sustainability

Review

A Comprehensive Review of Performance Augmentation of Solar Stills Using Common Non-Metallic Nanofluids

Anwur Alenezi [1,*] and Yousef Alabaiadly [2]

[1] Water Research Centre, Kuwait Institute for Scientific Research, Safat 13109, Kuwait
[2] Power Stations and Water Distillation Sector, Ministry of Electricity and Water, Ministries Zone 12010, Kuwait
* Correspondence: anwenezi@kisr.edu.kw; Tel.: +96-524-989-338

Abstract: All living organisms depend on water for their survival. Therefore, sufficient water availability is necessary for health. During the last few years, considerable progress has been made in the production of clean drinking water—particularly in the desalination industry. Various methods have been explored to boost the productivity of solar stills. The present review focuses on recent enhancement techniques aimed at boosting their performance—particularly those incorporating non-metallic nanofluids into the base fluid. The nanomaterials examined in this review include Al_2O_3, CuO, ZnO, and TiO_2. Several studies adding Al_2O_3 in a solar-still desalination system resulted in an increase in distillate yield, better efficiency, reduced energy consumption, reduced thermal loss, and better productivity. The incorporation of CuO in a solar-still desalination system led to major improvements in performance. These included enhanced daily efficiency, better productivity, improved production of freshwater, and higher energy and exergy efficiency. The incorporation of TiO_2 in a solar-still desalination system resulted in increased productivity, better thermal conductivity, better thermal efficiency, higher daily distillate output, and high levels of water temperature. It was also evident that the incorporation of ZnO in a solar-still desalination system resulted in a substantial increase in the output of clean water and occasioned improvements in productivity and overall efficiency. Together, these findings demonstrate the potential of these nanomaterials to significantly enhance the performance of solar-still desalination systems. Other nanomaterials that are yet to gain increased use, such as SiO_2 and SnO_2, have also been discussed. The collective results in this paper demonstrate the potential of nanofluids to enhance the performance and effectiveness of solar-still desalination systems. This review provides conclusive evidence of the positive effects of different nanofluids on the yield, productivity, energy, and efficiency of diverse types of solar stills, offering promising advancements in the sustainable production of water.

Keywords: solar still technology; nanomaterials; desalination; nanofluid; productivity; efficiency

check for updates

Citation: Alenezi, A.; Alabaiadly, Y. A Comprehensive Review of Performance Augmentation of Solar Stills Using Common Non-Metallic Nanofluids. *Sustainability* **2023**, *15*, 10122. https://doi.org/10.3390/su151310122

Academic Editors: Mariusz Sojka and Dariusz Młyński

Received: 15 May 2023
Revised: 8 June 2023
Accepted: 14 June 2023
Published: 26 June 2023

1. Introduction

All living organisms require water for survival. Thus, the availability of sufficient water is necessary for their well-being. However, limited access to safe drinking water remains a major concern in the 21st century. According to United Nations International Children's Fund (UNICEF), about one in four people lacked access to safe drinking water in their homes in 2020 [1]. The disastrous nature of the global water crisis has probably been exacerbated by the coronavirus pandemic, which highlights the need for everyone to maintain good hand hygiene. The UNICEF report further notes that billions of people worldwide could lack access to safe drinking water, sanitation, and hygiene services by 2030, unless the rate of progress increases fourfold [1]. Achieving access to clean drinking water remains a dream for many people worldwide.

In recent years, considerable progress has been made in the production of clean drinking water, particularly in the desalination industry. Globally, there are over 20,000 desalination plants, generating approximately 95 billion litres of desalinated water every day [2]. Approximately 4% of water desalination initiatives globally occur in the Middle East and North Africa, and the global market is expected to reach an estimated USD 32.1 billion by 2027 [2]. However, desalination cannot solve the water-shortage crisis that affects most parts of the world. Nevertheless, the approach is proving to be effective in reducing the loss of water and enhancing supply with the technological advancements in the recycling process. Therefore, desalination processes help supply clean and affordable water to millions of people who would otherwise struggle to access it.

