency across various CSP configurations. There is a specific need to explore nanofluids in volumetric solar energy collectors that are typically more economical compared to surface collectors. Both empirical and computational investigations into the diffusion of nanomaterials in molten-salt-based fluids are crucial because of their capacity to enhance the working of CSP plants. Future research should aim to optimize operational factors and integrate nanofluids into CSP systems. Key

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Table 11. Current Research on Applications of Nanofluids in Concentrated Solar Power Technology

Nanomaterial/ Concentration	Base Fluid	Main Findings	Remarks	ref.
$SiO_{2\,3}$ by 1% wt. Al_2O_3 by 1% wt.	Solar salt	Minimize static corrosion but potential dynamic erosion/corrosion risks.	Enhances protection, affects viscosity and solidification without increasing static corrosion.	192
12 nm-Al_2O_3 by 1% wt.	Ternary eutectic carbonate salt	12% increase of thermal conductivity, 7% increase of heat capacity and 35% increase of viscosity.	Enhance thermophysical properties, reduce corrosion by 50%	193
SiO_2 by 1% wt.	Solar Salt	Enhanced energy storage by 20−50%, reduced corrosion by 50%	the specific heat of the molten salt nanomaterials was enhanced by 20−50% and 10−30%	194
Al_2O_3 by 1% wt. proportion ranges from 40:60.	Eutectic Salt	Al_2O_3-NPs and Al_2O_3−NRs nanofluids enhance specific heat by ∼3% and ∼6%, thermal conductivity by 12−20%, and viscosity by 25−37%.	Al_2O_3-NRs-nanofluid boosts solid-state properties, while Al_2O_3−NPs-nanofluid enhances liquid-state performance, improving CSP efficiency and reducing LCOE.	195
h-BN ranges from 0.5% to 2.0% wt.	Solar Salt	Thermal conductivity has increased by approximately 76.8%, while specific heat capacity has increased by 29.8%.	Decrease in supercooling degree from 12.2 to 4.7 °C.	191
Gr-h-BN by 0.10% wt.	Water	Increment by 12% for thermal conductivity at 20 °C and 64% at 60 °C, both at concentration of 0.10% wt.	The system reached a thermal effectiveness of 85% at 0.10% wt., which is 20% elevated compared to the water.	196
GO at 0.5%, 1%, and 2% wt.	Ionic liquid	Increase of 6.5% in thermal conductivity and 27% in specific heat capacity.	A 7.2% enhance in heat transfer coefficient was observed at concentration of 0.5% wt.	197
h-BN-titanium nitrate at 20−100 ppm	Water	Exergy efficiency of 83% at a concentration of 80 ppm.	The photothermal conversion efficiency reached a maximum of 78% at a concentration of 80 ppm	198
h-BN ranges from 0.25% to 2.0% wt.	Water	The highest level of energy efficiency attained was around 72.1% when the volume fraction was 1.5% and the mass flow rate was 0.051 kg/s. Highest improvement in energy efficiency, almost 84%, was seen when the volume fraction was 1.5% and the mass flow rate remained constant. Highest exergy efficiency of 13.1% was achieved when the volume fraction was 1.25% and the mass flow rate was 0.017 kg/s.	The minimum entropy production of 42.9 W/K was achieved at a concentration of 1.25% vol. It was observed that entropy generation increased with higher mass flow rates and lower concentrations.	199

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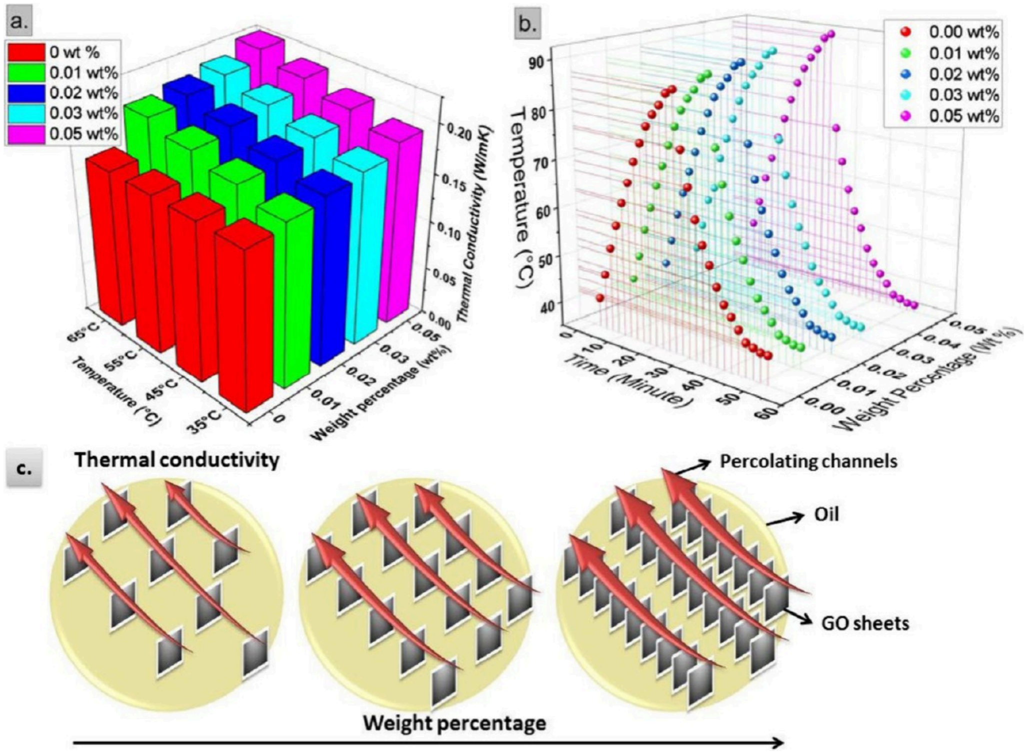

