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REVIEW ARTICLE

Enhancing Solar Distillation Efficiency with Nanofluids: A Comprehensive Review

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ABSTRACT: Solar distillation offers an eco-friendly and sustainable solution for producing freshwater from seawater or contaminated sources, particularly in arid regions where water scarcity is a pressing issue. However, the efficiency of traditional solar distillation systems is often limited by low heat transfer rates, resulting in suboptimal performance. In recent years, the introduction of nanofluids—suspensions of nanoparticles within base fluids—has emerged as a promising avenue to overcome these limitations. Nanofluids exhibit superior thermal properties, such as enhanced thermal conductivity and convective heat transfer coefficients, which have been shown to significantly improve the productivity of solar distillation systems. This comprehensive review examines the principles of solar distillation, the challenges inherent in conventional systems, and the transformative role of nanofluids in addressing these inefficiencies. Key mechanisms responsible for the improved heat transfer characteristics of nanofluids are discussed, along with the impact of factors such as nanoparticle material, size, shape, and concentration. The review critically analyzes recent experimental and theoretical studies, highlighting significant advancements in system performance, including increased freshwater yield and reduced thermal resistance. Additionally, it identifies gaps in the current body of knowledge, emphasizing the need for further research into optimizing nanofluid formulations, scaling up experimental findings, and exploring long-term environmental and economic impacts. By bridging these knowledge gaps, nanofluid-enhanced solar distillation systems could play a pivotal role in addressing global water scarcity challenges while promoting sustainable development.

Keywords: Nanofluid Solar Stills, Solar Distillation Efficiency, Nanoparticle-Based Heat Transfer, Hybrid Nanofluids.

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1. INTRODUCTION

Nanofluids represent a significant advancement in the field of heat transfer fluids, offering unique thermophysical properties that set them apart from conventional fluids [1, 2]. These engineered colloidal suspensions, composed of nanometer-sized particles uniformly dispersed in a base fluid, can significantly alter the fluid's thermal conductivity, viscosity, and specific heat capacity. By harnessing these enhanced properties, nanofluids have become the focus of extensive research aimed at improving heat transfer processes across a wide range of applications. One particularly promising area of application is in solar distillation systems, where the integration of nanofluids has been shown to address longstanding efficiency challenges [3, 4].

The global water crisis, driven by factors such as climate change, rapid population growth, and industrial expansion, has intensified the demand for innovative, sustainable, and cost-effective water purification technologies. According to the United Nations, more than two billion people currently lack access to safely managed drinking water, and this number is expected to rise if urgent measures are not taken. Solar distillation, a technique that utilizes renewable solar energy to convert saline or contaminated water into potable water, has emerged as a promising solution to address water scarcity. Its simplicity, low operational costs, and reliance on an abundant energy source make it an attractive option for remote and arid regions. However, conventional solar distillation systems are often hindered by low efficiency, stemming from limitations in heat transfer, high thermal

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losses, and low evaporation rates [1, 2].

To overcome these limitations, researchers have turned to nanofluids as a potential game-changer in solar distillation technology. Nanofluids offer enhanced heat transfer characteristics, primarily due to their improved thermal conductivity and convective heat transfer properties, which arise from the unique interactions between nanoparticles and the base fluid. These enhancements have been linked to increased evaporation rates and thermal efficiency, leading to significant improvements in water production rates. For example, studies have shown that incorporating metal oxide nanoparticles, such as aluminum oxide (Al_2O_3) or titanium dioxide (TiO_2), into a water-based fluid can increase the thermal conductivity by as much as 20–40%, depending on the nanoparticle concentration and size [3, 4].

The principles of solar distillation are straightforward: water is heated using solar energy until it evaporates, leaving behind impurities and salts, and the vapor is subsequently condensed into fresh water. However, the efficiency of this process is inherently limited by the ability of the system to effectively transfer heat from the solar collector to the water. Nanofluids address this bottleneck by acting as superior heat transfer media. The nanoparticles in nanofluids absorb and distribute thermal energy more effectively than conventional fluids, thereby accelerating the evaporation process. Additionally, some nanoparticles exhibit photothermal properties, directly converting absorbed solar energy into heat, further enhancing the performance of the system [5].

Despite these promising advancements, the application of nanofluids in solar distillation is not without challenges. One critical issue is the stability of nanofluids over time. Nanoparticles tend to aggregate or settle under certain conditions, reducing the effectiveness of the fluid and potentially clogging system components. Researchers have explored various stabilization techniques, such as the use of surfactants or surface modifications, to maintain uniform dispersion of nanoparticles in the base fluid [6]. Another concern is the potential environmental impact of nanoparticles, particularly if they are released into the environment during system operation or disposal. Studies have emphasized the importance of assessing the long-term ecological and health implications of nanofluid use in water purification technologies [7].

Furthermore, the economic feasibility of nanofluid-based solar distillation systems remains an area of active investigation. While the cost of nanoparticles has decreased over the years, large-scale implementation of nanofluids still poses challenges in terms of material costs, preparation techniques, and maintenance requirements. Advanced manufacturing methods, such as green synthesis of nanoparticles, have been proposed to address these issues and make the technology more accessible for widespread adoption [8].

Recent advancements in computational modeling and simulation have also contributed to the growing body of knowledge on nanofluid behavior in solar distillation systems. Techniques such as computational fluid dynamics (CFD) and machine learning are being employed to optimize nanofluid formulations and predict system performance under various operating conditions. These tools enable researchers to better understand the complex interactions between nanofluids and solar distillation components, paving the way for more efficient and cost-effective designs [9].

In addition to their technical benefits, nanofluid-enhanced solar distillation systems align well with global sustainability goals. By utilizing renewable energy and reducing dependence on energy-intensive desalination methods, such as reverse osmosis or multi-stage flash distillation, these systems offer an environmentally friendly alternative for addressing water scarcity. Moreover, their potential to operate effectively in off-grid settings makes them particularly suitable for deployment in rural and underserved regions, where access to clean water is often most limited [10].

Figure 1 illustrates the working principle of a solar distillation system, a sustainable method for water purification using solar energy. The system consists of a transparent glass cover, which allows sunlight to penetrate and heat the water contained in a basin. As the water absorbs heat, it evaporates, leaving behind salts, impurities, and contaminants. The vapor rises and comes into contact with the cooler inner surface of the glass cover, where it condenses into water droplets. These droplets flow down the inclined surface of the glass cover and are collected in a dedicated channel, resulting in clean, distilled water. This process, driven entirely by solar thermal energy, mimics the natural water cycle of evaporation and condensation. Solar distillation systems are particularly beneficial in arid and remote regions, offering a low-cost, environmentally friendly solution for obtaining potable water from saline or contaminated sources [11].

