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# SUSTAINABLE NANOFLUIDS FOR FUTURE HEAT TRANSFER APPLICATIONS: A REVIEW

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## ABSTRACT

*Sustainable nanofluids are recognized for their enhanced thermal efficiency and lower environmental footprint. This review analyzes recent progress in sustainable nanofluids, focusing on eco-friendly synthesis, biodegradable fluids, and safe nanoparticles. Green synthesis utilizing plant extracts and waste is highlighted as a viable alternative to traditional methods. The review also investigates key factors impacting the thermal performance of sustainable nanofluids, such as nanoparticle properties and stability. It evaluates how these factors influence critical thermo-physical characteristics, including thermal conductivity and viscosity. The innovative application of hybrid and bio-based nanofluids, which integrate diverse nanoparticles or renewable fluids for enhanced performance, is emphasized. Current research indicates a trend towards the adoption of sustainable and hybrid nanofluids across various applications, particularly in solar thermal systems and electronic cooling. Despite notable progress in heat transfer efficiency, challenges concerning stability, cost, and environmental safety persist. In conclusion, the review proposes future research avenues, including enhancements in stabilization techniques, life-cycle evaluations, and scalable green synthesis approaches.*

**Keywords:** Nanofluids, Hybrid Nanofluids, Heat transfer, Thermal conductivity, Green synthesis.

## 1. INTRODUCTION

With the rapid growth of industrialization, urbanization, and other advanced technologies, global energy consumption is increasing rapidly, which is creating a high demand for efficient thermal management systems. The processes of heat transfer are vital to a large number of engineering applications including power generation, electronic cooling, transport systems, renewable energy systems, refrigeration, chemical processing, thermal energy storage, and manufacturing operations [1-4]. In all these applications, the ability to transfer heat effectively has a direct impact on system performance, operational reliability, energy efficiency and environmental sustainability[4]. As a result, the development of advanced heat transfer fluids has emerged as an area of importance in modern thermal engineering. Conventional heat transfer fluids such as water, ethylene glycol, propylene glycol, mineral oils, and their mixtures have been extensively employed in thermal systems due to their low cost, availability, and ease of handling[26]. Although they offer a number of benefits, their relative low thermal conductivity limits heat dissipation, particularly in high-heat-flux scenarios[25]. Due to a rising interest in compact and efficient thermal systems, the limitations of conventional working fluids have been exposed. Consequently, researchers have been looking for new ways to improve heat transfer performance. For the last two decades, the use of nanofluids developed from nanotechnology has proved to be a viable mechanism to counter to these obstacles[1-3].

Nanofluids are formed when metal or non-metallic nanoparticles are added to the base fluids to enhance their thermal conductivity[1-3]. In a liquid medium, when nanoparticles are added, the thermophysical properties of the liquid change. Generally, the thermal conductivity of the liquid increases, the convective heat transfer performance improves, and the thermal management capabilities become better[4,5]. Nanoparticles that have been studied for thermal applications include metallic particles; metal oxides; carbon-based nanomaterials; graphene derivatives; ceramic nanoparticles, etc. Experimental as well as numerical studies have shown that suitably manufactured nanofluids can outperform standard heat transfer fluids under a wide range of operating conditions[6]. Hence, the growing interest in nanofluids is closely linked to their potential to improve the thermal efficiency of engineering systems. Enhanced heat transfer performance can contribute to reduced equipment size, lower energy consumption, improved operational stability, and increased system lifespan. Additionally, as a result, nanofluids have been explored in numerous applications such as heat exchangers, automotive cooling systems, solar thermal collectors, photovoltaic thermal units, electronic devices, nuclear systems, refrigeration technologies, and waste heat recovery systems. Hence, in many cases, significant improvements in thermal conductivity and heat transfer coefficients have been reported, demonstrating the potential of nanofluids to support next-generation thermal technologies.

Although formal nanofluids have shown remarkable heat transfer enhancement capability, several technical and environmental concern remain unresolved[15,32]. One of the most frequently reported challenges is dispersion stability. Nanoparticles tend to agglomerate and sediment during long-term operation, resulting in reduced thermal performance and possible system blockage[15,32]. Additionally, Furthermore, increased viscosity associated with higher nanoparticle concentrations may lead to elevated pumping power requirements, partially offsetting the benefits of improved thermal conductivity[28,34]. Furthermore, Additional concerns include erosion of system components, material compatibility issues, long-term reliability, and difficulties associated with large-scale production. Aside from the technical limitations, environmental sustainability is now a major contributor to the development of nanofluid technology in the future. Many nanoparticle materials that are used to produce the nanofluid are produced in energy-intensive processes that use dangerous chemical materials and produce by-products that have harmful impacts on the environment[16,30,33]. The potential to inadvertently release nanoparticles into the natural ecosystem raises significant concerns regarding the toxicity of those materials in the environment thereafter, their persistence in the environment, and the potential for impacts on human health. As attention globally continues to change toward sustainable engineering practices and low-carbon methodologies, researchers have increasingly determined that the decision of thermal performance alone cannot be the only consideration in evaluating advanced heat transfer fluids. Because of these concerns, sustainable nanofluids, which represent a newly developed type of thermal fluid, are being developed that will improve thermal performance while having reduced environmental impacts[16,30]. Sustainable nanofluids are being designed and manufactured with principles of green chemistry, the use of renewable resources, the use of environmentally responsible and energy-efficient materials in nanofluid development and manufacture, and by adopting environmentally-friendly methods of manufacturing the nanofluid. Sustainable nanofluids will also include the use of bio-based materials, renewable feedstocks, reduced levels of toxic chemicals and consideration of life-cycle environmental impacts throughout the manufacture of the nanofluid.