Figure 17. Enhancements in thermal conductivity of GO-based CSO nanofluids: (a) thermal conductivity, (b) thermal response, and (c) proposed heat transport mechanism.

research areas include enhancing solar absorbers and thermal energy tubes, improving nanofluid performance, evaluating steam generation in direct steam systems, and advancing thermal energy storage in CSP plants. These studies will be instrumental in advancing the CSP technology and optimizing its efficiency.

5.5. Transformers. Nanofluids with superior thermal conductivity and dielectric properties offer a cost-effective solution for thermal management in electrical transformers. While vegetable oils are traditionally used for insulation and cooling, their performance is limited by contamination and degradation. Integrating nanoparticles such as silica−alumina or CNTs into these base fluids enhances heat transfer efficiency stability and dielectric strength, improving thermal stability lifespan and efficiency of transformer systems. Siddique et al.[200] reviewed the progress in transformer insulating oils, highlighting the shift from mineral oils to eco-friendly esters and nanofluids, and discussing issues related to stability and environmental impact. Farade et al.[201] examined the thermal properties of cotton oil-based nanofluids with graphene oxide (GO) concentrations of 0.01, 0.02, 0.03, and 0.05 wt %. Their results showed a continuous increase in thermal performance up to 0.05 wt %, as shown in Figure 17. Maharana et al.[201] demonstrated that exfoliated h-BN nanosheets in mineral oil improved heat transfer, insulation, and AC breakdown voltage. Future studies should focus on optimizing the performance, stability, and synthesis of nanofluids for use in transformers.

The authors derived the following outcomes from the results:

- The incorporation of 0.01 wt % exfoliating h-BN nanoparticles into mineral oil leads to the making of a highly stable solution exhibiting enhanced cooling and insulating characteristics.
- Exfoliated h-BN nanoparticles enhance nanofluid thermal conductivity and improve AC breakdown voltage by reducing moisture affinity, outperforming mineral oil and other fillers.

The research performed by Almeida et al.[202] by investigating electrical and thermophysical characteristics of transformer oil with varying concentrations (0.01%, 0.03%, 0.05% wt.) of graphene nanoparticles. The examination was carried out throughout the temperature limit of 20−90 °C. The study resulted in the following conclusions:

- The 0.05% wt. graphene nanofluid demonstrated a 2.5% increase in viscosity and a 16.6% increase in density associated with conventional transformer oil.
- The nanofluid containing 0.05% weight of Gr indicated a significant decrease in surface tension, with a maximum reduction of 10.1%. Elevated temperature and concentration of Gr nanoparticles augmented Brownian motion, resulting in a more homogeneous temperature distribution and reduced intermolecular interactions among nanoparticles, hence enhancing heat transfer rates.
- All tested nanofluids, including 0.05% wt. Gr, showed reduced specific resistance, with a 79% decrease at 90 °C compared to conventional transformer oil, enhancing electrical conductivity and breakdown voltage. Table 12 summarizes recent experimental research on nanofluids in transformer technology.

Table 12 presents current experimental research on the usage of nanofluids in electrical transformer technology. In summary, a significant research gap exists regarding the application of nanoparticles in transformer oils compared

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Table 12. Current Research on the Utilization of Nanofluids in Electrical Transformers

Nanomaterials/Concentration	Base Fluid	Main Findings	Remarks	ref.
Gr quantum dots at 0.001% wt.	Transformer oil	23.9% Augmentation in heat transfer coefficient	A minimal increase of 1.3% in viscosity was observed.	203
Hexylamine-functionalized carbon nanotubes at concentrations of 0.001% and 0.005% by wt.	Transformer oil	A 10% increase in thermal conductivity (TC) compared to the transformer oil alone by the concentration of 0.005% wt.	Increases of 23% and 28% were observed in the forced and natural convection heat transfer coefficients, at concentration of 0.005% wt.	204
MWCNTs up to 0.02 g/L	Disposed Transformer oil	A concentration of 0.005 g/L resulted in a significant increase of roughly 212.6% in AC breakdown strength and 40% in lightning impulse performance, compared to the performance of the transformer oil alone.	The incorporation of multiwalled carbon nanotube outcome in reduce dissipation factor, with concurrent enhancements for the permeability and resistance of the transformer oil.	205
CNTs ranging starts by 0.01 g/L to 0.2 g/L	Mineral oil	An increase of approximately 118.3%, interruption in voltage was observed at a 1% possibility and a concentration of 0.01 g/L.	The nanofluid, with a concentration of 0.01 g/L, had a substantial influence on storage modulus, viscosity, and thermal behavior, resulting in improved breakdown performance.	206
MWCNTs operationalized with OH from 0.001% wt. and 0.01% wt.	Transformer oil	Enhancement of about 26.2% and 30.1% in heat transfer coefficient were observed at concentrations of 0.01% wt. and 0.001% wt., respectively.	Reduction of approximately 28.4% in breakdown voltage at a concentration of 0.01% wt.	207

with the more extensively studied synthetic oils. Future investigations should prioritize the development of eco-friendly synthesis methods and the formulation of more stable nanofluids by exploring the use of quasi-amorphous graphene and carbon nanotubes in enhancing transformer performance, particularly in improving breakdown voltage and extending operational lifespan, which is essential. Research should focus on understanding the effects of nanofluids on electrical stress distribution, permittivity, and loss factors to mitigate potential damage to transformer components. The exploration of phase-change nanofluids and sustainable, nonedible oils such as cottonseed oil for energy-efficient thermal management should be prioritized.

