

Review

## Nanofluids: Preparation, Stability Factors, Environmental Impacts, and Applications

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### Abstract

Nanofluids, suspensions of nanoparticles in base fluids, have emerged as a transformative technology in thermal management and energy systems. This article explores the preparation methods of nanofluids, including one-step and two-step approaches, and examines critical factors influencing their stability, such as nanoparticle shape, size, Brownian motion, zeta potential, surfactants, and pH. The characterization techniques for nanofluids are discussed, alongside their environmental implications. The essay further highlights diverse applications, including solar energy, heat exchangers, refrigeration, transportation cooling, transformer oil, and electronics cooling. By synthesizing current knowledge, this review underscores the potential of nanofluids to enhance efficiency in various industries while addressing stability and environmental challenges.

### 1. Introduction

Nanofluids, defined as engineered suspensions of nanoparticles in base fluids such as water, oil, or ethylene glycol, have garnered significant attention in materials science and engineering due to their enhanced thermal and physical properties. Unlike traditional fluids, nanofluids exhibit superior thermal conductivity, viscosity, and heat transfer capabilities, attributed to the presence of nanoparticles typically ranging from 1 to 100 nanometers in size[1]. These particles, which can be metals, oxides, or carbon-based materials, are dispersed in a base fluid to create a stable colloidal suspension. The discovery of nanofluids, pioneered by researchers like Stephen Choi in the 1990s, marked a paradigm shift in thermal management, offering potential solutions to longstanding challenges in energy efficiency and heat dissipation across various industries[2, 3].

The development of nanofluids has been driven by the need for advanced materials to meet the demands of modern technologies, particularly in energy and electronics sectors. Traditional heat transfer fluids, such as water or oils, often fall short in applications requiring high thermal conductivity or efficient cooling under extreme conditions[4]. Nanofluids address these limitations by leveraging the unique properties of nanoparticles, which enhance heat transfer through mechanisms like Brownian motion and increased surface area. Moreover, the ability to tailor nanofluid properties by adjusting nanoparticle type, size, shape, and concentration has opened new avenues for innovation, making them versatile for applications ranging from solar energy systems to high-performance computing[4].

The preparation of nanofluids, a critical aspect of their development, involves complex processes to ensure stability and performance. Two primary methods dominate: the one-step method, which synthesizes and disperses nanoparticles simultaneously in the base fluid, and the two-step method, which involves synthesizing nanoparticles separately before dispersing them. Each approach has distinct advantages and challenges, particularly concerning the

stability of the resulting suspension. Factors such as nanoparticle aggregation, sedimentation, and interaction with the base fluid can significantly affect nanofluid performance, necessitating a deep understanding of preparation techniques and stability mechanisms to optimize their practical use[5, 6].

Beyond preparation, the stability of nanofluids is influenced by multiple factors, including nanoparticle shape and size, Brownian motion, zeta potential, surfactants, and pH. These factors determine the dispersion quality and long-term usability of nanofluids in real-world applications. For instance, the zeta potential, which measures the electrostatic repulsion between particles, plays a crucial role in preventing aggregation, while surfactants and pH adjustments can further enhance stability. Additionally, the environmental implications of nanofluids, including their potential toxicity and lifecycle impact, are increasingly under scrutiny as their applications expand, highlighting the need for sustainable practices in their development and deployment[7, 8].

This review essay aims to provide a comprehensive analysis of nanofluids, focusing on their preparation, stability factors, characterization, environmental impact, and diverse applications. By synthesizing current research and technological advancements, the essay seeks to elucidate the potential of nanofluids to revolutionize thermal management and energy systems while addressing challenges related to their stability and environmental footprint.

## 2 .Preparation of nanofluid

Nanofluids are engineered by suspending nanoparticles within a base fluid, such as water, oil, or ethylene glycol, to enhance properties like thermal conductivity or viscosity. Achieving uniform dispersion is critical for practical applications, as poor dispersion can lead to nanoparticle aggregation and reduced performance. To improve stability, techniques such as adding surfactants, modifying nanoparticle surfaces, or applying external forces (e.g., ultrasonication) to break up particle clusters are often employed. Two primary approaches for preparing nanofluids are the two-step method and the one-step method, with emerging chemical synthesis techniques also gaining attention. The volumetric concentration of nanoparticles in the nanofluid, a key parameter, is calculated using the following Eq.1[1]:

$$\text{Volume concentration, } \phi = \left[ \frac{\frac{W_{np}}{\rho_{np}}}{\frac{W_{np}}{\rho_{np}} + \frac{W_{bf}}{\rho_{bf}}} \right] \quad (1)$$

where  $W_{np}$  is the weight of the nanoparticles,  $W_{bf}$  is the weight of the base fluid,  $\rho_{np}$  is the density of the nanoparticles, and  $\rho_{bf}$  is the density of the base fluid. This equation quantifies the nanoparticle volume fraction, which influences the nanofluid's properties and stability.