This comprehensive review seeks to synthesize the current state of research on the application of nanofluids in solar distillation systems. It begins by exploring the fundamental preparation techniques for nanofluids and their thermophysical properties. It then delves into the mechanisms through which nanofluids enhance heat transfer and evaporation processes in solar distillation systems. The review also examines the practical challenges associated with implementing nanofluid-based systems, including stability, environmental impact, and economic feasibility. Through a critical analysis of recent experimental and theoretical studies, this review aims to provide valuable insights into the potential of nanofluids to revolutionize solar distillation technology.

While significant progress has been made in understanding and harnessing the benefits of nanofluids in solar distillation systems, there remain key areas for further exploration. These include optimizing nanofluid formulations, scaling up experimental findings for real-world applications, and addressing long-term environmental and economic considerations. By bridging these knowledge gaps, nanofluid-enhanced solar distillation has the potential to become a cornerstone technology in the global effort to achieve sustainable water purification and mitigate the growing challenge of water scarcity.

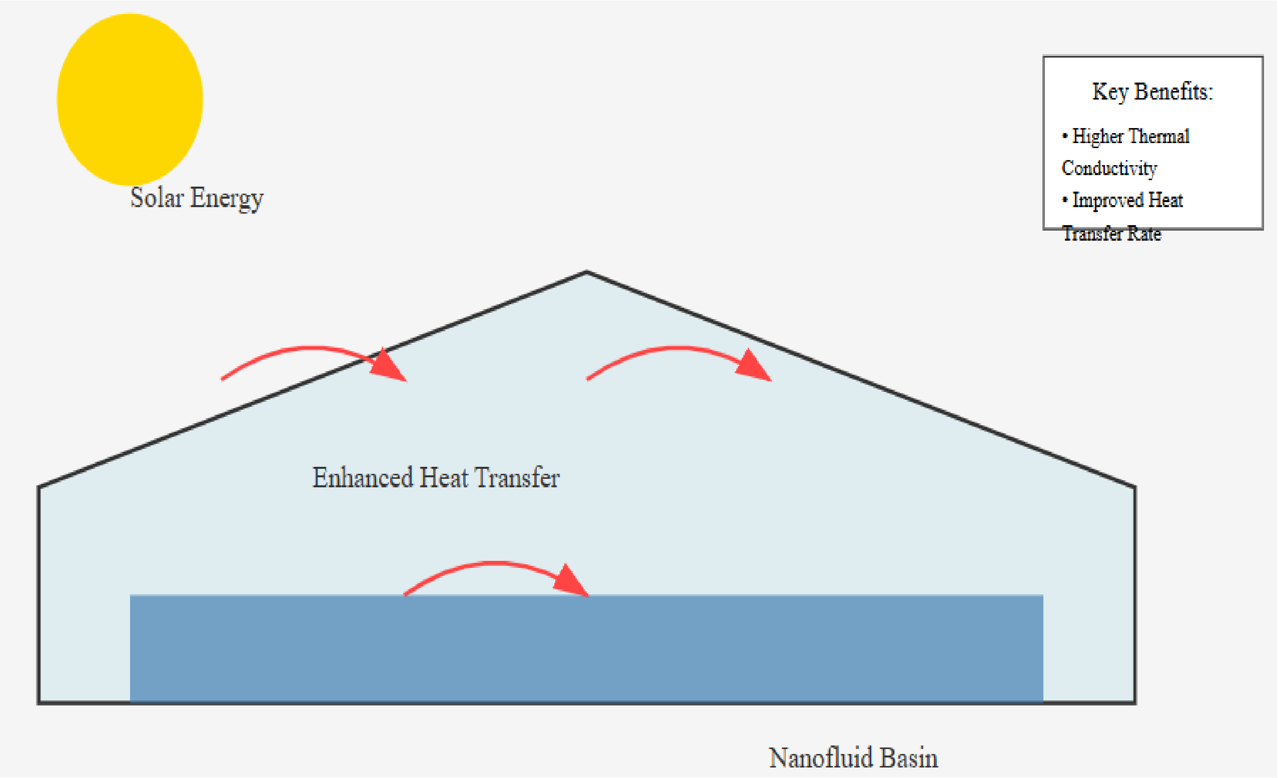

Fig. 1. Schematic for the Solar Distillation System.

2. THE CONCEPT OF NANOFLUID

Nanofluids represent a groundbreaking advancement in heat transfer technology, offering unique properties that make them highly effective for solar energy applications. Their enhanced thermal conductivity, improved convective heat transfer, and superior optical properties enable them to overcome the limitations of conventional fluids, paving the way for more efficient and sustainable water purification systems. However, the preparation and stabilization of nanofluids remain areas of active research, with ongoing efforts focused on optimizing synthesis techniques, minimizing environmental impact, and reducing production costs to facilitate their widespread adoption.

2.1. Definition and Composition

Nanofluids are advanced fluids engineered by suspending nanometer-sized particles (typically 1–100 nanometers) within a conventional base fluid. These colloidal suspensions are designed to enhance the heat transfer properties of the base fluid by leveraging the unique characteristics of nanoparticles. The base fluid serves as the primary medium for heat transfer and is typically a conventional heat transfer fluid, such as water, ethylene glycol, or oil, chosen for its availability and thermal properties [12]. The nanoparticles, which constitute the dispersed phase, are either metallic or non-metallic and are carefully selected based on their thermal conductivity, stability, and compatibility with the base fluid. Common examples of metallic nanoparticles include copper (Cu), aluminum (Al), and silver (Ag), while non-metallic nanoparticles often include aluminum oxide (Al_2O_3), copper oxide (CuO), and titanium dioxide (TiO_2) [13].

The composition of nanofluids plays a critical role in determining their overall performance. The base fluid provides the foundational properties, such as viscosity and heat capacity, while the nanoparticles enhance the thermal conductivity and optical absorption characteristics. The synergy between these two components results in a fluid with superior heat transfer capabilities compared to the base fluid alone. For instance, water-based nanofluids containing metal oxide nanoparticles like TiO_2 and ZnO are commonly used in solar distillation due to their high thermal stability, low toxicity, and compatibility with solar energy systems.

2.2. Unique Properties of Nanofluids

Nanofluids are distinguished by their unique properties, which make them highly effective for heat transfer and energy applications. One of the most notable attributes of nanofluids is their enhanced thermal conductivity. Compared to traditional base fluids, nanofluids exhibit significantly higher thermal conductivity due to the inclusion of nanoparticles with superior thermal properties. For example, the thermal conductivity of a water-based nanofluid containing Al_2O_3 nanoparticles can be 20–40% higher than that of pure water, depending on factors such as nanoparticle concentration, size, and shape [14]. Another critical property of nanofluids is their improved convective heat transfer coefficient. The presence of nanoparticles enhances the fluid's ability to transfer heat through convection, a phenomenon attributed to the Brownian motion of the nanoparticles and the resulting micro-convection effects. This increased convective heat transfer capability makes nanofluids particularly effective in applications where efficient heat exchange is essential, such as in solar collectors and distillation systems [15].