5.6. Cold Thermal Energy Storage. Efficient thermal energy storage is critical for applications, such as air conditioning in large buildings. Nanofluids containing graphene, with their high latent heat capacity and 2D structure, are highly suitable for this purpose. The integration of nanofluids with phase change materials (PCMs) in hybrid systems has shown promise in improving cold thermal energy storage. While ethylene glycol-based nanofluids are commonly used in subzero systems, they face challenges, including significant supercooling, extended freezing times, low storage capacity, and limited colloidal stability. By addressing the following issues, Song et al.[208] developed nanofluid stability by suspending graphene oxide nanosheets in ethylene glycol. Their formulation achieved an 87.2% reduction in supercooling and a 78.2% decrease in freezing time and retained 98.5% of latent heat. Similarly, Roy et al.[209] demonstrated that incorporating Al_2O_3-water nanofluids in a shell-and-tube heat exchanger with PCM significantly enhanced thermal conductivity, discharge efficiency, and the Nusselt number. The thermal conductivity elevated by 12.1% compared to ethylene glycol alone, and the nanofluids showed stable performance after 50 freeze-melt cycles, proving their effectiveness in advanced subzero phase change storage systems with exceptional performance capabilities. Bibi et al.[210] investigated time-dependent laminar convective heat transfer in coaxial pipes with variable surface temperature and heat radiation, employing a two-dimensional mathematical model solved via the implicit finite difference method, with a focus on radiation's effect on flow and thermal efficiency. Zhang et al.[211] developed SAT-based eutectic hydrate salt composites (CPCMs) to mitigate supercooling and enhance thermal conductivity, with the SAT/SSD-9/1 blend achieving the highest latent heat (196.18 J/g) and optimal thermal performance. Geng et al.[212] synthesized ester-based phase change materials using PEG and lauric acid, achieving a phase change range of −10 to 30 °C, a latent heat of 92.45 J/g, and minimal supercooling (4.01 °C), with thermophysical properties and energy storage capacity shown in Figure 18. Despite these advancements, more research is needed to develop effective thermal energy management systems with speedy charging capabilities. Supplementary investigation is required to explore potential advantages of integrating nanofluids with PCMs, their influence on the rates of supercooling and freezing, and their utilization in energy-efficient air-conditioning systems based on chillers for large-scale buildings.

5.7. Geothermal Heat Recovery. Nanofluids exhibit significant potential for enhancing the thermal performance of geothermal borehole heat exchangers (GHEs) when used as heat transfer fluids, particularly in Ground Source Heat Pump Systems (GSHPS). These systems present a sustainable

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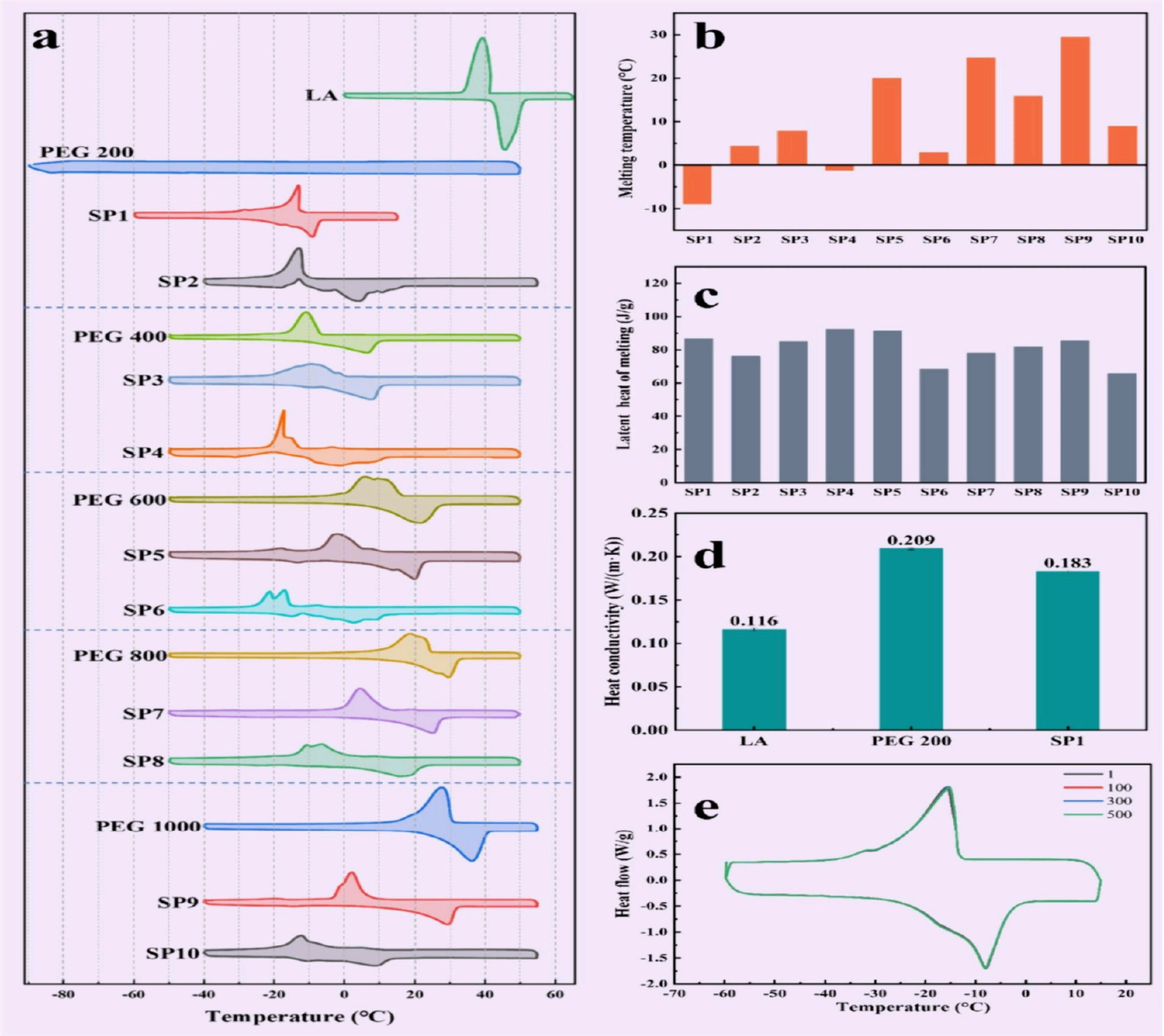