### 2.1 One-step method

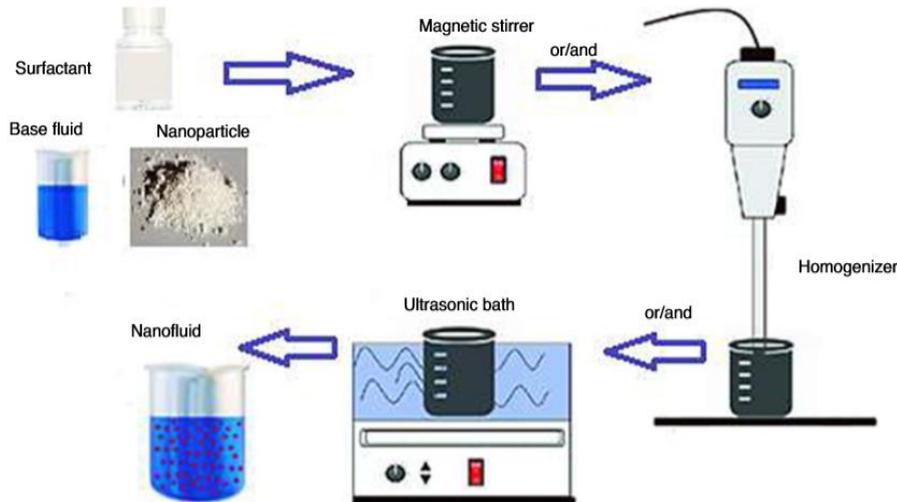
The one-step method integrates nanoparticle synthesis and dispersion into a single process, minimizing steps like drying, storage, or transportation that can lead to aggregation. Techniques such as Physical Vapor Deposition (PVD) or laser ablation are used to directly produce and disperse nanoparticles into the base fluid, resulting in highly uniform and stable nanofluids. This approach reduces particle clustering and produces purer nanoparticles, but it is costlier and often leaves residual reactants in the fluid, which may affect performance. For example, copper-based nanofluids have been successfully prepared using one-step methods, showcasing enhanced stability but limited scalability due to high costs[9].

### 2.2 Two-step method

The two-step method is widely used for its cost-effectiveness and suitability for large-scale production. In this approach, nanoparticles are first synthesized as a dry nanopowder using physical or chemical techniques, in Figure 1 . These nanoparticles are then dispersed into a base

fluid using methods like magnetic stirring, ultrasonication, or high-shear mixing. This method is economical and allows flexibility in choosing nanoparticle and base fluid combinations.

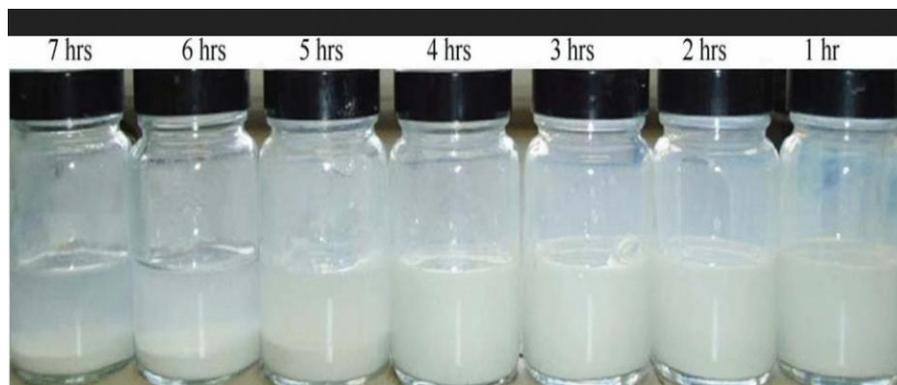
However, a significant challenge is the tendency of nanoparticles to aggregate due to strong interparticle forces, which can compromise stability. To mitigate this, surfactants or dispersants are often added, though they may alter the nanofluid's properties. For instance, studies have demonstrated the preparation of aluminum oxide ( $\text{Al}_2\text{O}_3$ )/water nanofluids using this method, highlighting its scalability despite stability challenges [10].