In addition to their thermal properties, nanofluids also exhibit enhanced optical properties. Certain nanoparticles, such as carbon-based materials or metal oxides, possess the ability to absorb a broader spectrum of solar radiation. This property is particularly advantageous in solar distillation systems, where maximizing the absorption of solar energy is critical for efficient operation. By tailoring the optical properties of nanofluids, researchers have developed fluids that not only improve heat transfer but also enhance the overall energy conversion efficiency of solar systems [16]. The unique combination of enhanced thermal, convective, and optical properties makes nanofluids an ideal candidate for improving the performance of solar distillation systems. These properties enable nanofluids to overcome the limitations of conventional fluids, such as low thermal conductivity and limited solar energy absorption, thereby significantly enhancing the efficiency and productivity of solar water purification technologies.

2.3. Preparation Methods

The preparation of nanofluids is a crucial step that directly impacts their stability, performance, and overall effectiveness in practical applications. The process involves dispersing nanoparticles into a base fluid to form a stable suspension. The type of nanoparticles and base fluid used is determined by the specific requirements of the application. For instance, in solar distillation, metal oxide nanoparticles such as TiO_2, ZnO, and Al_2O_3 are preferred due to their high thermal stability, low toxicity, and strong interaction with solar radiation. Base fluids typically include water, ethylene glycol, or organic solvents, chosen for their thermal properties and compatibility with nanoparticles.

There are two primary methods for preparing nanofluids: the two-step method and the one-step method. The two-step method is the most commonly used approach and involves two distinct stages. First, nanoparticles are synthesized as a dry powder using techniques such as chemical vapor deposition, ball milling, or sol-gel processes. These nanoparticles are then dispersed into the base fluid using mechanical stirring, ultrasonication, or high-shear mixing. While the two-step method is cost-effective and suitable for large-scale production, it often faces challenges related to nanoparticle aggregation and stability. To mitigate these issues, surfactants or dispersants are frequently added to improve the uniform distribution of nanoparticles within the base fluid [17].

The one-step method, on the other hand, combines the synthesis and dispersion processes into a single stage. Nanoparticles are simultaneously produced and dispersed into the base fluid through methods such as chemical reduction, laser ablation, or microwave-assisted synthesis. This approach minimizes the risk of nanoparticle aggregation and ensures better stability of the nanofluid. However, the one-step method is generally more expensive and less scalable than the two-step method, making it less suitable for large-scale industrial applications [18]. Both methods have their advantages and limitations, and the choice of preparation technique depends on factors such as the desired properties of the nanofluid, the scale of production, and the specific application. For solar distillation systems, achieving a stable nanofluid with high thermal conductivity and minimal sedimentation is critical for long-term performance and efficiency.

3. IMPACT OF NANOFLUIDS ON SOLAR DISTILLATION SYSTEMS

3.1. Thermal Conductivity and Heat Transfer Enhancement

The incorporation of nanoparticles into base fluids results in nanofluids with significantly enhanced thermal conductivity, a property that plays a critical role in improving the efficiency of solar distillation systems. Nanoparticles such as TiO_2, CuO, and Al_2O_3 have a high intrinsic thermal conductivity, and their dispersion within the base fluid creates more efficient pathways for heat transfer. This phenomenon facilitates faster heat distribution, which directly enhances the thermal performance of solar stills. Studies by Elsheikh et al. [19] showed that adding TiO_2 nanoparticles to water increased the thermal conductivity of the base fluid by up to 25%, leading to higher evaporation rates. This enhancement was reflected in a notable increase in productivity, as more water could be distilled in a shorter time. The improvement in heat transfer rates not only optimizes energy utilization but also addresses one of the key limitations of conventional solar distillation systems, which often struggle with heat loss and inefficient thermal performance. The thermal conductivity of nanofluids is influenced by various factors, including the type, size, shape, and concentration of nanoparticles, as well as the stability and uniform dispersion of the nanofluids. Ensuring proper preparation methods, such as ultrasonication and surfactant use, can maximize the benefits of increased thermal conductivity and result in significantly better solar still performance.

Figure 2 highlights the impact of nanofluids on the performance of solar distillation systems. Nanofluids, which are engineered by dispersing nanoparticles such as CuO, Al_2O_3, or TiO_2 into base fluids like water, enhance the thermal and optical properties of the fluid used in solar stills. The figure likely demonstrates how nanofluids improve critical parameters such as heat transfer, evaporation rate, and overall efficiency. By increasing the thermal conductivity of the working fluid, nanofluids ensure faster and more efficient heat absorption, leading to quicker evaporation. Furthermore, their superior optical properties enhance solar energy absorption by scattering and trapping more sunlight within the distillation unit.

The figure may also depict productivity improvements achieved through the use of nanofluids compared to conventional fluids, illustrating a substantial increase in distilled water output. It underscores the role of nanoparticle concentration, size, and type in determining the system's efficiency, emphasizing nanofluids as a key innovation for enhancing the sustainability and productivity of solar distillation systems.

3.2. Optical Properties and Solar Absorption

Nanoparticles in nanofluids exhibit remarkable optical properties that enhance the absorption of solar radiation, which is critical for improving the evaporation process in solar stills. Nanoparticles such as graphene, carbon nanotubes, and metal oxides can absorb a broader spectrum of solar radiation compared to conventional fluids. This enhanced solar absorption allows more energy to be converted into heat, accelerating the water evaporation process. Eltawil et al. [20] demonstrated that carbon-based nanofluids, such as those containing graphene nanoparticles, improved solar absorption by 15-20%. This improvement translated into higher evaporation rates, as the absorbed solar energy was efficiently converted into heat within the system. The scattering effect of nanoparticles further ensures that sunlight is uniformly distributed within the fluid, maximizing energy utilization. By optimizing nanoparticle concentration and type, researchers have developed nanofluids with tailored optical properties that effectively enhance the productivity of solar distillation systems. However, challenges such as maintaining nanoparticle dispersion and preventing sedimentation must be addressed to sustain these optical advantages over extended periods.

3.3. Nanofluid Stability and Long-Term Performance

The stability of nanofluids is a crucial factor in maintaining their enhanced properties over time. Stability issues, such as nanoparticle agglomeration and sedimentation, can significantly diminish the thermal and optical properties of nanofluids, thereby affecting the long-term performance of solar distillation systems [21]. Agglomerated nanoparticles reduce the effective surface area and hinder the uniform dispersion required for optimal heat transfer and solar absorption. To address these issues, various stabilization techniques have been employed, including the use of surfactants, pH adjustment, and ultrasonication. Surfactants reduce the surface tension between nanoparticles and the base fluid, promoting better dispersion and preventing aggregation. Similarly, ultrasonication ensures the uniform distribution of nanoparticles by breaking up agglomerates through high-frequency sound waves.