Green synthesis represents a highly promising approach for improving sustainability[22,30]. Through the use of plants, microorganisms, agricultural and natural products as reducing and stabilizing agents, green synthesis offers numerous advantages over traditional chemical synthesis, including reduced energy consumption, reduced amount of chemical waste generated, improved compatibility with the environment, and potentially lower cost of production[16,22]. The process of developing nanoparticles using environmentally friendly pathways is a key element in achieving sustainable thermal technologies. In addition to the development of green-synthesized nanoparticles, there has been an emphasis on the development of eco-friendly materials and renewable base fluids for use as nanoparticle-composite fluids. Some materials currently being explored include biomass-derived carbon nanomaterials, cellulose-based nanostructures, plant-derived nanoparticles, and naturally sourced additives[23,30]. There is also research being conducted to develop biodegradable and renewable base fluids for use in heat transfer systems, which may help mitigate environmental risks associated with leakage, disposal, and long-term use. The co-development of green nanoparticles and environmentally responsible base fluids presents a unique opportunity for developing sustainable heat transfer media that will be able to satisfy future energy requirements[15,32].

The use of Green Synthesis has gained much popularity among all the different techniques to help improve sustainability[16,22]. Such methods rely on biological materials to create new materials, unlike traditional chemical synthesis. The biological materials used in these processes can be plant extracts/solutions, microbes, agricultural crop waste products and naturally occurring substances to provide a reducing agent and/or stabiliser. By taking advantage of these naturally occurring biological materials there are many benefits associated with them such as > Lower energy consumption > Less chemical waste produced > Greater compatibility with the environment > Potentially lower cost of production. The production of nanoparticles through environmentally-friendly methods of synthesis is an important step toward developing sustainable thermal technologies. Along with energy-efficient synthesis of nanoparticles, there has been a lot of research and development into producing environmentally-friendly base fluids (nanoparticle carriers) made from renewable resources. Researchers are also focusing their efforts on sourcing carbon nanomaterials from biomass, cellulose-based nano-structures, nanoparticle (NP) carriers from plants as well as utilizing naturally sourced NPs. The development of biodegradable as well as renewable base fluids will assist in decreasing the environmental impacts associated with their use (e.g., leakage, disposal of waste fluids and long-term usage). The combination of naturally-sourced green NPs with base fluids that are environmentally responsible presents opportunities to develop sustainable heat transfer fluids to satisfy the anticipated future energy requirements[22].

The commercialisation of nanofluids has achieved significant progress, but many challenges remain as barriers to its widespread adoption as a solution for heat transfer applications that promote energy efficiency, sustainability, and environmental protection. These challenges include the lack of standardisation in synthesis procedures and protocol development, the need for long-term stability testing, large-scale manufacturing and the assessment of environmental risks associated with the use of nanofluids, as well as potential agronomic benefits and techno-economic assessments[15,32]. In addition, there is a need for comprehensive studies to evaluate all aspects of nanofluid technology including thermal performance, sustainability metrics, the economics of production, and the environmental impact of production. The application of AI, machine learning and advanced optimisation methods brings new possibilities for accelerating the progression towards next generation sustainable nanofluids[19,38].

Sustainable nanofluid technology will be a major contributor to improved heat transfer capabilities in future applications due in large part to the ongoing emphasis placed on achieving higher levels of energy efficiency, sustainable technology development and environmental stewardship. Sustainable nanofluids will produce enhanced thermophysical properties while continuing to be environmentally responsible, making them a very favourable solution for resolving the thermal management issues associated with modern engineering systems.

Thus, this review intends to analyze recent advancements in sustainable nanofluids meant to use in future heat transfer applications. Sustainable synthesis techniques, thermophysical characteristics, ways of enhancing heat transfer, those factors impacting the environment, and future direction will also be addressed in this review. In addition, by compiling the most current trends and some of the current research gaps, the goal of this review is to provide an understanding of the current state of sustainable nanofluid technology as well as the future possibilities for sustainable nanofluid technology.

## 2. EVOLUTION OF NANOFLUIDS AND SUSTAINABLE NANOFLUIDS

The creation of nanofluids represents an ongoing attempt to address the limitations of conventional heat transfer fluids with respect to heat transfer capability[25,26]. In the past, conventional fluids such as water, ethylene glycol, propylene glycol and mineral oils were widely used in thermal applications due to their availability, cost-effectiveness, and ease of use. However, as industrial processes have become increasingly complex and as the need for greater efficiency in thermal systems has arisen, the thermal conductivity limits of these traditional fluids created a significant obstacle to achieving thermal system efficiency. As a result, researchers began looking for other ways to increase heat transfer performance without fundamentally changing the design of existing thermal systems. Prior to the development of nanofluids, numerous attempts were made on enhancing heat transfer through the use of solid particulates or solids dispersed in traditional liquids. Although the use of these particle suspensions showed improvements in thermal conductivity, they could not be employed in practice due to the excessively rapid sedimentation characteristics of the larger particles, leading to clogging and sedimentation issues, as well as erosive properties on system parts, resulting in excessive pressure drop, and poor long-term stability of the resulting suspensions all served to reduce their suitability for long-term use. Therefore, the need exists for a newer and more effective solution that can integrate better thermal performance and reasonable fluid properties.