Commercial desalination plants were an early-20th-century invention established first in the Middle East. The first desalination plant within the Gulf region was established in 1907 in Jeddah, Kingdom of Saudi Arabia [3,4]. Various small- and average-sized plants have been established across other parts of the Gulf, particularly in Qatar and Kuwait. There was a rapid expansion in the establishment of large-scale desalination plants around the globe in the middle of the 20th century, with the Middle East still leading the adoption of these facilities [5]. The United States Congress ratified “The Saline Water Act” in 1952 and established the Office of Saline Water to support the federal government in setting up desalination facilities. In the 1960s, desalination technologies became popular, a period during which most plants were dependent on thermal processes. A few years later, multi-stage flash-distillation processes became commonplace [5,6].

Research efforts over the years have made seawater desalination a sustainable solution that can ensure future water supply. Researchers have attempted to establish novel hybrid-desalination systems using clean energy. Among the popular efforts, modified solar still (MSS) is a new method [7,8]. This method is considered revolutionary because it is designed to reduce the cost of desalination while simultaneously quadrupling the production volume. This invention is relevant today, as the major concern of the 21st century is to enhance the efficiency and effectiveness of water-purification technology to sustainably generate clean water.

Researchers have over time concentrated on capturing solar radiation and using nanomaterials to deal with the increasing demand for industrial expansion, energy optimisation, as well as cost-effective solutions [9,10]. The use of solar energy and nanotechnology has a lot of promise in different applications, including solar thermal aircraft and photovoltaic cells. One such study explored the flow characteristics, thermal distribution, as well as entropy generation of a magnetised hybrid Prandtl–Eyring nanofluid [9]. The nanofluid used in the study was flowing through the interior of a parabolic solar collector located on an aircraft wing. The results of the study revealed that $CoFe_20_4$-Cu/EG nanofluid showed higher thermal conductivity compared to a Cu-EG nanofluid. Another study concentrated on enhancing the efficiency of solar aircraft wings through the use of hybrid nanofluids and a parabolic-trough solar collector (PTSC) [10]. The study used zirconium dioxide and copper (Cu) nanoparticles together with non-Newtonian ethylene glycol (EG) as the base fluid. The findings of the study revealed the viscoelastic properties of the thermal transfer process and the possibility of optimising energy balance and physical parameters [10]. The findings from these two studies support advancements in thermal engineering and the use of nanotechnology in solar-powered systems.

Various studies have been conducted on techniques to increase the productivity of solar stills. This review focuses on recent performance-enhancement techniques that particularly involve the incorporation of non-metallic nanofluids in the base fluid. Good predictions for solar-still performance under particular weather conditions and design parameters can save time and money.

2. Design Aspects and Operation of a Solar Still

A solar still is a conventional device used to convert saline and brackish water into clean freshwater (Figure 1). The device uses solar energy, which is converted into the thermal energy required to control the phase change process. Alternatively, the device can also operate by producing the energy needed to control membrane processes [11]. Most desalination techniques used today are energy-intensive, and the solar-still approach presents a viable opportunity to use the sun—a renewable energy source [12]—thus making this approach economical for generating clean drinking water.