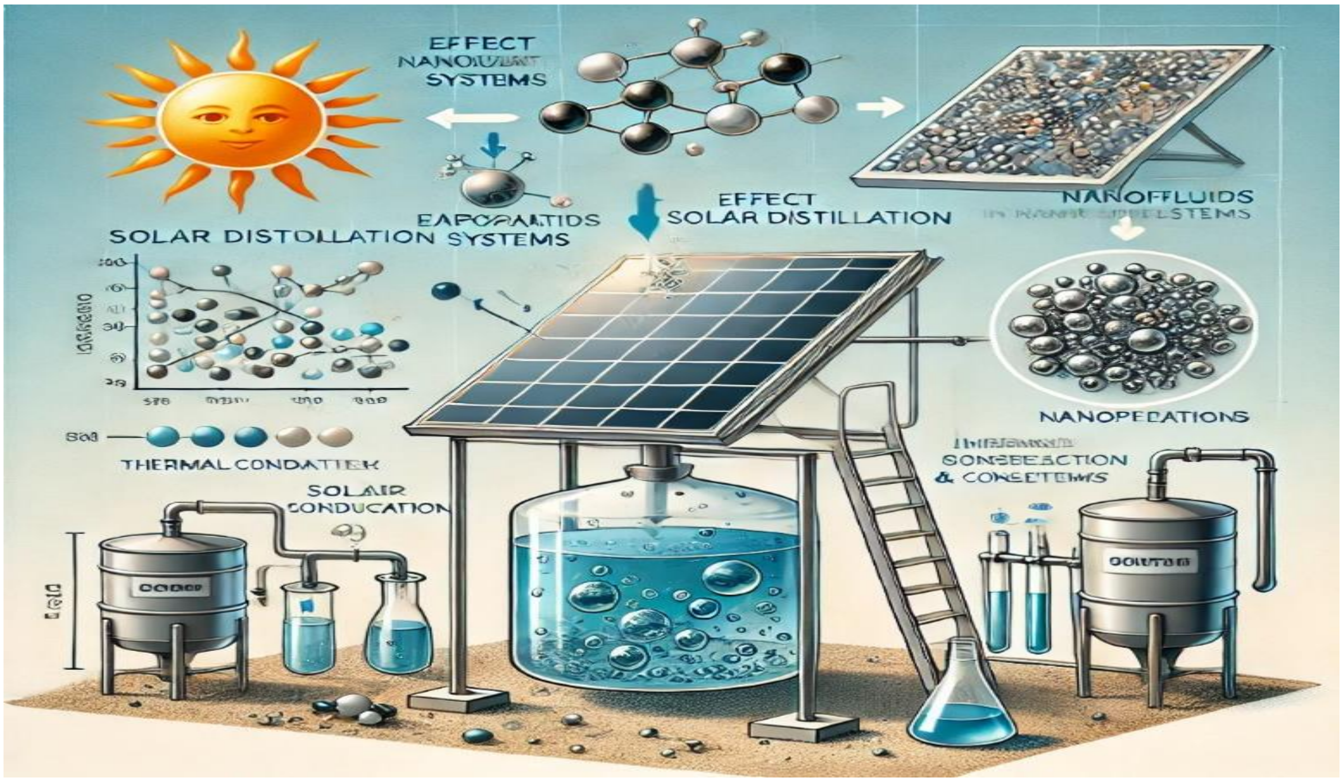

Fig. 2. Nanofluids in Solar distillation.

However, despite these methods, long-term stability remains a challenge, as nanoparticles may still settle over time, particularly in static systems like solar stills. Researchers are exploring alternative approaches, such as surface modification of nanoparticles and the use of advanced nanomaterials with inherently stable properties, to overcome these challenges. Ensuring the stability of nanofluids is not only essential for maintaining system efficiency but also for reducing maintenance requirements and ensuring the economic viability of solar distillation technologies over extended periods.

3.4. Effect on Heat Transfer

The superior heat transfer properties of nanofluids make them a valuable addition to solar distillation systems. The high thermal conductivity of nanofluids facilitates faster heat distribution, which reduces the temperature gradients within the system and enhances overall efficiency. This increased heat transfer capability is particularly beneficial for solar stills, where the goal is to maximize the conversion of absorbed solar energy into heat for water evaporation. Li et al. [22] reported that the use of nanofluids in solar stills increased the distillate output by up to 66%, demonstrating the profound impact of enhanced heat transfer on system productivity. Similarly, Menten et al. [23] observed a 50% increase in distillate output when nanofluids were used, highlighting their potential to significantly improve the performance of solar distillation systems. Factors such as nanoparticle type, concentration, and base

3.5. Effect on Evaporation Rate

The evaporation rate in solar distillation systems is a critical factor that determines the overall productivity of distilled water. The use of nanofluids has been shown to substantially enhance this rate due to their unique thermal and optical properties. When nanoparticles are added to a base fluid, they alter its thermal characteristics, including its specific heat capacity, thermal conductivity, and, importantly, vapor pressure. These changes lead to a faster and more efficient evaporation process. Specifically, nanoparticles increase the absorption of solar radiation, leading to higher localized temperatures and accelerated water evaporation.

Studies have demonstrated the profound effect nanofluids have on evaporation rates. Sun et al. [24] observed that the introduction of nanofluids into a solar still improved the evaporation rate by up to 30% compared to conventional systems using plain water. This enhancement was attributed to the increased thermal conductivity and superior solar energy absorption provided by the nanoparticles. Similarly, Masood et al. [25] reported a significant 50% increase in the evaporation rate in a nanofluid-based solar still.

Nanoparticles such as TiO_2, Al_2O_3, and graphene oxide are particularly effective in enhancing evaporation. Their high thermal conductivity and capacity to scatter and absorb solar energy create a highly efficient environment for vapor generation. Furthermore, the nanoparticles' small size and high surface area increase the interaction between the fluid and solar energy, intensifying the heat transfer process. However, the effect of nanofluids on the evaporation rate is influenced by factors such as nanoparticle type, size, and concentration, as well as the stability of the nanofluid. Excessive nanoparticle concentration may lead to agglomeration, reducing the fluid’s efficiency and potentially clogging the system. Therefore, optimizing the formulation of nanofluids is essential for maximizing evaporation rates. The results of these studies underline the potential of nanofluids to revolutionize solar distillation by significantly increasing the productivity of distilled water.

3.6. Effect on Efficiency

The efficiency of a solar distillation system measures how effectively it converts solar energy into usable distilled water. Incorporating nanofluids into these systems has shown considerable promise in improving their efficiency. The enhanced thermal conductivity and increased evaporation rates achieved through nanofluids directly contribute to greater efficiency by maximizing energy utilization and minimizing losses. Nanofluids improve efficiency through several mechanisms. First, their ability to absorb and scatter solar radiation enhances the heat transfer to the water, enabling faster evaporation. Second, their thermal conductivity allows for more uniform heat distribution, reducing energy wastage. Studies, such as those conducted by Chenche et al. [26], have reported a 24% increase in the efficiency of solar stills using nanofluids compared to conventional systems. These findings highlight the transformative impact of nanotechnology in renewable energy applications.