The rapid rise of nanotechnology has presented researchers with an opportunity to create new materials with unique properties through reduction of particle size to the nanoscale level. One key discovery related to this move towards nanotechnology was that reducing particle size causes particles to interact differently with liquids surrounding them. Compared to macro-sized particles, nanoparticles have a very high surface area to volume ratio, which allows them to stay suspended in a fluid for longer periods of time, as well as improve thermal transfer between fluid and particles. From this discovery arose nanofluids, which are commonly defined as stable colloidal solutions of nanoparticles suspended in traditional heat transfer fluids[1,3]. Initial investigations on nanofluids were conducted on mono nanofluids (a type of nanofluid containing only one type of nanoparticle). Early on, metallic nanoparticles, including copper, silver, and aluminium, were given much interest due to their very high thermal conductivity[1,17]. Unfortunately, their application was limited due to problems associated with oxidation of the metals, stability of the nanoparticles once manufactured, and the costs associated with producing the metallic nanoparticles. Therefore, researchers began to explore metal-oxide nanoparticles, which would provide a more balanced approach to creating thermal enhancement with chemical stability and cost feasibility in nanofluids. Commonly used nanoparticles in heat transfer nanofluid research include aluminium oxide ($Al_2O_3$), copper oxide (CuO), titanium dioxide ($TiO_2$), zinc oxide (ZnO), silicon dioxide ($SiO_2$), and magnesium oxide (MgO)[5,20].

The development of nanofluids technology reached an important milestone with the successful use of metal oxide nanoparticles in nanofluids; many studies documented significant increases in thermal conductivity, heat transfer performance and interest in using nanoparticle-based fluids for heating applications, cooling systems, solar thermal devices, and energy storage systems[4,5]. These studies showed that nanofluids have great potential to serve as viable alternatives to traditional heat transfer fluids and stimulated additional research into novel nanoparticle systems. As research continued, it became apparent that just improving one property is not enough for practical applications. Increasing the concentration of nanoparticles usually improves the conductivity; however, it will result in higher viscosity and greater pumping power. Furthermore, particle agglomeration and sedimentation continue to be major obstacles because of stability problems associated with the use of nanoparticles in fluids. Therefore, it is necessary to develop compatible thermal fluids that can provide improved thermal performance without sacrificing operating reliability.

In response to these issues, several researchers have turned their attention to developing hybrid nanofluids. Hybrid nanofluids consist of two or more types of nanoparticles distributed within the same base fluid, which provides a means of taking advantage of different types of nanomaterials at once[9,10]. Compared to many conventional mono nanofluids, hybrid nanofluids demonstrate greater thermal conductivity and stability, as well as enhanced heat transfer rates, making them one of the most actively researched areas in the field of nanofluids today. The scope of nanofluid research has recently expanded from predominantly addressing thermal performance issues to also addressing the issues of environmental sustainability. Because there are significant concerns regarding the use of significant energy to create nanoparticles, the use of chemicals in their production and toxicity, and their overall environmental impact, there has been increased momentum toward developing sustainable nanofluids that provide effective heat transfer enhancement through the use of environmentally sound materials and manufacturing processes[16,30].

One of the emerging trends in this evolution is the use of green synthesis techniques. The use of plant extracts, biological materials, and agricultural waste products to create nanoparticles are potentially viable, sustainable alternatives to traditional chemical methods of synthesizing nanoparticles. This approach reduces the amount of chemicals used during production and provides an overall lower environmental impact than traditional nanoparticle production methods. At the same time, continuing efforts to develop renewable nanomaterials and biodegradable base fluids are supporting the development of green thermal management systems.

Sustainable nanofluids, which are the most up-to-date form of heat transfer fluids, are currently being studied as searches for a balance between thermal performance and stability; economic feasibility; and, environmental sustainability.

## 3. SUSTAINABLE NANOFLUID SYNTHESIS AND PREPARATION METHODS

The method used to prepare a nanofluid has a significant impact on its performance, stability, and sustainability. Over the years, methods of synthesizing nanofluids have changed from traditional to more eco-friendly ones focused on less chemical use and increased sustainability. The type of synthesis route used has a direct effect on the dispersion of nanoparticles, thermo-physical properties, and long-term operable performance of the nanofluid.

### 3.1 CONVENTIONAL PREPARATION METHODS

Nanofluids are generally produced using one-step or two-step preparation methods[7,49]. In the case of one-step methods, nanoparticles are produced and dispersed in the base fluid simultaneously. This results in lower agglomeration of particles, and improved stability of the nanofluids. However, the one-step route is often associated with high production costs and has relatively limited scalability. The two-step method remains the most common method for preparing nanofluids because it is relatively simple and economically viable. The two-step method produces nanoparticles separately, and then disperses them into a base liquid by using mechanical mixing (stirring) or ultra-sonication. Despite its widespread use, agglomeration and sedimentation of the nanoparticles are two major issues[3,49].

### 3.2 GREEN SYNTHESIS OF SUSTAINABLE NANOFLUIDS

Due to the growing awareness of the environmental consequences of traditional nanomaterials, many researchers are exploring "green" methods to produce nano-particles[22,30]. Green synthesis methods differ from traditional synthesis in that rather than using chemicals to reduce and stabilize the nanoparticles, they use biological sources (i.e. plants) through extracts (i.e. algae) or biomass waste[16,22]. Green synthesis methods also reduce the amount of hazardous chemicals used during synthesis and the amount of energy required for synthesis, thus reducing the environmental impact of the synthesis process.