**Fig.1** Preparation of nanofluids using a two-step method ( Reproduced with permission from Yilmaz et al.[11] ).

### 2.3 Factors Influencing Nanofluid Stability

The stability of nanofluids is crucial for maintaining consistent thermophysical properties, such as thermal conductivity and viscosity, over time. Stability is governed by the balance between attractive and repulsive forces acting on the nanoparticles. The Van der Waals attractive forces promote particle clustering, which can lead to sedimentation under gravitational forces, causing nanoparticles to settle at the bottom of the container. Conversely, the Electrical Double Layer Repulsive Force (EDLRF) counteracts these attractive forces by creating a repulsive barrier that keeps particles dispersed. For a nanofluid to remain stable, the EDLRF must dominate over the Van der Waals forces. Factors such as pH, surfactant concentration, and nanoparticle surface charge play critical roles in enhancing EDLRF[12, 13]. For example, sedimentation studies of  $\text{Al}_2\text{O}_3$  nanoparticles in water-based nanofluids without stabilizers show rapid particle settling over time, underscoring the need for effective stabilization strategies like surfactant addition or surface functionalization in Figure 2.



**Fig.2** Deposition of aluminum oxide ( $\text{Al}_2\text{O}_3$ ) nanoparticles without stabilizer ( Reproduced with permission from Wen et al. [14]).

### 3. Factors affecting the stability of nanofluid

#### 3.1. The effect of the shape and size of nanoparticles

The shape and size of nanoparticles are critical factors influencing the stability and thermophysical properties of nanofluids. Small-sized nanoparticles, when present in high concentrations within the base fluid, significantly enhance the thermal conductivity of nanofluids [15]. However, the impact of nanoparticle shape and size on nanofluid density is minimal. Increasing the size and altering the type of nanoparticles can influence the thermal behavior of nanofluids, with thermal conductivity being primarily associated with the type and size of nanoparticles. Smaller nanoparticles, in particular, are known to increase thermal conductivity [16]. Additionally, smaller nanoparticles and higher temperatures lead to an increase in Brownian motion [17, 18]. These smaller particles exhibit higher kinetic energy due to Brownian motion, which can contribute to the instability of nanofluids under the influence of gravity. A study by Hong et al. [15] also highlighted that the shape of nanoparticles affects both the stability and thermal conductivity of nanofluids. Nanoparticles with cylindrical shapes have a lesser impact on the thermal conductivity of nanofluids compared to those with spherical shapes. Therefore, the shape, size, and type of nanoparticles are vital considerations for achieving stable and effective nanofluids.

#### 3.2. Brownian motion

The formation of nanoparticle clusters in the base fluid is an inherent challenge for nanofluids, primarily caused by the collisions between particles due to Brownian motion [19]. High-velocity particle collisions with slower-moving particles in the fluid result in erratic particle motion driven by thermal diffusion, a process known as Brownian motion. Nanoparticles continuously collide because of this motion, as particles with larger surface areas exhibit greater activity. Several factors, such as smaller particle sizes, reduced viscosity, and higher temperatures, promote increased Brownian motion [17, 18]. Nanoparticles of extremely small sizes are characterized by higher kinetic energies resulting from Brownian motion. However, despite these high energies, nanoparticles still struggle to remain suspended in the base fluid over extended periods, which impacts the stability of the nanofluid [20].

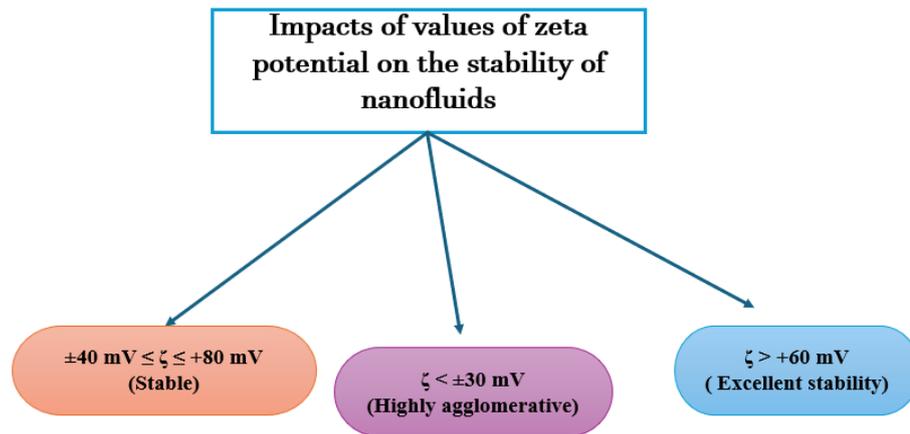
When the nanoparticles form solid clusters, their interactions with neighboring particles intensify as Brownian motion persists, resulting in strong attractive forces between the particles. This leads to a gradual increase in agglomeration, with gravity further exacerbating the instability of the nanofluids [21]. Variations in the temperature of the nanofluid directly affect Brownian motion, influencing phenomena such as thermal interactions, particle collisions, and diffusion. Furthermore, as the mass of the clusters increases, Brownian motion diminishes during cluster formation, while the adhesion between nanoparticles enhances the cluster formation and increases thermal conductivity [22]. Consequently, Brownian motion plays a crucial role in enhancing the thermal conductivity of nanofluids through interactions between nanoclusters and nanolayers, which is significant for the overall performance of nanofluids [23].