Additionally, nanofluids can extend the operational period of solar stills. By maintaining a higher temperature for a longer duration, nanofluids enable consistent evaporation even in less favorable sunlight conditions. This property is especially advantageous in regions with fluctuating solar intensity, as it ensures a steady supply of distilled water. Despite these benefits, certain challenges must be addressed to sustain efficiency improvements. Nanofluid stability is a significant concern, as sedimentation and aggregation can reduce heat transfer efficiency over time. The choice of nanoparticles and their concentration also plays a crucial role in determining system performance. High concentrations may cause an adverse effect due to increased viscosity, which can impede fluid flow and reduce heat transfer efficiency. The incorporation of nanofluids into solar distillation systems has the potential to significantly enhance their efficiency. By optimizing nanoparticle properties and addressing stability issues, researchers can further improve the practicality and scalability of this technology.

3.7. Effect of Nanoparticles

The selection of nanoparticles significantly influences the performance of nanofluids in solar distillation systems. Different nanoparticles exhibit unique thermal, optical, and physical properties, which impact their effectiveness in enhancing system efficiency. Commonly used nanoparticles include copper oxide (CuO), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), and carbon nanotubes (CNTs). These nanoparticles are selected for their high thermal conductivity, stability, and compatibility with base fluids. Copper oxide nanoparticles, for instance, are highly effective in enhancing the thermal conductivity of nanofluids, making them suitable for solar distillation applications. Ghalamchi et al. [27] demonstrated that using CuO nanofluids in a solar still improved its efficiency by 25%. Similarly, Al_2O_3 and TiO_2 nanoparticles have been extensively studied for their ability to improve solar absorption and evaporation rates, resulting in higher water distillation outputs. The physical dimensions and surface area of nanoparticles also play a crucial role. Smaller nanoparticles with higher surface areas facilitate better interaction with the base fluid and enhance energy transfer. Carbon-based nanoparticles, such as graphene and CNTs, are particularly advantageous due to their exceptional thermal conductivity and ability to absorb a broad spectrum of solar radiation. Their inclusion in nanofluids has shown remarkable improvements in solar still productivity.

However, the effectiveness of nanoparticles depends on their dispersion stability within the base fluid. Agglomeration and sedimentation can diminish their thermal and optical properties, reducing their impact on system performance. To address this, stabilization techniques such as surfactant addition, pH adjustment, and ultrasonication are employed. These methods ensure uniform dispersion and prevent particle settling, maintaining the nanofluid's enhanced properties over time.

3.8. Effect of Concentration

The concentration of nanoparticles in a nanofluid significantly influences its thermal and optical properties, directly affecting the efficiency of solar distillation systems. Higher concentrations of nanoparticles generally lead to improved thermal conductivity and solar absorption, enhancing heat transfer and evaporation rates. However, this improvement is only observed up to a certain concentration, beyond which adverse effects such as particle aggregation and increased viscosity can occur. Ghalamchi et al. [27] explored the impact of CuO nanoparticle concentration on the efficiency of solar stills. Their findings revealed that increasing the concentration of CuO nanoparticles up to 0.1% resulted in a marked efficiency improvement. However, concentrations beyond this threshold led to particle agglomeration, reducing the nanofluid's thermal conductivity and overall system performance. This phenomenon underscores the importance of identifying the optimal nanoparticle concentration for maximizing efficiency. The balance between nanoparticle concentration and fluid stability is critical. Higher concentrations may enhance the nanofluid's thermal properties, but they can also increase the risk of sedimentation and clogging within the system. Moreover, excessive concentrations may lead to higher operational costs, as nanoparticles are often expensive to produce and stabilize. Thus, optimizing nanoparticle concentration is a key focus in nanofluid research for solar distillation. By identifying the ideal concentration range and employing stabilization techniques, researchers can ensure maximum efficiency while minimizing potential drawbacks.

3.9. Effect of Base Fluid

The choice of the base fluid in nanofluids is a crucial determinant of their thermal and physical properties, ultimately affecting the efficiency of solar distillation systems. Base fluids serve as the medium for dispersing nanoparticles and play a pivotal role in heat transfer processes. Water is the most commonly used base fluid due to its high specific heat capacity, low cost, and non-toxic nature. However, other fluids, such as ethylene glycol, propylene glycol, and engine oil, have also been explored to enhance thermal properties under varying operational conditions.

In a study conducted by Singh et al. [28], the impact of different base fluids—water, ethylene glycol, and engine oil—on the performance of a solar still was investigated. The results revealed that water was the most effective base fluid, achieving the highest efficiency. This superior performance can be attributed to water's excellent thermal conductivity, lower viscosity (leading to improved heat transfer), and high compatibility with various nanoparticles. Conversely, ethylene glycol and engine oil, while offering higher boiling points, were less effective due to their higher viscosities, which impede fluid flow and heat transfer. The choice of the base fluid is also influenced by the specific operational environment and desired thermal properties. For instance, ethylene glycol is often used in cold climates due to its antifreeze properties, whereas oil-based fluids are preferred in high-temperature environments due to their stability and thermal resilience. However, these alternatives come with trade-offs, including increased costs, potential environmental impacts, and lower thermal conductivity compared to water.

Furthermore, the compatibility of the base fluid with nanoparticles is a significant consideration. The base fluid must provide a stable dispersion for nanoparticles, ensuring minimal aggregation and sedimentation over time. This stability is critical for maintaining the enhanced thermal properties of the nanofluid. Techniques such as ultrasonication, surfactant addition, and pH adjustment are commonly used to stabilize nanoparticles in various base fluids. Overall, water remains the most widely used and effective base fluid for nanofluids in solar distillation due to its superior thermal and physical properties. However, exploring other base fluids may be necessary for specialized applications or challenging environmental conditions. The selection of the base fluid should consider factors such as thermal conductivity, viscosity, operational conditions, and compatibility with nanoparticles to optimize the performance of the solar distillation system.