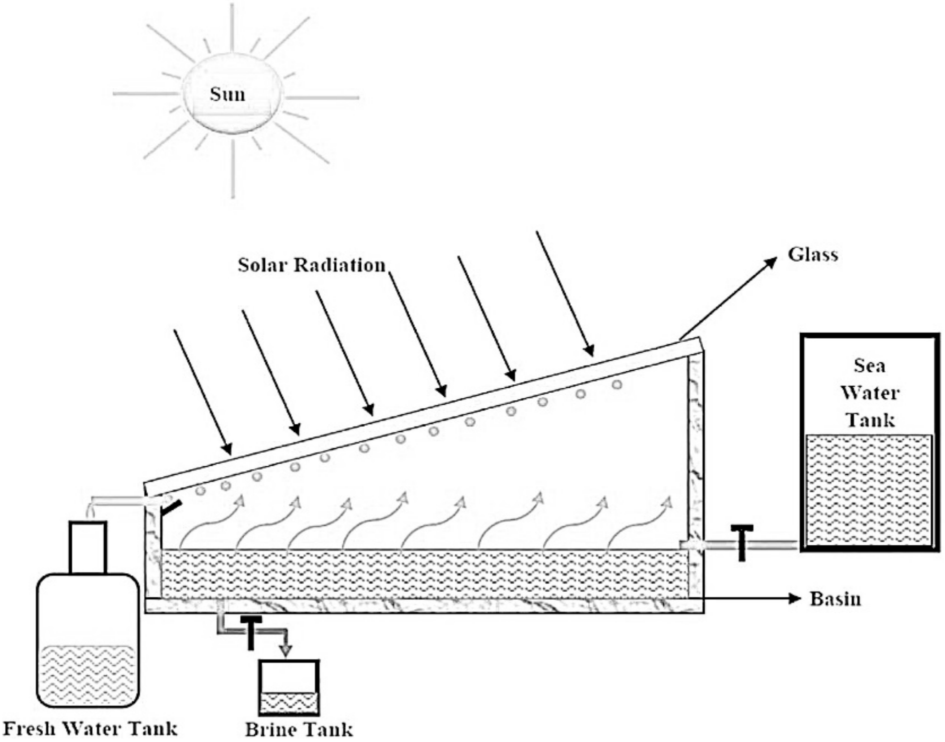

Figure 1. Illustration of a basic solar-still system [13]. The solar-still system uses solar radiation to heat the saltwater in the basin. The water evaporates and condenses on the glass cover, collecting as freshwater and flowing into the freshwater tank. The concentrated brine collects in the brine tank. This illustration showcases the process of solar-powered desalination.

Clean-water production from saline water involves a common basic principle regardless of the collection system used. In a direct collection system, solar energy is directly absorbed by the solar collectors to produce distillate [10,11]. In contrast, an indirect collection system uses two subsystems: one harnessing solar energy and the other facilitating the desalination process [10,11]. A standard solar still is an example of a direct collection system. The system features a water basin and a glass cover. Solar radiation penetrates the glass cover and is absorbed by the basin absorbers—which heat the water—leading to an increase in the vapour pressure. This is followed by condensation on a cooler glass cover, after which the water flows down into the collection reservoir. The glass cover reduces evaporation losses and prevents the wind from cooling the water in the basin [10,12].

Efficiency, productivity, internal heat, and mass transfer coefficients are among the key performance indicators for solar stills [14,15]. Experiments with solar stills determine efficiency based on the ratio of the latent heat energy of the condensed water to the total solar energy received by the still. The daily water output for every unit area of the solar still refers to productivity. The difference in temperature between the water in the basin and the inner surface of the glass cover plays an important role in controlling the productivity rate of the solar still. The temperature difference is mostly influenced by the evaporation rate of water from the basin and the condensation rate of vapour at the lower surface of the glass cover [14,15].

Because the solar-still system traditionally has a low productivity and efficiency compared with those of other desalination techniques, various enhancement methods and modifications have been attempted, which has led to suggestions on distinctive design parameters that are likely to enhance the solar-still productivity. Some of the major parameters suggested in recent research on enhancing solar-still productivity are reviewed further in the subsequent sections.

3. Bibliometric Study

A bibliometric study was conducted to identify influential papers in the field of performance augmentation for solar stills. Conducting this study led to insights about the most influential papers, popular authors, and emerging trends in the field. The bibliometric study proved to be a valuable resource for this review study. Scopus was selected as the preferred database since it offers detailed and multidisciplinary coverage of scientific literature. Equally, Scopus provides extensive citation data, allowing the evaluation of the impact and the influence of papers through citation counts and h-index. Keywords used to search in the Scopus database included "solar stills", "performance augmentation", "nanofluids", and "non-metallic". The search query found 4246 documents for solar-still-related literature and 1206 documents for nanofluids and performance-augmentation-related literature. The retrieved documents were of different types, ranging from research articles to editorials, reviews, and conference papers.