#### 3.3. Zeta potential ( $\zeta$ )

Zeta potential is a crucial factor in assessing the stability of nanofluids, both in the short-term and long-term, depending on the magnitude of the zeta potential, as illustrated in Figure 3 [24]. It is commonly used to evaluate the stability of colloidal solutions, and nanofluids are a specific example of such solutions [25]. Zeta potential (electrical potential) refers to the degree of repulsion between the charges of particles dispersed in the fluid. An increase in the zeta potential value indicates stronger Coulombic repulsive forces between the dispersed particles, particularly when the attractive van der Waals forces are weak. Therefore, nanofluids are considered electrically stable when their zeta potential is high, regardless of whether the value is negative or positive. On the other hand, low zeta potentials promote clustering and sedimentation of nanoparticles. The electric potential generated between the dispersant in the Stern layer and the base fluid, which adheres to the particle surface, can be measured using zeta

meters [25], with the zeta potential value being dependent on the pH level [18]. Zeta potential values vary with changes in pH [26].

Surfactants play a significant role in influencing the zeta potential of nanoparticles, with an increase in surfactant concentration leading to higher zeta potential values [27]. The zeta potential is also affected by the pH of the solution: at lower pH, the zeta potential is typically negative, whereas at higher pH, it becomes positive [28]. In essence, the repulsive interaction energy between nanoparticles is primarily governed by the zeta potential, which is influenced by factors such as surface energy and surface area [29]. Additionally, the shape of the nanoparticles can alter the zeta potential. Therefore, zeta potential analysis is an essential and widely used technique for assessing the stability or instability of nanofluids.



**Fig. 3** Effect of zeta potential values on the stability of nanofluids.

### 3.4. Surfactants

Surfactants play a crucial role in acting as a bridge between nanoparticles and the base fluids, with their effectiveness depending on the specific type of nanoparticles and base fluids involved. They significantly reduce the interfacial tension between nanoparticles suspended in the base fluid and increase the repulsive forces between the particles, enhancing their dispersion [27]. Surfactants, also known as dispersants, are commonly employed to prevent or minimize nanoparticle agglomeration by lowering the surface tension of the base fluid, thereby improving the stability of nanofluids. The addition of surfactants is vital for enhancing the stability of nanofluids and preventing nanoparticle sedimentation. However, excessive use of surfactants can negatively impact the thermophysical properties of the nanofluid, such as reducing thermal conductivity and compromising the chemical stability of the nanofluid [30].

The primary function of surfactants and additives in nanofluids is to prevent the precipitation of nanoparticles in the base fluid. Factors like the viscosity and properties of the base fluids also influence the clustering behavior of nanoparticles [31]. At elevated temperatures, some challenges may arise with surfactants and pH regulators that impact nanofluid stability, including the breakdown of stabilizers, which can lead to alterations in the fluid's properties, such as viscosity and surface tension. Additionally, surfactants typically have lower thermal conductivity than the base fluid, which can reduce the overall thermal conductivity of the nanofluid [27]. Therefore, it is essential to use surfactants at the optimal concentration to maintain the desired properties of the nanofluid.

### 3.5. Effect of pH

pH (potential hydrogen) is used to assess the acidity or basicity of solutions, and it plays a crucial role in determining nanofluid stability, as it influences the zeta potential [29, 32]. By regulating the pH of the fluid, it is possible to improve nanofluid stability by controlling the surface charge of the nanoparticles. This surface charge results in the formation of an electrical double layer around the nanoparticle, which generates repulsive Coulombic forces that aid in nanoparticle dispersion [33]. Variations in pH can also alter the thermal properties of

nanofluids, making pH a key factor in determining both the thermal conductivity and stability of the nanofluid [34]. Several studies have explored the effects of pH variations on nanofluid dispersion stability and other related properties.

One study investigated the use of surfactants (such as SDBS) along with hydrochloric acid to control the pH value in Al<sub>2</sub>O<sub>3</sub> and Cu-based nanofluids. It was found that the viscosity of Al<sub>2</sub>O<sub>3</sub>-based nanofluids was higher than that of Cu-based nanofluids at the same pH and weight fraction. Stable nanofluids were achieved within specific pH ranges: for Al<sub>2</sub>O<sub>3</sub>, the stable range was between 7.5 and 8.9, and for Cu, it was at pH 7.6. However, when the pH value was reduced to 7, both Al<sub>2</sub>O<sub>3</sub> and Cu nanoparticles experienced agglomeration and rapid sedimentation, leading to nanofluid instability [35]. In contrast, Ghadimi et al. [36] demonstrated that increasing the mass fraction of nanoparticles at a pH of 8 enhanced both nanofluid stability and thermal conductivity.