3.10. Increased Absorption of Solar Radiation

Nanofluids have demonstrated the ability to significantly enhance the absorption of solar radiation in solar distillation systems. This capability stems from the unique optical properties of nanoparticles, which allow them to absorb and scatter a broader spectrum of sunlight compared to conventional fluids. By improving solar energy absorption, nanofluids contribute to higher localized temperatures, faster boiling, and increased evaporation rates, ultimately boosting the productivity of solar distillation systems. The enhanced absorption is primarily attributed to the plasmonic and photothermal effects of nanoparticles. Metallic nanoparticles such as gold, silver, and copper exhibit localized surface plasmon resonance (LSPR), enabling them to absorb solar radiation efficiently. Similarly, carbon-based nanoparticles, including graphene and carbon nanotubes (CNTs), possess high solar absorptivity and thermal conductivity, making them ideal for solar energy applications. For instance, studies such as those conducted by Alawi et al. [29] have shown that nanofluids containing carbon nanotubes or graphene nanoparticles can absorb up to 20-30% more solar radiation than water. This increased absorption translates to higher heat generation within the distillation system, accelerating the evaporation process and improving water productivity.

The optical properties of nanofluids are influenced by factors such as nanoparticle size, shape, concentration, and type. Smaller nanoparticles with larger surface areas offer greater interaction with sunlight, while certain shapes, such as rods or plates, may enhance absorption efficiency. The concentration of nanoparticles also plays a role; however, excessive concentrations may lead to shading effects, reducing the overall effectiveness of the nanofluid. Despite these advantages, challenges exist in optimizing the absorption of solar radiation by nanofluids. Stability issues, such as nanoparticle sedimentation, can reduce the efficiency of solar energy absorption over time. To address this, researchers have focused on improving nanoparticle dispersion and employing additives or surface modifications to enhance stability. The increased absorption of solar radiation by nanofluids is a critical factor contributing to their effectiveness in solar distillation systems. By leveraging the unique optical properties of nanoparticles and optimizing their dispersion and stability, nanofluids can significantly improve the productivity and efficiency of solar distillation.

3.11. Stability and Agglomeration Issues

While nanofluids offer numerous advantages in solar distillation systems, maintaining their stability over time is a significant challenge. Stability refers to the ability of nanoparticles to remain uniformly dispersed in the base fluid without aggregation or sedimentation. Agglomeration, the clustering of nanoparticles, can diminish the enhanced thermal and optical properties of nanofluids, leading to reduced system efficiency. Agglomeration occurs due to the attractive van der Waals forces between nanoparticles, which can overcome the stabilizing forces in the fluid. This results in larger particle clusters that settle at the bottom of the container, rendering the nanofluid less effective. Several factors influence stability, including nanoparticle type, concentration, size, and the properties of the base fluid.

To mitigate stability issues, researchers have explored various stabilization techniques. One common approach is the use of surfactants—chemical agents that reduce surface tension and create a repulsive force between nanoparticles, preventing aggregation. Another method involves adjusting the pH of the nanofluid to enhance electrostatic repulsion between particles. Ultrasonication, which uses high-frequency sound waves to break apart agglomerates, is also widely used to achieve uniform dispersion.

Surface modification of nanoparticles is another effective strategy. By coating nanoparticles with functional groups or polymers, their compatibility with the base fluid can be improved, reducing the likelihood of aggregation. For example, Alawi et al. [30] demonstrated that surface-modified TiO_2 nanoparticles exhibited superior stability in water-based nanofluids compared to unmodified particles. However, ensuring long-term stability remains a challenge, particularly in real-world applications where nanofluids are subjected to varying temperatures, flow rates, and environmental conditions. The development of robust stabilization techniques and advanced nanofluid formulations is crucial to overcoming these limitations. Addressing stability and agglomeration issues is essential for maximizing the benefits of nanofluids in solar distillation systems. Through innovative stabilization methods and optimized formulations, researchers can ensure the reliable and sustained performance of nanofluid-based systems.

3.12. Environmental Impact

The environmental impact of nanofluids in solar distillation systems is an important consideration, particularly given the increasing emphasis on sustainable and eco-friendly technologies. While nanofluids can significantly improve the efficiency of solar distillation systems and reduce energy consumption, their production, usage, and disposal may pose environmental challenges. The manufacturing of nanoparticles often involves energy-intensive processes and the use of hazardous chemicals, which can contribute to environmental pollution. Additionally, the extraction of raw materials for nanoparticles, such as metals and carbon, may have ecological implications, including habitat destruction and resource depletion. Addressing these issues requires the development of sustainable manufacturing methods and the use of renewable or abundant resources for nanoparticle production.

The disposal of nanofluids also raises concerns about their potential impact on aquatic and terrestrial ecosystems. If nanoparticles are released into the environment, they may accumulate in water bodies or soil, posing risks to plant and animal life. For instance, metallic nanoparticles such as silver or copper can be toxic to aquatic organisms, even at low concentrations. To mitigate these risks, researchers are exploring methods for recycling and reusing nanoparticles, as well as developing biodegradable or eco-friendly nanofluids.

Despite these challenges, the use of nanofluids in solar distillation offers substantial environmental benefits. By improving the efficiency of water purification systems, nanofluids can reduce the reliance on fossil fuels and lower greenhouse gas emissions. Furthermore, solar distillation systems using nanofluids can provide a sustainable solution for freshwater production in regions facing water scarcity. While nanofluids have the potential to enhance the sustainability of solar distillation systems, their environmental impact must be carefully assessed and managed. Through sustainable manufacturing practices, responsible usage, and effective disposal methods, the environmental footprint of nanofluids can be minimized, ensuring their long-term viability as a green technology.

Table 1 provides a comprehensive summary of various studies that explore the use of nanoparticles to enhance the efficiency and productivity of solar desalination systems. It highlights the types of research conducted, including experimental and analytical approaches, and the diverse configurations of solar stills, such as single slope, double slope, modified stills with phase change materials (PCM), and inclined stills. The table underscores the significance of nanoparticle type, concentration, and size in boosting productivity. For instance, Al_2O_3 nanoparticles were extensively studied, achieving productivity enhancements of up to 67.18% at a 0.02% concentration in modified solar stills with PCM. Similarly, carbon nanotubes demonstrated a remarkable 50% improvement in a single basin solar still. Analytical studies, such as those by Mahian et al., reported productivity enhancements of up to 125% with varying nanoparticle types and concentrations. This table effectively demonstrates how nanoparticle selection and system design optimize thermal performance, making solar desalination more sustainable and efficient.

4. MATHEMATICAL MODELLING OF NANOFLUID SOLAR STILL

The mathematical modeling of nanofluid solar stills has emerged as a critical tool in advancing our understanding of these systems and optimizing their design and operational efficiency. Recent advancements in this field have combined experimental data, computational methods, and machine learning algorithms to provide more accurate and predictive models. These models play a vital role in identifying the influence of nanoparticles, phase change materials (PCMs), and other design variables on the thermal and economic performance of solar stills.

4.1. Thermo-Economic Models

Thermo-economic models have been pivotal in assessing the interplay between thermal efficiency and economic viability of nanofluid solar stills. A comprehensive thermo-economic model developed by researchers has incorporated the effects of various nanoparticles, such as CuO, Al_2O_3, and TiO_2, on the performance of an inclined wick solar still [40].