Figure 18. Thermophysical properties and energy storage capacity of the as-prepared PCM. (a) DSC curves of the melting and freezing process of LA, PEG 200, PEG 400, PEG 600, PEG 800, PEG 1000, and SP1–SP10. (b) Melting temperature of SP1–SP10. (c) Latent heat of melting of SP1–SP10. (d) Thermal conductivity of LA, PEG 200. and SP1. (e) Freezing and melting cycling curves of SP1.

alternative to fossil fuel-based energy solutions by leveraging stable subterranean temperatures, typically found at depths greater than 15 m, to effectively meet both heating and cooling demands. Despite their environmental advantages, GSHPS face challenges due to their high initial capital cost compared to that of conventional HVAC systems. Current research is focused on optimizing GHE efficiency, exploring methods to reduce borehole depth, and enhancing the overall system performance without compromising operational efficiency or thermal stability. Wang et al.[213] established and validated a dynamic heat transfer model used for Double-Borehole Heat Exchangers (DBHEs) in Multi-Directional Ground-Source Heat Pumps (MD-GHPs), optimizing insulation, flow rates, and geothermal gradients to enhance heating efficiency. Graphite nanofluids were found to offer the best performance, with other nanofluids also showing significant improvements. Key conclusions from the study include:

- When nanofluids are utilized instead of water alone, the working process of fluids output temperature increased, and the necessary pipe length dropped.
- An enhanced flow rate of the nanofluid led to a decline in outlet temperature difference.
- When nanofluids were used, the temperature of the fluid being utilized at the output was raised and the length of pipe needed dropped in comparison. Enhancement in greenhouse effect efficiency achieved using nanofluids declined as the flow rates increased and temperature variations between the soil and the intake fluid became smaller. Increased efficiency was observed while using longer pipe and borehole radius as well as increased overall depth to water.
- At a flow rate of 0.4 L/s, outlet fluid temperature decreased by approximately 65% with the use of MWCNTs and graphene nanoparticles.

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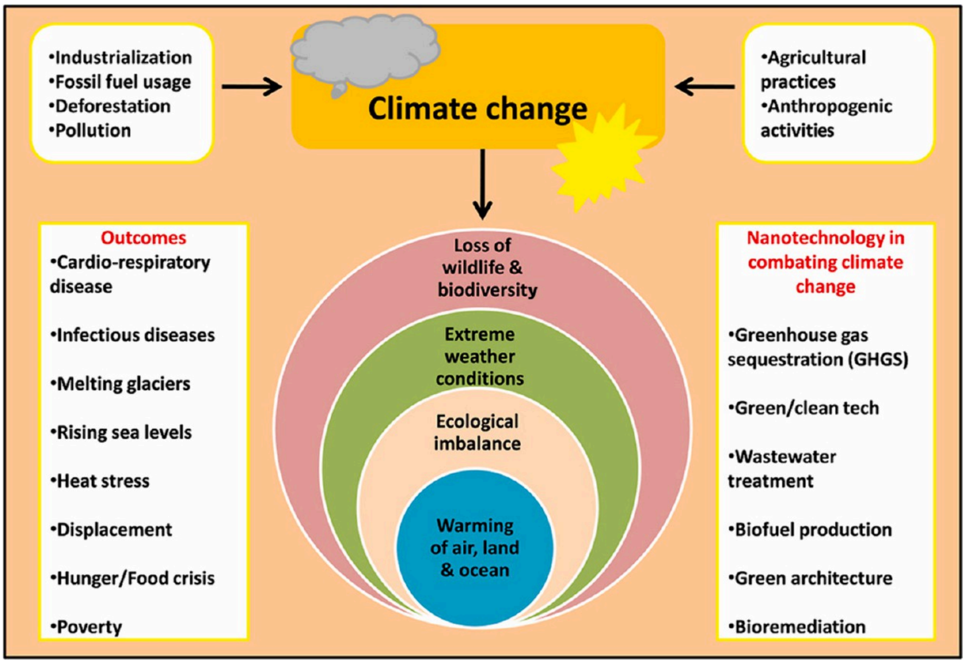

Figure 19. Nanotechnology as a sustainable approach for combating the environmental effects of climate change.