#### 4.Characterization of Nanofluids

This section discusses the characterisation approaches commonly employed by researchers to analyze nanofluids. Nanofluids are characterized by the following techniques: SEM, TEM, XRD, FT-IR, DLS, TGA, and zeta potential analysis. SEM examination is conducted to examine the microstructure and morphology of nanoparticles or nanostructured materials, while TEM offers far greater resolution than SEM. XRD pictures are acquired to analyze and examine the crystalline structure of nanoparticles. FT-IR spectroscopy is conducted to investigate the surface chemistry of solid particles and solid or liquid particles. DLS analysis is executed to determine the average dispersed size of nanoparticles in the base liquid medium, while TGA is utilized to examine the effects of heating and melting on the thermal stability of nanoparticles. The zeta potential value correlates with the stability of nanoparticle dispersion in the base fluid. A selection of the characterisation analyses documented in the literature is presented in Table 1.

An examination of characterisation research indicates that crucial information such as nanoparticle size, shape, chemical bonding, distribution, and stability is obtained through characterization procedures. However, several researchers employed disparate approaches, and no standardized tests are proposed to validate the homogeneity and stability of the nanofluid. Standardized accelerated tests are necessary to verify the long-term stability of disseminated nanoparticles in the base fluid.

**Table 1.** Characterization techniques.

Basic Particles/Liquids	Characterization Techniques Used	Results	Ref.
Al <sub>2</sub> O <sub>3</sub> /DI-water, EG	TEM	In TEM images, the alumina nanoparticles appear to be roughly spherical in shape, while copper oxide nanoparticles exhibit some deviations from spherical forms. The size of alumina nanoparticles varies significantly, ranging from a few nanometers to 55 nm. In contrast, copper oxide nanoparticles do not exhibit very small particle sizes.	[37]
Ag/ EG	TEM, XRD, EDX, Zeta potential analyzer, UV-vis spectroscopy	The stability of silver nanofluid is significantly influenced by the characteristics of the suspended particles and the base fluid, including particle morphology, and the chemical structure of both the particles and the base fluid. UV-vis spectroscopy results indicate that as the PAA-co-AA/AgNO <sub>3</sub> ratio increases, the particle size decreases. Zeta potential analysis further shows	[38]

		improved dispersion behavior in the suspension with the addition of the dispersant, as evidenced by a more favorable particle size distribution.	
ZnO/EG, glycerol	SEM, XRD, TEM	The samples remained stable for several months, with no signs of agglomeration or sedimentation of the particles. The shape of the ZnO nanoparticles was found to be approximately spherical.	[39]
SiC/water, EG	SEM, TEM, DLS, XRD, FT-IR and Zeta potential analysis	A detailed physico-chemical evaluation revealed various characteristics of Silicon Carbide (SiC) nanoparticles (NPs), including their crystal structure, primary and dispersed particle sizes, surface functionality, surface charge, and purity levels. These properties were examined to highlight the promising potential of SiC NPs for heat transfer applications.	[40]

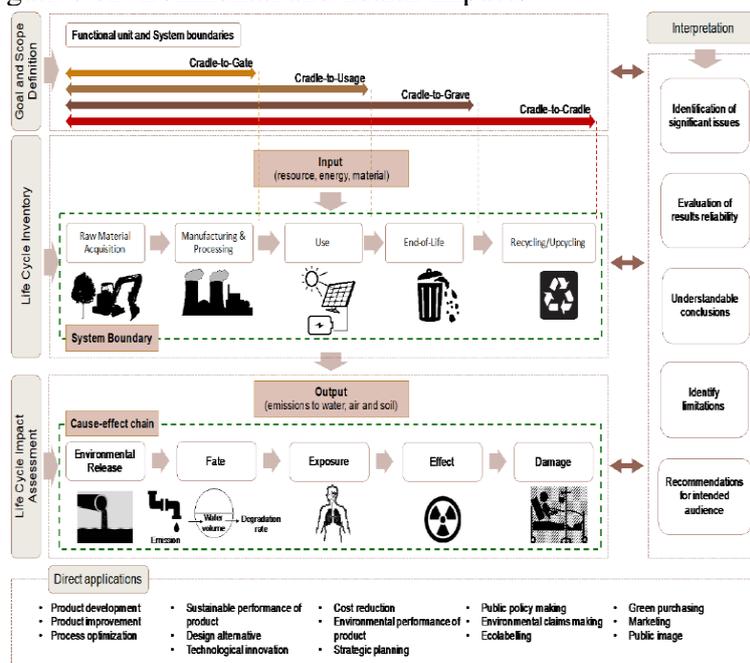
## 5.Environmental influence of Nanofluids