Table 1. Use of nanoparticles to boost the efficiency and productivity of solar desalination systems.

Type of Solar Still	Type of Nanoparticle	Concentration of Nanoparticle (%)	Size of Nanoparticle	Enhancement in Productivity	Ref.
Single slope solar still	Al_2O_3	0.1%	50 nm	29.95%	[32]
Modified solar still with PCM and internal condenser	Al_2O_3	0.02%	20 nm	43.8%	[33]
Modified solar still with PCM	Al_2O_3	0.02%	20 nm	67.18%	[34]
Double slope solar still	TiO_2	0.12%	30 nm	8.4%	[35]
Single basin solar still	Carbon nanotubes	0.5%	10-12 nm diameter, 0.1-10 μm length	50%	[17]
Various	Various (Al_2O_3, TiO_2 etc.)	0.01-4%	10-100 nm	Up to 125% (depending on type and concentration)	[36]
Single slope solar still	Al_2O_3	0.1%	50 nm	29.5%	[37]
Flat plate solar collector	CuO	0.1-0.4%	29 nm	Up to 22.76% (thermal efficiency)	[38]
Inclined solar still	ZnO	0.1%	30 nm	16.1%	[39]

By integrating experimental data, this model analyzed the impact of nanoparticle concentration, type, and operating conditions on system productivity and cost-effectiveness. The study found that CuO nanoparticles at a concentration of 0.1% provided the most significant enhancement, yielding a productivity increase of 62.9%. This improvement was attributed to the superior thermal conductivity and heat transfer characteristics of CuO nanoparticles, which accelerated the evaporation process. The economic aspect of the model highlighted the cost-effectiveness of using nanofluids by quantifying the reduction in freshwater production costs due to higher efficiency. These findings underscore the importance of selecting the right type and concentration of nanoparticles to balance thermal and economic performance.

4.2. Artificial Neural Networks (ANNs) and Genetic Algorithms

Incorporating artificial intelligence into mathematical modeling has opened new avenues for optimizing nanofluid solar still performance. Margoum et al. [41] introduced a novel approach by integrating artificial neural networks (ANNs) with genetic algorithms to model and optimize the performance of nanofluid-based solar stills. The ANN component of the model was trained on experimental data to predict system efficiency with remarkable accuracy. Genetic algorithms were then used to optimize the design and operational parameters, such as nanoparticle type, concentration, and flow rates, to achieve the highest possible efficiency. The integration of ANNs and genetic algorithms provided significant insights into the complex, non-linear relationships between various system variables. This approach also enabled rapid optimization without the need for exhaustive experimental trials, reducing the time and cost associated with system development. The study demonstrated that combining machine learning with traditional modeling techniques can be a powerful tool for designing next-generation solar stills.

4.3. Nanoparticles and Phase Change Materials (PCMs)

Phase change materials (PCMs) have been increasingly used in conjunction with nanofluids to enhance the thermal performance of solar stills. Said et al. [42] proposed an advanced mathematical model that accounts for the synergistic effects of nanoparticles and PCMs. The model demonstrated that the inclusion of PCMs, combined with the enhanced heat transfer properties of nanofluids, resulted in productivity enhancements of up to 73.8%. The model highlighted how PCMs could store excess thermal energy during peak solar radiation hours and release it during low-radiation periods, ensuring a more stable and efficient operation. Nanoparticles further enhanced this process by improving the thermal conductivity of the PCMs, leading to faster charging and discharging cycles. This synergistic effect not only improved the overall productivity of the solar still but also extended its operational hours, making it more suitable for regions with fluctuating solar radiation.

4.4. Stability and Agglomeration Modeling

Nanoparticle stability is a critical factor affecting the long-term performance of nanofluid solar stills. Addressing this challenge, researchers have incorporated nanoparticle agglomeration kinetics into their mathematical models [43]. These models account for the gradual aggregation and sedimentation of nanoparticles, which can diminish the enhanced thermal properties of the nanofluid over time. By integrating agglomeration dynamics, the models provide more realistic predictions of long-term performance and help in designing stabilization strategies. For instance, the addition of surfactants or the use of ultrasonication can be modeled to predict their impact on reducing agglomeration and maintaining nanofluid stability. This approach ensures that the performance improvements achieved through nanofluid usage are sustainable over the lifetime of the solar still.

4.5. Computational Fluid Dynamics (CFD) and Multiphase Modeling

Computational Fluid Dynamics (CFD) has become an indispensable tool for understanding the complex heat and mass transfer phenomena occurring in nanofluid solar stills. A recent study employed a multiphase mixture model in conjunction with CFD simulations to capture local temperature and concentration distributions within the solar still [44]. This model provided unprecedented insights into the intricate interactions between nanofluids, solar radiation, and the distillation process. The simulations revealed that nanoparticles created localized "hot zones" within the fluid, significantly enhancing evaporation rates. Additionally, the model identified regions of suboptimal performance, such as areas with lower fluid mixing or uneven nanoparticle distribution, enabling targeted design improvements. The use of CFD also facilitated the analysis of various configurations, such as inclined or stepped solar stills, to determine the optimal design for maximizing efficiency. The advancements in mathematical modeling have not only improved our understanding of nanofluid solar stills but also paved the way for practical applications. These models serve as valuable tools for designing and optimizing solar stills tailored to specific environmental conditions and operational requirements. For instance, regions with high solar irradiance can benefit from models that emphasize nanoparticle-induced heat transfer, while areas with intermittent sunlight may prioritize PCM integration for thermal energy storage. Future directions in this field include the integration of hybrid models that combine experimental, computational, and machine learning approaches. Additionally, the development of user-friendly simulation tools based on these models can facilitate their adoption by engineers and researchers worldwide. Emphasis should also be placed on incorporating environmental and economic factors into the models to ensure the sustainability and scalability of nanofluid solar still technologies. Mathematical modeling has become a cornerstone in the development of nanofluid solar stills, offering detailed insights into their performance and enabling significant efficiency enhancements. By integrating thermo-economic analyses, machine learning techniques, phase change material dynamics, and nanoparticle stability considerations, these models provide a comprehensive framework for optimizing solar still designs. The incorporation of CFD and multiphase modeling has further expanded our understanding of the complex processes within these systems. As the field continues to evolve, mathematical modeling will remain a vital tool in achieving more efficient, cost-effective, and sustainable desalination solutions.