- The pipe length was reduced by approximately 32.9% with MWCNTs and 37.1% with graphene nanoparticles when flow rate increased to 0.4 L/s.
- MWCNTs achieved a maximum reduction of 11.4% in the output fluid temperature difference and 53.4% in the GHE length when the diameter of pipe grew from 20 to 50 mm. The reductions for graphene nanoparticles were 12.06% to 50.2%.
- With an increase in borehole size from 70 to 110 mm, there was a 14% elevation in outlet temperature and a 20% decline in pipe length for MWCNTs. For graphene nanoparticles, these values were 18.9% and approximately 20%, respectively.
- The maximum enhancement in outlet fluid temperature and reduction in pipe length were approximately 68% and 61.7%, respectively, for both MWCNTs and graphene nanoparticles when the temperature difference among the inlet and soil increased from 7 to 15 °C.

It is recommended that future research directions in nanofluids for geothermal heat exchangers should prioritize numerical simulations across both laminar and turbulent flow regimes. Emphasis should be placed on exploring advanced nanofluids and hybrid formulations in innovative heat exchanger designs such as finned conical helical structures to improve flow rates and enhance the ground heat extraction efficiency. The issue of nanoparticle sedimentation in borehole heat exchangers requires attention, as long-term operation at low flow velocities could lead to blockages. Numerical simulations are pivotal in addressing these challenges and improving the operational stability. Future research could also focus on creating eco-friendly synthesis methods, developing more stable nanofluid formulations, and investigating phase-change nanofluids for energy-efficient applications.

6. ENVIRONMENTAL IMPACT OF NANOFLUIDS

Nanofluids are recognized as viable substitutes for conventional heat transfer fluids, but evaluating their environmental impact is crucial. Although research on this aspect is limited, some studies suggest that nanofluids could be a more sustainable option. Their impact on the environment is determined by several features such as thermal conductivity, heat transfer coefficient, emissions, energy efficiency, and pressure drop, which is a ratio of energy output to total energy intake. Said et al.[214] highlighted the environmental considerations of nanofluids used in solar collectors, focusing on nanoparticle emissions, fluid stability, and potential ecological effects. Given the current environmental challenges, renewable energy sources are a key area of focus, and harnessing these sources effectively is essential. With their higher surface area and thermal conductivity, nanomaterial-based thermal fluids demonstrate enhanced performance and can lead to reduced equipment size, as shown by Sundar et al.[215] This reduction in the equipment size contributes to lower CO_2 emissions and more environmentally friendly processes. However, despite low emissions through the generation of nanoparticles, these factors must be considered when assessing the thorough environmental impact.

Nanomaterials have the potential to enhance renewable energy technologies and carbon capture systems, offering significant opportunities for mitigating greenhouse gas emissions. Nanotechnology can also help reduce the environmental impact of industries through improved energy efficiency and cleaner production methods, as shown in Figure 19. However, the production of nanomaterials is often energy-intensive, and emissions associated with their lifecycle could contribute to climate change. Additionally, the release of nanomaterials into the environment may disrupt ecosystems and atmospheric processes, impacting biogeochemical cycles. Therefore, a comprehensive Life Cycle Assessment (LCA) is crucial for evaluating their net impact on climate change and ensuring their sustainable use.[216]

A comprehensive tool like Life Cycle Assessment can offer valuable insights into potential environmental issues and support the environmental sustainability of nanomaterials.[217] Life Cycle Assessment provides a systematic approach to