Studies have recently shown that a variety of "green" approaches can effectively produce environmentally friendly nano-particles, including (but not limited to) silver and zinc oxide via plant-based synthesis methods[16,30]. The development of these types of nano-particles has led to the possibility of developing sustainable working fluids with improved thermal performance while remaining environmentally friendly.

### 3.3 HYBRID NANOFLUID PREPARATION

Hybrid nanofluids consist of two or more types of nano-particles dispersed in a common working fluid. The purpose of developing hybrid nanofluids is to combine two or more different types of nano-material to produce a working fluid that is more effective due to either one of the constituent nano-materials providing synergetic properties[10,34]. Different combinations of metal oxide, carbon-based materials, and metal types of nano-particles have been developed to improve thermal conductivity, stability, and heat transfer performance relative to mono-nanofluids. The thermophysical properties of hybrid nanofluids compared to mono-nanofluids have shown that hybrid nanofluids can have much better thermophysical properties and be viable candidates for new thermal management systems.

### 3.4 STABILITY ENHANCEMENT TECHNIQUES

The long term effectiveness of nanofluids hinges significantly upon their dispersion stability. Ultrasonication, surfactants, surface functionalization, and pH adjustment are various methods researchers have utilized to achieve greater stability through minimizing particle aggregation and allowing for uniform distribution of nanoparticles within their host fluid[3,15].

### 3.5 CHALLENGES AND FUTURE OUTLOOK

Despite remarkable advancements in preparing nanofluids, challenges like achieving long-term stability, mass production, and standardization must still be addressed. Future efforts in creating nanofluids will likely revolve around utilizing eco-friendly methods of producing and creating renewable materials; as well as using intelligent techniques to optimize both the thermal efficiency and sustainability of nanofluids; thus increasing the commercialization of eco-friendly nanofluids for future applications in heat transfer systems.

## 4. THERMOPHYSICAL PROPERTIES OF SUSTAINABLE NANOFLUIDS

The effectiveness of heat transfer with nanofluids is primarily affected by the thermophysical characteristics of the nanofluids. The addition of nanoparticles to typical base fluids changes many of their key thermophysical characteristics, such as the thermal conductivity, viscosity, density, specific heat capacity and stability of the base fluid. All these parameters affect heat transfer enhancement, pressure drop characteristics, energy use, and general system performance. Therefore, it is important to understand how these thermophysical characteristics will behave when designing and/or optimizing sustainable nanofluids.

## 4.1 THERMAL CONDUCTIVITY

Nanofluids have been shown to have very little effect on thermal conductivity, which is the predominant characteristic in terms of heat transfer capability[5,23]. The enhancement of thermal conductivity through the addition of nanoparticles to base fluids is due to the superior heat transfer characteristics of the solid particle phase of materials. The enhancement of thermal conductivity is also dependent on the conditions under which the nanoparticle was added, including the type of nanoparticle and its concentration, the temperature of the sample and the particle size, and how well the nanoparticles are dispersed or homogenized in the fluid[23]. Nanofluids composed of carbon-based materials, such as graphite and graphene derivatives, carbon nanotubes, and hybrid nanoparticles, tend to outperform conventional metal oxide-based fluids in terms of enhancement of thermal conductivity. Most studies on nanofluids report continuous enhancement of thermal conductivity as the temperature and concentration of the nanoparticles within the base fluid increases, indicating that sustainable nanofluids may provide a viable option for advanced thermal management solutions[5,23].

## 4.2 DYNAMIC VISCOSITY

Fluid flow patterns and pumps power needs are largely affected by viscosity. Nanoparticle additions help thermal conductivity but tend to increase viscosity because there will be more particle-to-particle interactions with added nanoparticles[28,43]. On the other hand, increasing the temperature usually reduces viscosity because it increases particle mobility and lowers the intermolecular forces that are holding them together. The balance between enhancing thermal conductivity of nanofluids and increasing viscosity poses a main obstacle in developing sustainable nanofluids.

## 4.3 DENSITY AND SPECIFIC HEAT CAPACITY

Fluid momentum, Reynolds number, pressure drop, and convective heat transfer performance are all impacted by density. The density of a nanofluid typically increases as the concentration of nanoparticles increases, due to the fact that nanoparticles have much higher densities compared to their corresponding base fluids[3,25]. Depending on who or what characteristic of the nanoparticles or base fluid is taken into account, the specific heat capacity (the ability of a fluid to store thermal energy) may either increase or decrease. More recent research has indicated that when assessing the overall performance of nanofluids, it is equally important to consider density, specific heat capacity, and thermal conductivity[3,25].

## 4.4 STABILITY AND DISPERSION CHARACTERISTICS

Nanofluid stability plays an extremely significant role in their actual use. An increased amount of agglomeration and/or sedimentation can greatly impair their thermal performance and cause problems like fouling or blockage of channels[15,23]. Common practices to enhance dispersion stability are Ultrasonication, addition of surfactants, surface functionalization, and adjustment of pH levels. Stability evaluation methods typically used include sedimentation analysis, zeta potential measurements, UV-visible spectrometry, and centrifugation. Despite the advancements made in improving nanofluid stability, long – term stability will still be a significant barrier to their widespread use in large scale applications[15,32].

### 4.5 INFLUENCE OF OPERATING PARAMETERS

The most important factors that influence thermophysical properties are the concentration of nanoparticles and the temperature[5,23]. Increasing the temperature of the fluid can increase thermal conductivity and decrease its viscosity, while an increase in concentration of nanoparticles increases the thermal conductivity of the fluid, and thus the heat transfer capability of the fluid, but may increase the resistance to flow. Therefore, optimizing the concentration of nanoparticle and temperature will result in maximum thermal performance with minimum energy loss. In summary, the thermophysical properties of a green nanofluid will provide the basis for successful future applications of these fluids in heat transfer systems. Continued advancements in eco-friendly synthesis methods, hybrid nanofluids, and stability-enhancement methods will further enhance the thermal performance and commercial viability of green nanofluids.