Nanofluids are considered viable alternatives to conventional heat transfer fluids, but assessing their environmental impact is essential. Although research in this area is still limited, some studies suggest that nanofluids could offer a more sustainable solution. The environmental impact of nanofluids is influenced by various factors, including thermal conductivity, heat transfer coefficient, emissions, energy efficiency, and pressure drop, which represents the ratio of energy output to total energy input. Said et al. [41] discussed the environmental considerations of nanofluids used in solar collectors, focusing on nanoparticle emissions, fluid stability, and potential ecological effects. In light of current environmental challenges, renewable energy sources are a primary focus, and effective harnessing of these resources is crucial. Nanomaterial-based thermal fluids, with their higher surface area and improved thermal conductivity, demonstrate enhanced performance and can lead to reduced equipment sizes, as shown by Sundar et al. [42]. This reduction in equipment size can help lower CO<sub>2</sub> emissions, making processes more environmentally friendly. However, despite the low emissions associated with nanoparticle generation, these factors must be considered when evaluating the overall environmental impact.

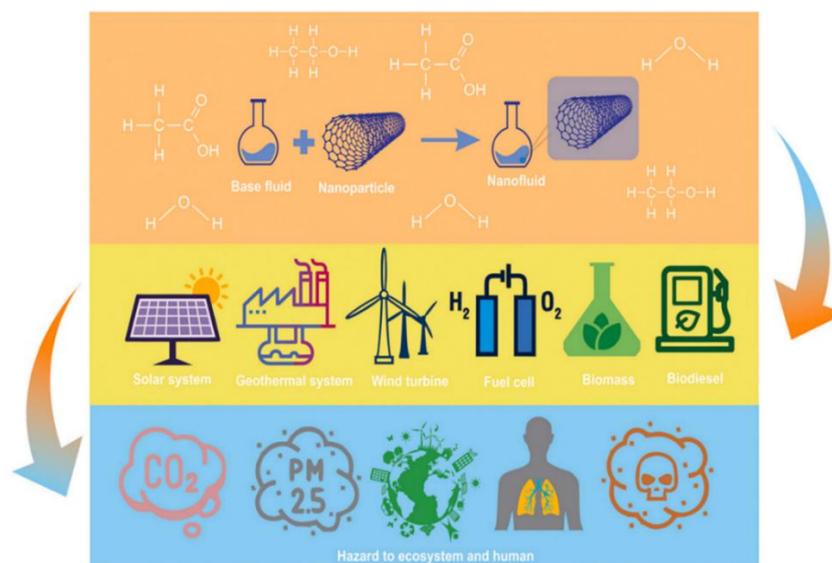
Nanomaterials hold the potential to enhance renewable energy technologies and carbon capture systems, offering significant opportunities for reducing greenhouse gas emissions. Nanotechnology also contributes to minimizing the environmental impact of industries by improving energy efficiency and promoting cleaner production methods. However, the production of nanomaterials is energy-intensive, and emissions throughout their lifecycle could contribute to climate change. Additionally, the release of nanomaterials into the environment could disrupt ecosystems and atmospheric processes, affecting biogeochemical cycles. Therefore, conducting a comprehensive Life Cycle Assessment (LCA) is vital for evaluating the net impact of nanomaterials on climate change and ensuring their sustainable use [43]. A robust tool like LCA provides valuable insights into potential environmental issues and supports the sustainable use of nanomaterials [44]. LCA offers a systematic approach to evaluating the environmental impacts of a product throughout its life cycle, considering materials, energy consumption, and emissions released into the environment. This methodology is especially important for assessing the consequences of nanomaterial release, as shown in Figure 4. LCA follows an internationally recognized framework, based on the ISO 14040 series (ISO 2006), and consists of 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 [45].

The widespread use of nanomaterials emphasizes the need to evaluate the potentially harmful synthesis processes associated with their production. Improper disposal of effluents and the release of toxic emissions during the production of nanomaterials can have detrimental effects on both ecosystems and human health. Nanomaterials are typically synthesized using methods such as laser ablation, chemical reduction, chemical vapor deposition (CVD), and sol-gel techniques. Among these, CVD is widely employed because it is cost-effective for producing large quantities of carbon nanotubes and other nanomaterials. Rehman et al. [46] assessed the environmental impact of nanofluids in tubular heat exchangers, stressing the importance of selecting appropriate source materials, implementing effective waste management practices, and addressing health risks to ensure the sustainable use of nanomaterials.