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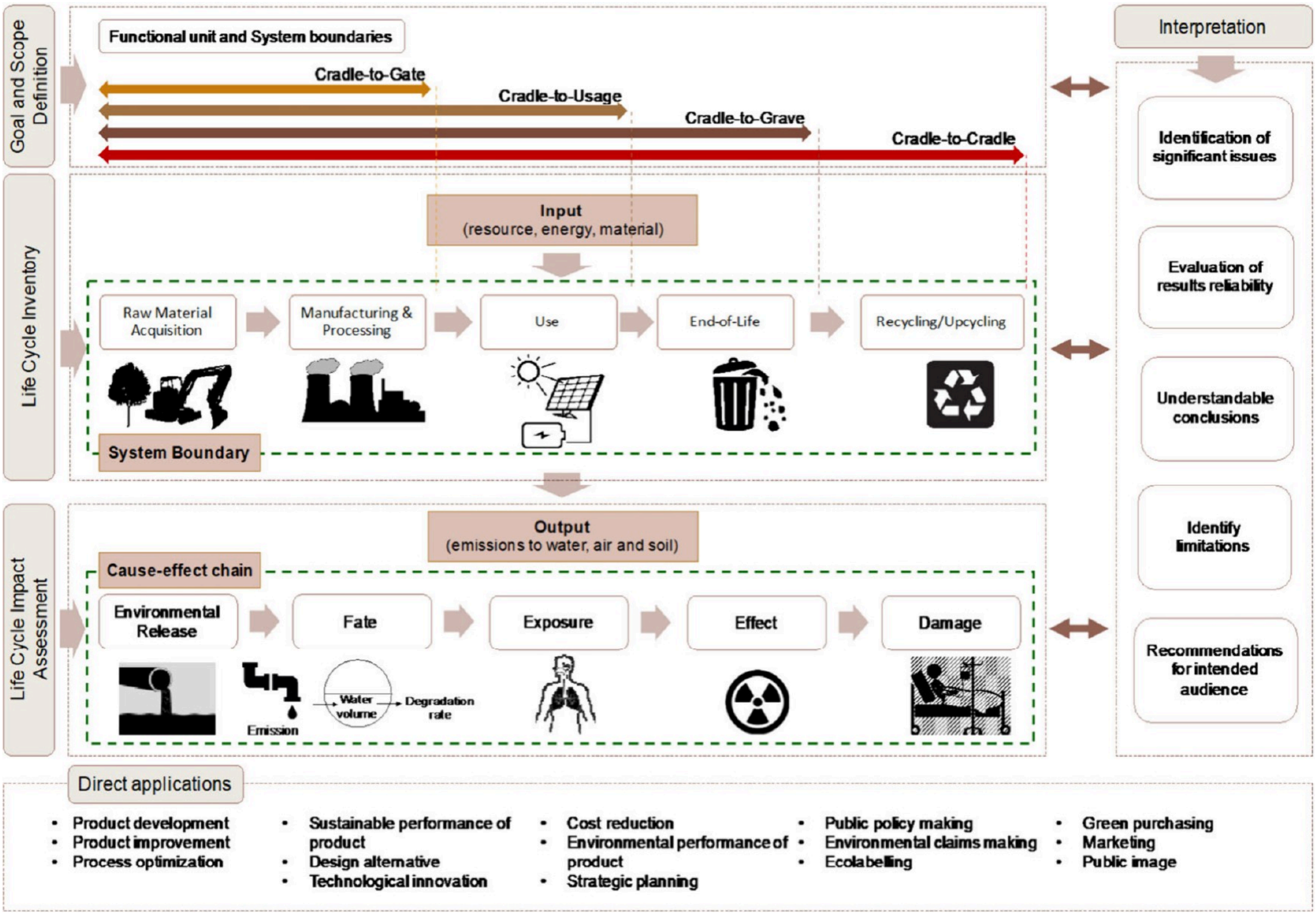

Figure 20. A generic life cycle assessment framework. Reproduced with the permission of Hanafiah.[220] Copyright 2021 MDPI.

evaluating the environmental impacts of a product across its entire life cycle by considering the materials used, energy consumption, and emissions released into the environment.[218] This method is particularly essential for assessing the potential consequences of nanomaterial release, as depicted in Figure 20. LCA follows an internationally recognized framework, based on the ISO 14040 series (ISO 2006), and includes four key phases: (i) goal and scope definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) life cycle interpretation. This methodology was developed as a tool to evaluate the environmental impacts of products and their associated processes.[219]

The widespread use of nanomaterials highlights the need to assess their potentially harmful synthesis processes. Improper disposal of effluents and the release of toxic emissions during nanomaterial production can adversely affect the ecosystem and human health. Nanomaterials are usually produced through methods such as laser ablation, chemical reduction, chemical vapor deposition, and sol−gel techniques. CVD is broadly utilized because it is economical in producing large quantities of carbon nanotubes and other nanomaterials. Rehman et al.[221] assessed the environmental impact of nanofluids in tubular heat exchangers, emphasizing the importance of careful source material selection, effective waste management, and addressing health risks to ensure sustainable applications.

Enhancing the recovery of primary fluids and nanoparticles from nanofluids is essential for mitigating environmental harm by decreasing water contamination. Efficient techniques for recovery, such as centrifugation pursued by evaporation of the liquid above the sediment, are crucial for this objective. Nevertheless, some cutting-edge materials and chemicals continue to present environmental and health hazards, such as benzene, halocarbons, polychlorinated biphenyls, and dichlorodiphenyltrichloroethane. A thorough assessment is necessary for these chemicals to minimize the potential health risks. Nanoparticles can pass into the human body mainly via the respiratory tract, which means that the lungs are particularly vulnerable to their presence. The detrimental effects of nanoparticles are significantly influenced by their chemical and structural features, including factors such as size, aggregation, and chirality. Nanomaterial exposure can damage the cytoskeleton, disrupt DNA repair mechanisms, impede cell signaling, and induce synthesis of cytokines associated with inflammation and chemokines. Figure 21 shows the preparation, application, and environmental hazards. Research has shown that toxicity increases as the size of nanomaterials decreases and studies on materials like graphene and molybdenum disulfide (MoS_2) have highlighted this trend; to limit the intake of nanoparticles through the respiratory and digestive systems and mitigate health hazards, it is advisable to utilize air purifiers and water filtration devices.[223] Moreover, rigorous testing of commercially accessible nanomaterials for environmental toxicity is essential. Conducting comprehensive life cycle assessments on various nanomaterials will support the