## 5. HEAT TRANSFER ENHANCEMENT MECHANISMS IN SUSTAINABLE NANOFLUIDS

In the past two decades, the exceptional ability of nanofluids to transfer heat compared to traditional heat-transfer fluids has generated a great deal of interest[28,43]. The increased rate of heat transfer as a result of using nanofluids has been shown through both experimental and theoretical studies; however, the actual reasons for this increased heat transfer are still being studied. The enhancement to heat transfer when using nanofluids is caused by many different physical phenomena, including Brownian movement, thermophoretic movement, the formation of an interfacial nanolayer, particle aggregation, and synergistic effects when using hybrid nanofluids[9,10]. The specific contributions of each of these phenomena depend upon the type and size of the nanoparticles, the properties of the base fluid, temperature, concentration of the nanoparticles in the base fluid, and the conditions under which the heat transfer occurs.

### 5.1 BROWNIAN MOTION

One of the most talked about physical phenomena that causes the enhancement to heat transfer when using nanofluids is Brownian movement. As a result of continuous collisions with the surrounding molecules in the base fluid, Brownian movement refers to the random motion of the nanoparticles as they are dispersed in the base fluid[28,43]. The greater the temperature of the fluid containing the nanoparticles, the greater the amount of Brownian movement will occur. With the increased temperature of the nanofluid, the higher intensity the Brownian motion achieves; therefore, there is a greater number of molecules that are transported microscopically due to the Brownian motion and thus a greater amount of thermal conductivity and heat transfer capability of the nanofluid becomes possible. The effect of Brownian motion is most significant in nanofluids that have a small nanoparticle size and are used at high temperature[28,43].

### 5.2 THERMOPHORESIS

Thermophoresis refers to the movement of nanoparticles from a hotter region to a cooler region[28,43]. Nanoparticles moving because of temperature differences in a thermal system are a result of the temperature gradients in a thermal system. The movement of these nanoparticles increases the ability for energy to be transferred and changes the heat transfer characteristics of the local area. The impact of this effect on the ability of a thermal system to thermally transmit energy and heat is magnified where temperature gradients are larger within the thermal system, such as with solar thermal collectors, heat exchangers and electronic cooling devices[29,43].

### 5.3 INTERFACIAL NANOLAYER FORMATION

Another important mechanism is the creation of an ordered layer of liquid (a nanolayer) on the surface of a suspended nanoparticle[31]. This nanolayer has different thermal properties than the bulk fluid surrounding it, which may create additional routes for transferring heat[31]. The nanolayer effect will be more pronounced with nanoparticles that have a large surface-area-to-volume ratio, where there will be large amounts of interaction between the surface of the nanoparticle and the base fluid.

### 5.4 PARTICLE AGGREGATION AND CLUSTERING EFFECTS

Controlled cluster formation of particles has been identified as a method to improve the thermal conductivity of fluids through the establishment of conductive networks which create preferential paths for heat transfer and result in increased thermal transport efficiency within the fluid[3,15]. However, excessively high levels of particle aggregation can lead to sedimentation and degrade the performance of the nanofluid. Therefore, maintaining a proper balance between dispersion stability and particle interaction is critical[15,32].

## 5.5 SYNERGISTIC EFFECTS IN HYBRID NANOFLUIDS

Hybrid nanofluids exhibit additional mechanisms for enhancing heat transfer due to the synergistic interactions of the multiple types of nanoparticles present[9,10]. The heat-transfer ability of a fluid comprised of two or more types of nanoparticles (that is, carbon-based and metal oxide nanoparticles) may be greater than that when using each type of nanoparticle separately[34]. One reason for this is that the complementary properties of the various types of nanoparticles may work in concert to provide a synergistic effect that enhances thermal conductivity, stability and overall heat transfer performance. This synergy has become a major driver for interest in hybrid and sustainable nanofluids.

The enhancement of heat transfer in sustainable nanofluids results from the interaction of multiple mechanisms rather than being exclusively due to one mechanism. The relative contributions of each mechanism to the enhancement of heat transfer will depend upon type, particle concentration, fluid characteristics, and operating conditions. Understanding these mechanisms is key to achieving optimal nanofluid design to maximize thermal performance.

## 6. SUSTAINABLE NANOFLUIDS FOR FUTURE HEAT TRANSFER APPLICATIONS

The ever-growing need for better thermal management systems has led to the increased use of sustainable nanofluids across many different engineering areas. Sustainable nanofluids have improved thermophysical properties and heat transfer capabilities, which makes them more versatile than conventional heat transfer fluids. According to numerous studies done recently, sustainable nanofluids show a great deal of promise in renewable energy systems, industrial heat recovery, thermal energy storage, cooling technologies and advanced heat exchangers[18,20]. Not only do sustainable nanofluids improve thermal performance in these applications, but they also promote energy conservation and protect the environment.

## 6.1 HEAT EXCHANGERS

The heat exchanger is perhaps the most studied application of nanofluids, and many researchers have documented the improved convective heat transfer coefficients and overall thermal performance achieved through the addition of nanoparticles to conventional working fluids[20,21]. Researchers have shown that metal oxide nanofluids, carbon-based nanofluids and hybrid nanofluids are all effective ways to increase heat transfer rates while decreasing the size and energy requirements of heat exchange systems;

thus, sustainable nanofluids are an excellent choice for enhancing thermal efficiency in heat exchangers while employing environmentally sound design[39].