Enhancing the recovery of primary fluids and nanoparticles from nanofluids is crucial for reducing environmental harm by preventing water contamination. Techniques such as centrifugation followed by evaporation of the liquid above the sediment are essential for this purpose. However, some advanced materials and chemicals, such as benzene, halocarbons, polychlorinated biphenyls, and dichlorodiphenyltrichloroethane, continue to present environmental and health hazards. These substances require thorough assessment to minimize potential health risks. Nanoparticles can enter the human body primarily through the respiratory tract, making the lungs particularly vulnerable to their presence. The harmful effects of nanoparticles are strongly influenced by their chemical and structural characteristics, including factors such as size, aggregation, and chirality. Exposure to nanomaterials can damage the cytoskeleton, disrupt DNA repair mechanisms, impair cell signaling, and induce the synthesis of cytokines linked to inflammation and chemokines. Figure 5 illustrates the preparation, application, and environmental hazards of nanomaterials. Research has demonstrated that toxicity increases as the size of nanomaterials decreases, with studies on materials like graphene and molybdenum disulfide ( $\text{MoS}_2$ ) highlighting this trend. To limit the intake of nanoparticles through the respiratory and digestive systems and mitigate associated health risks, the use of air purifiers and water filtration systems is recommended [47]. Additionally, rigorous testing of commercially available nanomaterials for environmental toxicity is vital. Conducting comprehensive life cycle assessments on various nanomaterials will help develop strategies to minimize their negative environmental and health impacts.



**Fig.4** A general framework for life cycle assessment. (Reproduced with permission from Nizam et al. [48]).



**Fig. 5** Environmental implications of nanofluids: synthesis, uses, and ecological hazards (Reproduced with permission from Mahian et al. [8]).

## 6.Applications of nanofluid

### 6.1. Solar energy and desalination

Numerous studies in the domain of solar collectors utilizing nanofluids indicate superior performance compared to conventional base fluids [49-51]. Saffariana et al. [52] observed a 78.25% enhancement in heat transfer utilizing CuO/water nanofluid in wavy pipe solar collectors. Li et al. [53] employed EG-based SiC-MWCNTs hybrid nanofluid in direct absorption solar collectors (DASC). Their analysis revealed a solar-thermal conversion efficiency that was 48.6% greater than that of pure EG in DASC. Choudhary et al. [54] observed a 16.36% enhancement in thermal efficiency while utilizing MgO nanofluid compared to EG/DW in a solar collector.

Numerous researchers conducted investigations on solar thermal desalination systems utilizing nanofluids, which enhance efficiency and yield greater quantities of drinkable drinking water [55]. Parsa et al. [56] conducted an experimental investigation of a solar desalination system utilizing silver nanofluid. Their study demonstrates that the integration of silver nanoparticles enhances the rate of heat transfer while simultaneously functioning as an antibacterial agent.

### 6.2. Heat exchanger

Various types of heat exchangers, including shell and tube, plate-type, microchannel, and compact heat exchangers, are widely used in heavy industries, processing sectors, and more. Recently, researchers have focused on enhancing heat transfer performance by replacing traditional heat transfer fluids with nanofluids [57]. Lotfi et al. [58] investigated the use of MWNT/water nanofluid in a shell and tube heat exchanger, observing significant heat transfer enhancement due to the presence of multi-walled nanotube particles. Farajollahi et al. [59] examined the effects of nanoparticle volume concentration and Peclet number for Al<sub>2</sub>O<sub>3</sub>/water and TiO<sub>2</sub>/water nanofluids in a shell and tube heat exchanger, finding a higher heat transfer coefficient for the nanofluids. Pantzali et al. [60] conducted experimental and CFD analyses of CuO/water nanofluid in a plate heat exchanger, revealing an increase in thermal conductivity of the nanofluid. Asirvatham et al. [61] reported a 69.3% increase in heat transfer coefficient when using silver nanofluid in a double-pipe heat exchanger, with a 0.9% nanoparticle volume fraction. Additionally, compact heat exchangers using nanofluids were investigated by Humnic et al. [62], Leong et al. [63], and Vasu et al. [64], all finding enhancements in heat transfer performance. Nanoparticles have also been explored for water desalination in solar heat

exchangers, where their presence increases the rate of evaporation and condensation, making the system more cost-effective. Taghizadeh-Tabari et al. [57] investigated the performance of TiO<sub>2</sub> nanofluid in a plate heat exchanger for the milk pasteurization industry, finding that all volume fractions of TiO<sub>2</sub> nanofluid resulted in higher heat transfer rates.