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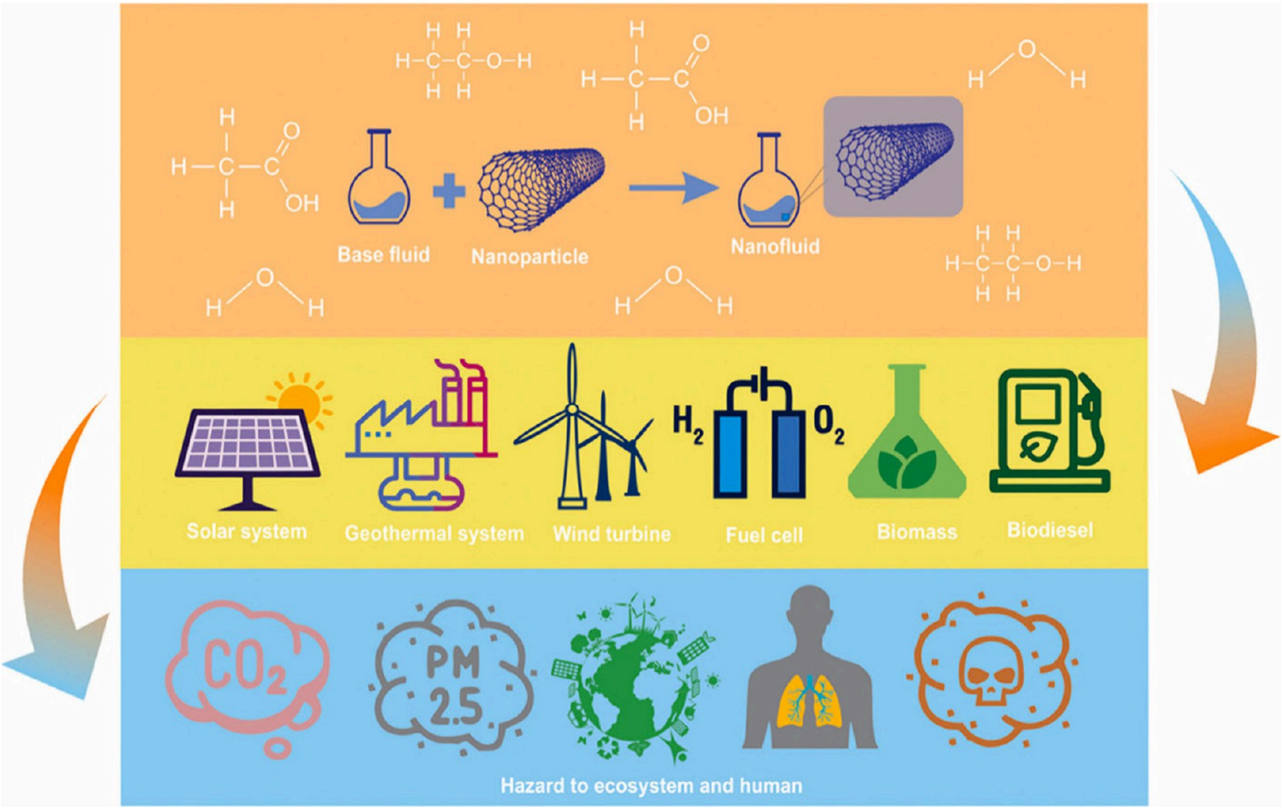

Figure 21. Environmental impacts of nanofluids: preparation, applications, and ecosystem hazards. Reproduced with the permission of Mahian.[222] Copyright 2021 Elsevier Ltd.

development of measures to minimize their negative environmental and health impacts.

7. RESULTS AND DISCUSSION

Nanofluids have emerged as a transformative type of heat transfer fluid, exhibiting outstanding thermophysical characteristics that position them as a feasible alternative to conventional fluids across diverse advanced engineering applications. The incorporation of nanoparticles into base fluids fundamentally alters their thermal conductivity, viscosity, and overall heat transfer performance. Such integration gives a substantial enhancement of these properties, making nanofluids particularly advantageous in high-demand areas like electronics cooling, heat exchangers, photovoltaic/thermal (PV/T) systems, concentrated solar power (CSP) technologies, electrical transformers, and geothermal heat recovery systems.

The development of thermal conductivity is one of the most important findings in nanofluid research. Complex mechanisms behind this improvement include the formation of nanolayers around the nanoparticles, Brownian motion, and nanoparticle aggregation. These processes contribute to the enhanced heat transfer capabilities observed in nanofluids. Notably, hybrid nanofluids combining different types of nanoparticles such as graphene and carbon nanotubes exhibit a particularly high degree of thermal conductivity enhancement because of synergistic connections between the nanoparticles. However, this enhancement often comes at the cost of increased viscosity, which can adversely affect the fluid's flow dynamics and energy efficiency. The intricate balance among nanoparticle size, shape, and concentration is critical to optimizing both thermal conductivity and viscosity, underscoring the need for precise control over these parameters to maximize the heat transfer efficiency while minimizing the associated energy consumption.