## 6.2 SOLAR THERMAL SYSTEMS

Efficient fluid transfers are necessary for solar thermal technology to effectively utilize sunlight as an energy source. The usage of nanofluids has exhibited improvements towards solar collector efficiencies by providing better ability to conduct heat away from solar panels, and additionally providing better ability to absorb sunlight[11,13]. The use of carbon based nanoparticles (CNBP), graphene bases nanoparticles (GBNP), and hybrid nanofluidic combinations, have been researched extensively as it relates to enhancing heat transfer from the solar collector both externally as well as internally[13,23]. Enhancing the heat transporting capabilities of the heat transfer fluid translates into increased collection of solar energy within the collector system itself, thus providing for improved performance of thermal collection systems under various operational conditions.

## 6.3 CONCENTRATED SOLAR POWER AND PV/T SYSTEMS

The emerging technologies of CSP and PV/T have developed into systems that incorporate efficient heat transfer mediums using sustainable nanofluids in both the heat transfer process as well as thermal storage processes[12,35]. There is significant potential for enhancing both the efficiency of these thermal collection processes through the use of sustainable nanofluid mediums, and the reductions of thermal losses resulting from the use of nanofluids during both of the operational phases of thermal collection. In addition, the use of sustainable nanofluids for cooling photovoltaic panels (PV/T), creates benefits through reducing their operational temperatures, while providing the opportunity to utilize the resultant thermal energy captured through the cooling process[12]. Therefore, the development of sustainable nanofluid technologies will be effective at creating synergies between these two needed renewable energy technologies.

## 6.4 SOLAR DESALINATION AND WATER TREATMENT

In recent years, there has been more focus on desalination technologies that are powered by solar energy due to increased scarcity of fresh water. A coating of nanofluids has been used successfully in solar stills and other desalination systems to improve heat absorption, vaporization rate, and fresh water productivity[14]. Increased rate of thermal transport in the working fluid allows for more effective use of the solar energy that is captured, which translates to greater efficiency of water production. Moreover, continued use of sustainable nanofluids produced via environmentally friendly synthesis processes adds to the sustainability of these systems.

### 6.5 THERMAL ENERGY STORAGE SYSTEMS

Thermal Energy Storage is extremely important when it comes to using renewable energy (RE) as well as managing waste heat from different processes. The addition of nanoparticles into the storage medium will improve the rate at which the storage medium can be charged or discharged, through enhanced thermal conductivity[11,13]. Sustainable nanofluids have shown great potential for both sensible and latent heat storage applications; therefore, they can lead to an overall increase in thermal energy storage efficiency and the reliability of the overall system.

### 6.6 ELECTRONIC COOLING AND REFRIGERATION SYSTEMS

There has been a growing demand for more effective cooling technologies due to the rapid advancements in high-performance electronic devices. Nanofluids have exhibited much greater rates of heat removal than standard coolants; therefore, they are becoming more widely used for electronic cooling applications[29,44]. Similarly, improved cooling performance and overall energy efficiency can be achieved through utilizing nanofluids as the working fluids in refrigeration and air conditioning systems[44]. These applications are expected to become increasingly important as thermal management requirements continue to grow.

### 6.7 WASTE HEAT RECOVERY AND INDUSTRIAL APPLICATIONS

A lot of energy produced from industrial processes is wasted in the form of excess heat[18,37]. One way that sustainable nanofluids can help to reduce the amount of waste heat generated is by being more effective than standard fluids when it comes to transferring heat and thermally transporting it. When used in industrial heat exchangers or process heating systems as well as in energy recovery systems, nanofluids can improve the efficiency of energy usage while lowering utility costs. In addition, using nanofluids that are environmentally safe and friendly also supports today's focus on sustainability and reducing carbon emissions within the manufacturing sector[18,37].

### 6.8 BUILDING THERMAL MANAGEMENT

Sustainable nanofluids are an area of growth within the construction industry. The enhancement of heating, ventilation and air conditioning of buildings through enhanced heat transfer, will reduce energy consumption and increase occupant comfort[27]. Incorporating sustainable nanofluids into energy systems in buildings can help promote the development of more energy efficient and sustainable infrastructure[41].

In summary, sustainable nanofluids have great potential when it comes to transferring heat in various applications. They offer a unique combination of high thermal performance, energy efficiency, and environmentally friendly products, making them ideal for use in next generation thermal management technologies. However, there are a number of issues such as long term stability, large scale production, economic viability, and standardization that still need to be resolved before sustainable nanofluids can be commercially used in large quantities.

## 7. SUSTAINABILITY AND TECHNO-ECONOMIC ASSESSMENT

Sustainable nanofluids offer superior heat transfer properties and can support energy-efficient and environmentally sustainable thermal systems[16]. Sustainable nanofluids can lead to improvements in thermal efficiency versus traditional heat transfer fluids, decreased energy usage, and increased use of renewable energy sources. Therefore, many of the benefits of using sustainable nanofluids lead to a decrease in greenhouse gas emissions and help to promote sustainable energy development globally[30,33]. Studies have shown that green synthesis processes of nanoparticle production using biomass waste, plant extracts, and other naturally derived materials are important[22,30]. Green-synthesized nanoparticles can help decrease reliance on hazardous chemicals, reduce environmental impacts, and contribute to a more sustainable way to manufacture nanofluids. The creation of hybrid and bio-based nanofluids provides further opportunities for environmentally friendly methods of thermal management.