5. CONCLUSION

The integration of nanofluids into solar distillation systems marks a transformative step in sustainable water purification technologies. The reviewed studies consistently highlight the potential of nanofluids to significantly enhance the efficiency and productivity of solar distillation, addressing a critical bottleneck in conventional systems. Key findings reveal that nanofluids can achieve performance enhancements such as up to an 84% increase in heat transfer coefficient, a 65% reduction in thermal resistance, and a 56% improvement in freshwater yield. These results are primarily attributed to the superior thermal conductivity, stability, and convective heat transfer properties of nanofluids. However, the effectiveness of nanofluids is highly dependent on optimizing parameters such as nanoparticle type, size, concentration, and base fluid properties. For instance, selecting nanoparticles with high thermal conductivity, such as metal oxides or carbon-based materials, can significantly enhance system performance. Similarly, achieving the optimal balance in nanoparticle concentration is crucial, as excessively high concentrations may lead to aggregation and increased viscosity, which could offset performance gains. While the potential of nanofluids is evident, several challenges must be addressed before their widespread adoption. These include long-term stability of nanofluids, environmental impacts of nanoparticle disposal, economic feasibility, and the scalability of nanofluid-based systems. Advanced modeling techniques, such as computational fluid dynamics and machine learning, are paving the way for more accurate predictions and optimized designs. Nanofluid-enhanced solar distillation offers a promising pathway to address global water scarcity by providing a sustainable, efficient, and cost-effective solution. With continued research and development, particularly in optimizing nanofluid formulations and scaling up technologies, this innovative approach has the potential to significantly impact water purification systems worldwide, fostering resilience in water-stressed regions.

6. FUTURE DIRECTIONS FOR NANOFLUID SOLAR STILLS

As the field of nanofluid solar distillation continues to evolve, several future directions present opportunities for advancing the technology. These areas encompass both scientific research and practical applications, aiming to address existing challenges, enhance system performance, and ensure sustainability.

Development of Advanced Nanoparticles: Future research should focus on the development of novel nanoparticles with superior thermal, optical, and stability properties. Current studies have primarily explored materials such as CuO, Al_2O_3, TiO_2, and carbon-based nanomaterials (e.g., graphene and carbon nanotubes). However, emerging materials, such as MXenes, metal-organic frameworks (MOFs), and quantum dots, hold the potential for even greater efficiency improvements. These materials can be tailored to optimize specific properties, such as thermal conductivity, solar absorption, and anti-agglomeration characteristics.

Hybrid Nanofluids: The use of hybrid nanofluids, which combine two or more types of nanoparticles, is a promising direction for enhancing solar still performance. Hybrid nanofluids can leverage the unique properties of different nanoparticles to achieve synergistic effects. For example, combining metal oxide nanoparticles with carbon-based materials may enhance both thermal conductivity and solar absorption. Research should also explore the optimal ratios, combinations, and methods for synthesizing hybrid nanofluids.

Integration with Advanced Materials: The integration of nanofluids with advanced materials, such as phase change materials (PCMs) and hydrophilic coatings, offers another avenue for enhancing solar still efficiency. PCMs can store excess thermal energy and release it during non-sunny periods, ensuring continuous operation. Future studies could investigate the compatibility of nanofluids with PCMs, focusing on improving heat transfer rates and thermal stability. Hydrophilic and anti-reflective coatings, when combined with nanofluids, could further enhance solar absorption and evaporation rates. Exploring novel surface modifications, such as nanostructured coatings, may provide additional performance benefits.

Long-Term Stability and Durability: One of the primary challenges of nanofluid-based systems is maintaining stability over time. Nanoparticle agglomeration, sedimentation, and degradation can reduce the effectiveness of the nanofluid. Future research should focus on developing strategies to improve long-term stability, such as advanced surfactants, surface functionalization of nanoparticles, and self-stabilizing nanofluids. Additionally, studies on the durability of nanofluids under varying environmental conditions, such as high salinity or extreme temperatures, will be essential for their widespread application.

Sustainable and Eco-Friendly Solutions: While nanofluids enhance solar distillation efficiency, their environmental impact needs careful consideration. The production, usage, and disposal of nanoparticles could pose risks to ecosystems if not managed properly. Future efforts should prioritize sustainable practices, such as developing biodegradable or recyclable nanoparticles, minimizing the use of toxic chemicals, and establishing efficient recycling methods for used nanofluids. Research into the life cycle analysis (LCA) of nanofluids and their integration into solar still systems will help quantify their overall environmental footprint and guide the development of eco-friendly solutions.

Advanced Computational and Machine Learning Models: The integration of advanced computational techniques, such as machine learning, artificial intelligence (AI), and multi-physics simulations, will play a pivotal role in the future of nanofluid solar stills. Machine learning models can optimize system parameters, predict performance, and identify areas for improvement based on real-world data. AI-based algorithms can also facilitate the design of new nanoparticles and nanofluid formulations with enhanced properties. Additionally, multi-physics computational fluid dynamics (CFD) models can provide detailed insights into the complex heat and mass transfer processes within nanofluid solar stills. These models can be further refined to include dynamic variables such as weather fluctuations, fluid stability, and long-term degradation.

Scaling and Commercialization: Scaling up nanofluid solar still technology from laboratory prototypes to commercial-scale systems is a critical step for widespread adoption. Future research should focus on overcoming challenges associated with large-scale deployment, such as cost, manufacturing processes, and maintenance. Studies on the economic feasibility of nanofluid solar stills, particularly in remote and arid regions, will be essential to attract investment and promote commercialization. Additionally, collaboration with industry stakeholders, policymakers, and non-governmental organizations can facilitate the integration of nanofluid solar stills into water desalination and purification programs worldwide.

Hybrid Renewable Energy Systems: Nanofluid solar stills can be integrated into hybrid renewable energy systems to enhance their overall performance. For example, coupling solar stills with photovoltaic panels or solar thermal collectors can provide electricity for auxiliary components, such as pumps or fans, while simultaneously increasing water production. Future research could explore the feasibility of such hybrid systems, focusing on energy management, cost reduction, and scalability.

Real-Time Monitoring and Smart Systems: The incorporation of real-time monitoring and smart technologies into solar still systems is another promising direction. Sensors can be used to monitor parameters such as temperature, solar irradiance, and fluid stability, providing valuable data for optimizing system performance. Smart control systems, powered by IoT (Internet of Things) and AI, can adjust operating conditions dynamically to maximize efficiency and productivity.

Addressing Regional Needs: Future research should also focus on tailoring nanofluid solar still designs to meet specific regional needs. Factors such as climate, water quality, and socio-economic conditions vary widely across regions, necessitating customized solutions. For instance, systems designed for arid regions with high solar irradiance may prioritize efficiency, while those for low-income areas may focus on affordability and ease of maintenance. The future of nanofluid solar stills lies in the convergence of advanced materials, computational modeling, sustainable practices, and real-world applications. By addressing current challenges and exploring innovative solutions, researchers and engineers can unlock the full potential of nanofluid solar stills for efficient and sustainable freshwater production. This technology holds great promise for addressing global water scarcity, particularly in regions where traditional desalination methods are impractical or too costly. With continued interdisciplinary efforts, nanofluid solar stills can become a cornerstone of future desalination technologies.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

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Authors' contributions

All authors contributed equally in the preparation of this manuscript.

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