In practical applications, such as heat exchangers and electronics cooling systems, nanofluids have demonstrated substantial performance improvements. For instance, empirical studies report up to a 123% increase in convective heat transfer coefficients when nanofluids are used in heat exchangers. Such enhancements not only enhance energy efficiency but also enable the reduction of equipment size, contributing to more compact and efficient system designs. Similarly, in electronics cooling, nanofluids, particularly those based on graphene and carbon nanotubes, have been shown to significantly improve heat transfer rates, which are crucial for managing the intense thermal loads in modern electronic devices. However, these applications also present challenges, including the potential for increased pressure drops and nanoparticle sedimentation, which could undermine the long-term stability and efficiency of the nanofluids. These issues highlight the necessity for continued research into the formulation and stabilization of nanofluids to ensure their reliability in long-term industrial applications.

From an environmental perspective, while nanofluids offer considerable benefits in terms of reducing CO_2 emissions and enhancing energy efficiency, their environmental impact throughout their life cycle warrants careful consideration. The synthesis of nanomaterials often involves processes that may release hazardous byproducts, and the disposal of nanofluids poses potential ecological risks. The toxicity of nanoparticles, particularly when inhaled or ingested, raises significant health concerns, making it imperative to develop sustainable production and recovery methods. Future research

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should focus on environmentally friendly nanomaterial synthesis, comprehensive life cycle assessments, and the development of recovery techniques that mitigate the environmental footprint of nanofluids.

The future of nanofluid research holds substantial promise with several key areas poised for further investigation. A particularly exciting avenue is the development of hybrid nanofluids, which offer the potential for precisely tailored characteristics such as adjustable viscosity and enhanced thermal conductivity. These advancements can be applied in cutting-edge technologies such as PV/T systems and CSP plants, significantly improving energy efficiency and reducing operational costs. Future research should prioritize the creation of eco-friendly synthesis methods, the development of more stable formulations, and the investigation of phase-change nanofluids for energy-efficient applications. Additionally, the integration of nanofluids with phase-change materials (PCMs) and the exploration of novel nanomaterials such as metal chalcogenides are expected to enhance the sustainability and performance of thermal management systems. Nanoparticle dispersion stability, environmental safety, and scalable production methods must be explored through advanced numerical simulations and experimental studies to optimize the nanofluid performance. A promising direction includes addressing the corrosion challenges of molten salt nanofluids, which could further enhance their application in high-temperature systems. These advancements will be crucial in bridging the gaps between laboratory-scale research and large-scale industrial applications.

8. CONCLUSION

The essential findings from this study can be succinctly described as follows, highlighting the critical findings on nanofluid preparation, thermal conductivity, viscosity, and their environmental impacts:

- Nanofluids significantly improve thermal conductivity, viscosity, and heat transfer coefficients, making them superior to conventional fluids in applications such as heat exchangers, electronics cooling, PV/T systems, CSP technologies, and geothermal heat recovery.
- The use of hybrid nanofluids, particularly those incorporating graphene and carbon nanotubes, offers substantial gains in thermal performance due to synergistic effects, though viscosity management remains critical.
- Nanofluids have demonstrated up to a 123% boost in convective heat transfer coefficients and notable improvements in electronics cooling, highlighting their practical benefits in energy efficiency and system miniaturization.
- The environmental impact of nanofluids, including potential toxicity and hazardous byproducts, necessitates sustainable production methods, effective recovery techniques, and comprehensive life cycle assessments.
- Addressing challenges such as nanoparticle sedimentation, pressure drops, and environmental risks is essential for the long-term viability and widespread adoption of nanofluids in next-generation energy systems. Future research should focus on optimizing hybrid nanofluids, exploring novel nanomaterials like metal chalcogenides, and integrating phase change materials to improve the effectiveness and sustainability of thermal management systems.
- Findings of this review highlight the significant impact that nanofluids can have on improving thermal management systems. It introduces novel methods, such as combining phase change materials with hybrid nanofluids, which hold the capability to advance energy storage and thermal regulation applications.

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Notes

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NOMENCLATURE

MWCNT	Multiwall carbon nanotube
MHD	Magnetohydrodynamic
CNT	Carbon nanotube
CSD	Concentrated solar power
PV/T	Photovoltaic/thermal
nm	Nanometer
EO	Engine oil
EG	Ethylene glycol
HTF	Heat transfer fluid
T	Temperature
M	Magnetic/Hartmann parameter

K	Local permeability parameter
C_p	Specific heat capacity at constant pressure
K_{hnf}	Thermal conductivity
ρC_p	Heat capacity at constant pressure situation of the fluid
PVD	Physical vapor deposition
SDBS	Sodium dodecyl benzenesulfonate
SDS	Sodium dodecyl sulfate
CTAB	Cetyltrimethylammonium bromide
CMC	Critical micellar concentration
C_f	Coefficient of friction
THW	Transient hot wire
TCA	Thermal constant analyzer
ISP	Isoelectric point
ANN	Artificial neural network
GO	Graphene oxide
HVAC	Heating ventilation air conditioning
PCM	Phase change material
GSHPS	Ground source heat pump system
DBHE	Double borehole heat exchanger
CVD	Chemical vapor deposition
Re	Renold number

Greek symbols

γ	Eigen (value) parameter
η	Similarity variable
ρ	Density of the fluid
μ_{hnf}	Dynamic viscosity of the hybrid nanofluid
μ	Viscosity of the fluid
$(\rho C_p)_{hnf}$	Heat capacitance at constant pressure situation for the hybrid nanofluid
ζ	Zeta potential
φ/Φ	Volume concentration

Subscripts

nf	nano(mono)fluid
hnf	nano(hybrid)fluid
f	fluid (base)
∞	ambient situation

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