From an economic perspective, the ability of nanofluids to enhance heat transfer may result in the increase of smaller size heat exchangers, increase system efficiency, and decrease operating costs. Numerous applications for nanofluids have been demonstrated in solar thermal systems, waste heat recovery systems, and industrial heat exchange equipment on an energy savings basis. However, commercialization of nanofluids is still challenging due to the high cost of manufacturing nanoparticles, restrictions regarding nanoparticle stability, and the absence of standardized procedures for manufacturing nanofluids. Although there are many challenges, advancements made in green nanotechnology, sustainable synthesis methods, and intelligent optimization methods will help make nanofluid-based systems economically feasible in the future. Future work should be focused on performing comprehensive life-cycle assessments, studying the long-term impact of these materials on the environment, and conducting cost-benefit analysis to prove that sustainable nanofluids are practically viable for use in widespread industrial applications[15,22].

In general, sustainable nanofluids seem like an excellent option for creating a new type of high performing and environmentally friendly means of transferring heat. If successful in integrating sustainable nanofluids into future thermal systems, researchers must develop an adequate compromise between the thermal enhancement benefits, their economic feasibility, and their ability to be environmentally sustainable.

### 7.1 KEY SUSTAINABILITY ASPECTS

| Sustainability Aspect | Benefits | Challenges |
|---|---|---|
| **Energy Efficiency** | Improved heat transfer and lower energy consumption | Optimization required |
| **Environmental Impact** | Reduced emissions and greener synthesis routes | Limited long-term environmental data |
| **Economic Performance** | Lower operating costs and improved efficiency | High nanoparticle cost |
| **Renewable Energy Integration** | Suitable for solar and waste heat recovery systems | Scale-up challenges |
| **Commercialization** | High future potential | Lack of standardization |

*Table:06*

## 8. RESEARCH GAPS AND FUTURE PERSPECTIVES

While there has been a lot of progress made toward developing sustainable nanofluids, there are still many scientific, technical, economic, and environmental issues that need to be resolved. The existing literature reviewed here shows substantial improvements in thermophysical property and heat transfer performance; however, most published studies are laboratory investigations rather than large-scale studies[15]. Additionally, many of these studies have been prepared using different preparation techniques and with different methods of assessing stability and frameworks for evaluating sustainability, so direct comparisons cannot be made[16]. Future work should concentrate on filling the major gaps in knowledge that exist in the current literature in order to make it possible for nanofluid to be commercially developed and implemented on a larger scale.

### 8.1 KEY FINDINGS AND RESEARCH GAP

| Research Area | Key Findings | Research Gaps |
|---|---|---|
| **Sustainable Nanofluid Synthesis** | Green synthesis methods reduce environmental impacts and chemical consumption | Lack of standardized green synthesis protocols |

| | | |
|---|---|---|
| **Thermal Conductivity Enhancement** | Significant improvements achieved using hybrid and carbon-based nanofluids | Limited understanding of long-term thermal behavior |
| **Viscosity and Rheological Properties** | Improved heat transfer often accompanies increased viscosity | Need for optimal thermal-hydraulic balance |
| **Stability Assessment** | Ultrasonication and surfactants improve dispersion stability | Insufficient long-term stability studies under practical conditions |
| **Hybrid Nanofluids** | Superior performance compared with mono nanofluids in many applications | Lack of universal optimization guidelines |
| **Solar Thermal Applications** | Enhanced thermal efficiency and energy harvesting capability | Limited field-scale demonstrations |
| **Thermal Energy Storage** | Improved charging and discharging performance | Need for large-scale validation studies |
| **Waste Heat Recovery Systems** | Potential for increased energy recovery efficiency | Insufficient industrial implementation data |
| **Sustainability Assessment** | Environmental benefits have been widely reported | Limited life-cycle assessment and environmental impact studies |
| **Techno-Economic Analysis** | Potential operational cost savings observed | Lack of comprehensive economic evaluation frameworks |
| **Artificial Intelligence Applications** | AI and machine learning improve performance prediction and optimization | Limited integration with nanofluid design and development |
| **Commercialization** | Strong potential for future industrial adoption | Scale-up, regulatory, and standardization challenges |

*Table:07*

## 8.2 FUTURE PERSPECTIVES

Future research should aim at new environmentally friendly types of nanofluids that have both a high thermal performance and can be produced economically while having a sufficiently long shelf life to allow for their continued use over time. The role played by green synthesis methods that use renewable materials, biomass-derived components, and waste-based precursors in developing sustainable nanofluids will continue to grow[16,22]. In addition, there is a growing interest in hybrid nanofluids developed specifically to provide synergistic effects of thermo-physical improvements while minimizing viscosity-limiting attributes[10]. These types of nanofluids will also provide an opportunity for future work. Use of Artificial intelligence and machine learning with data-driven optimization will help speed up the design and prediction of performance for nanofluids[38,43]. The expectation is that these types of methodologies will help reduce the amount of time spent on experimentation and allow for better formulation of nanofluids along with a movement toward the development of application-specific nanofluids. The emphasis of future studies should be on the conduct of life cycle assessments, assessments of environmental impacts and techno-economic studies in order to demonstrate the ability of nanofluid technologies to be sustainable in practice.