### 6.3 Refrigeration

The performance of CNT, gold, and HAuCl<sub>4</sub> nanoparticles suspended in Polyalkylene Glycol lubricant was investigated by Mohan et al. [65] in a Vapour Compression Refrigeration System (VCRS). Their research made significant contributions to the field of nanofluids in refrigeration. The results showed that as the volume fraction of nano-lubricant increased, the compression work decreased, which led to an enhancement in the Coefficient of Performance (COP). The COP increased by 31.7% with the addition of 0.1% gold and 0.005% CNT in Polyalkylene Glycol lubricant, while exergy loss was reduced by 8% simultaneously. Wang et al. [66] investigated the use of R22 refrigerant with Al<sub>2</sub>O<sub>3</sub> nanoparticles, observing improved heat transfer characteristics. The addition of nanoparticles reduced the height of the boundary layer, which enhanced flow boiling heat transfer. Sheikholeslami et al. [67] conducted an experimental investigation using R600a/oil/CuO nano-refrigerant and found that boiling heat transfer increased as the concentration of nanoparticles increased.

### 6.4. Transportation cooling system

Automotive and heavy-duty engines generate significant amounts of heat, which can cause damage if not dissipated rapidly. The common coolant used in automotive cooling systems is ethylene glycol (EG)-based heat transfer fluid (HTF), typically mixed with water in volumetric ratios of 60/40 or 50/50. Ethylene glycol mixed with water raises the freezing point of pure water, preventing freezing in colder conditions. Nanofluids can be used to design more efficient and compact cooling systems. For the first time, Choi et al. [68] proposed the use of nanofluids in automotive cooling systems. Al<sub>2</sub>O<sub>3</sub>/water nanofluid was found to enhance heat transfer by up to 45% in car radiators compared to pure water [69]. Heris et al. [70] observed a 55% improvement in the heat transfer coefficient when using CuO/EG-water nanofluid, compared to the EG-water base fluid. Samira et al. [71] also studied CuO/EG-water nanofluid in car radiators and found that the addition of nanoparticles increased the heat transfer rate, although it also resulted in an increase in pressure drop.

### 6.5. Transformer oil

Transformer oil-based nanofluids are promising due to their superior thermophysical properties compared to conventional transformer oil. Carbon nanotubes (CNTs) exhibit enhanced thermophysical properties over other materials [72, 73]. Beheshti et al. [74] investigated oxidized multi-walled carbon nanotube (MWCNT) nanofluid based on transformer oil. Their study showed that the incorporation of oxidized MWCNTs in transformer oil improved both free and forced convective heat transfer rates. Additionally, the flash point of the transformer oil increased by 4.6% with the addition of 0.001 mass percentage of oxidized MWCNT nanoparticles.

### 6.6. Electronics equipment

In the power generation industry, transformer cooling plays a crucial role. Kulkarni et al. [75] utilized Al<sub>2</sub>O<sub>3</sub> nanofluid as jacket water coolant in a diesel-electric generator to dissipate excess heat. Researchers are continuously working to reduce the size and weight of transformers by enhancing their cooling systems. Nanofluids offer a promising alternative by improving the properties of conventional transformer oils [76]. Electronic equipment generates significant amounts of heat that must be dissipated quickly to ensure a long lifespan. Jang et al. [77] recently designed a microchannel heat sink where nanofluid was used as the heat transfer fluid (HTF). Their results showed better performance compared to pure water. Nanofluids can also help save electricity by improving the efficiency of chillers. Thermosyphons are now commonly used to cool the internal components of computers, including processors. Researchers have investigated various nanofluids in thermosyphons, where the heat transfer performance is largely influenced

by the thermal conductivity of the working fluid. Increasing the thermal conductivity of the working fluid in a thermosyphon enhances the boiling heat transfer, particularly in the nucleate boiling regime [78]. Sardarabadi et al. [79] investigated Na-MWCNT/water and K-MWCNT/water nanofluids in a thermosyphon for electronic chip cooling, with Na-MWCNT/water nanofluid showing higher thermal efficiency than K-MWCNT/water nanofluid.

## 7. Conclusion

Nanofluids represent a significant advancement in materials science, offering enhanced thermal properties for a wide range of applications, from solar energy to electronics cooling. Their preparation through one-step and two-step methods, coupled with careful control of stability factors like nanoparticle characteristics, Brownian motion, zeta potential, surfactants, and pH, is critical to their performance. While nanofluids hold promise for improving energy efficiency, their environmental impact requires further scrutiny to ensure sustainable adoption. Future research should focus on optimizing preparation techniques, enhancing stability, and mitigating environmental concerns to fully realize the potential of nanofluids in next-generation technologies.

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### Ethical Statement

This research does not contain any studies with human or animal subjects performed by any of the authors

### Data Availability Statement

Not Applicable

### Conflicts of Interest

The authors declare no conflicts of interest

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