Another area in which more research needs to take place is conducting large-scale validation studies with realistic operational characteristics. Most current research on nanofluids has been performed under laboratory conditions; however, most of the applications of these types of materials occur under complex thermal loading profiles and have variable operational profiles with extremely long operating times[15]. Thus, there is a need to conduct pilot studies at various industrial sites in order to verify that the results obtained from controlled laboratory research translate to commercial use. Ultimate sustainable nanofluids will rely on combining four elements to enhance their thermal performance sustainably, keep them environmentally friendly, ensure their cost effectiveness, and utilize intelligent design methods. Successful solutions to these challenges should help in moving sustainable nanofluids from being experimental research projects to viable industrial and renewable energy products of use.

## 9. CONCLUSION

Sustainable nanofluids (a new class of fluids) are considered future heating fluid for improving thermal performance while continuing to support long-term environmental sustainability. This review of literature shows evidence of rapid advancements in the areas of Green synthesis methods, development of hybrid nanofluids and the optimization of their thermophysical properties[34]. The potential to utilize sustainable nanofluids for future thermal management use can be attributed to: the increased ability to carry heat (high thermal conductivity), improved ability to transfer heat from one surface to another (improved heat transfer characteristics), and the potential extensive application of these fluids in heat exchangers, solar energy applications, thermal energy storage, refrigeration, and recovery of waste heat[18]. The widespread use of sustainable nanofluids will be hindered by a number of challenges including; Limited long-term stability, inability to produce at large-scale quantities, lack of economically viable options, and lack of standardization. Future research should focus on sustainable synthesis of nanofluids, conducting comprehensive life-cycle analyses of these fluids, implementing intelligent optimization techniques, and conducting validation studies at the industrial level[32].

Therefore, we feel confident in stating that sustainable nanofluids represent a significant opportunity to create energy-efficient and environmentally sustainable heat transfer technologies which will play an increasing role in the development of renewable energy sources and thermal management systems.

## NOMENCLATURE

- **LATIN SYMBOLS**

| Symbol | Description | Unit |
|---|---|---|
| **Cp** | Specific heat capacity | $J\ kg^{-1}\ K^{-1}$ |
| **h** | Convective heat transfer coefficient | $W\ m^{-2}\ K^{-1}$ |
| **k** | Thermal conductivity | $W\ m^{-1}\ K^{-1}$ |
| **Nu** | Nusselt number | – |
| **Pr** | Prandtl number | – |
| **Re** | Reynolds number | – |
| **T** | Temperature | K |
| **q** | Heat transfer rate | W |
| **Q** | Heat energy | J |
| **V** | Volume | $m^3$ |
| **d** | Nanoparticle diameter | nm |
| **r** | Nanoparticle radius | nm |
| **p** | Pressure | Pa |
| **L** | Characteristic length | m |

*Table:01*

- **GREEK SYMBOLS**

| Symbol | Description | Unit |
|---|---|---|
| ρ | Density | kg $m^{-3}$ |
| μ | Dynamic viscosity | Pa·s |
| ν | Kinematic viscosity | $m^2$ $s^{-1}$ |
| ϕ | Nanoparticle volume fraction | % or – |
| η | Efficiency | % |
| β | Thermal expansion coefficient | $K^{-1}$ |
| λ | Thermal conductivity ratio | – |
| τ | Shear stress | Pa |

*Table:02*

- **ABBREVIATION**

| Abbreviation | Description |
|---|---|
| NF | Nanofluid |
| HNF | Hybrid nanofluid |
| GNF | Green nanofluid |
| SNF | Sustainable nanofluid |
| BF | Base fluid |
| NP | Nanoparticle |
| HTC | Heat Transfer Coefficient |
| PCM | Phase Change Material |
| TES | Thermal Energy Storage |
| PV/T | Photovoltaic Thermal System |
| CSP | Concentrated Solar Power |
| LCA | Life Cycle Assessment |
| CFD | Computational Fluid Dynamics |
| ANN | Artificial Neural Network |
| ML | Machine Learning |
| AI | Artificial Intelligence |

| | |
|---|---|
| SEM | Scanning Electron Microscopy |
| TEM | Transmission Electron Microscopy |
| FESEM | Field Emission Scanning Electron Microscopy |
| XRD | X-ray Diffraction |
| FTIR | Fourier Transform Infrared Spectroscopy |
| UV–Vis | Ultraviolet–Visible Spectroscopy |
| DLS | Dynamic Light Scattering |
| ZP | Zeta Potential |

*Table:03*

- **COMMOM NANOPARTICLES**

| **Symbol** | **Material** |
|---|---|
| **$Al_2O_3$** | Aluminum Oxide |
| **CuO** | Copper Oxide |
| **$TiO_2$** | Titanium Dioxide |
| **ZnO** | Zinc Oxide |
| **$SiO_2$** | Silicon Dioxide |
| **MgO** | Magnesium Oxide |
| **$Fe_3O_4$** | Iron Oxide |
| **Ag** | Silver |
| **Cu** | Copper |
| **CNT** | Carbon Nanotube |
| **MWCNT** | Multi-Walled Carbon Nanotube |
| **SWCNT** | Single-Walled Carbon Nanotube |
| **GO** | Graphene Oxide |
| **rGO** | Reduced Graphene Oxide |
| **GNP** | Graphene Nanoplatelet |
| **CNC** | Cellulose Nanocrystal |

*Table:04*

- **BASE FLUIDS**

| Abbreviation | Description |
|---|---|
| **W** | Water |
| **EG** | Ethylene Glycol |
| **PG** | Propylene Glycol |
| **EO** | Engine Oil |
| **BO** | Bio-based Oil |
| **DW** | Distilled Water |
| **W–EG** | Water–Ethylene Glycol Mixture |

*Table:05*

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