Studies exploring solar-still technology were clustered as follows:

1. The first cluster comprised those examining the effects of Al_2O_3 nanofluid on solar-still performance.
2. The second cluster comprised those examining the effects of CuO nanofluid on solar-still performance.
3. The third cluster examined the effects of TiO_2 nanofluid on solar-still performance.
4. The fourth cluster included all the other nanomaterials that have been found to be useful in enhancing solar-still performance.

The reviewed studies used different types of nanofluids based on different nanomaterials, as mentioned above. The nanofluids were prepared by spreading nanoparticles into a base fluid, such as water or a saline solution. Methods that were used included ultrasonication, two-step processes entailing surfactants or dispersants, and magnetic stirring. A summary of the bibliometric study is as shown in Table 1.

Table 1. Bibliometric study of solar-still-related literature and nanofluids- and performance-augmentation-related literature.

Solar-Still-Related Literature			**Nanofluids- and Performance-Augmentation-Related Literature**		
Type of Document	**Frequency**	**%** **n = 4246**	**Type of Document**	**Frequency**	**%** **N = 1206**
Article	2660	62.6	Article	823	68.2
Review	701	16.5	Review	174	14.4
Editorial	352	8.2	Editorial	88	7.2
Note	202	4.7	Note	37	3.0
Conference Paper	157	3.6	Conference Paper	32	2.7
Short Survey	104	2.4	Short Survey	28	2.3
Undefined	70	1.6	Undefined	24	1.9

4. Parameters Affecting Solar-Still Productivity

There are various parameters that affect solar-still productivity, such as the intensity of solar radiation, wind velocity, ambient air-temperature variations, glass–water temperature difference, water-free-surface area and depth, inlet water temperature, absorber-plate area, glass-cover angle, brine depth, rubber-sheet thickness, and variation in black-gravel sizes. Some of these factors can be controlled, whereas others cannot. For instance, meteorological factors such as the intensity of solar radiation, wind velocity, and ambient temperature cannot be controlled. However, other factors can be adjusted to increase the solar-still productivity. This review considers the controlled factors and modifications proposed in recent studies to improve solar-still productivity, particularly those concerning the inclusion of nanomaterials.

5. Improving the Daily Output of Solar Stills Using Nanomaterials

Solar stills play a crucial role in the rate of production and thermal performance in solar desalination. Several experimental modifications have been attempted to enhance the productivity of solar stills. One of the modifications proposed in recent studies involves the inclusion of nanomaterials in the base fluid used in solar stills [14,16,17]. The addition of nanomaterials has been reported to increase the production rate. Common examples of nanomaterials used to enhance the productivity of different types of solar stills include Al_2O_3, CuO, ZnO, and TiO_2.

5.1. Effects of Al_2O_3 Nanofluid on Solar-Still Performance

Sahota and Tiwari [15] investigated the effect of Al_2O_3 on the yield performance of a passive double-slope solar still (DSSS). Al_2O_3 nanoparticles were added to the base fluid (water) at two different masses of 35 and 80 kg. The passive DSSS with the nanofluid worked as follows: Solar radiation penetrates the solar still through the transparent condensing cover. The radiation is first absorbed by the nanofluid and then by the blackened surface. A plasmon-resonance absorption band of metallic nanoparticles is clearly observed near the infrared spectrum. The mixture of metallic nanoparticles in the base fluid absorbs solar radiation. A common effect of energy transfer between the nanoparticles and the basin liner is that it increases the temperature of the nanofluid in the solar still. Sahota and Tiwari [15] developed and implemented a methodology to calculate the changes in hourly and daily yields resulting from the passive DSSS at 0.04%, 0.08%, and 0.12% concentrations. The findings showed an increase in the heat-transfer coefficient with an increase in the concentration of nanoparticles. One reason for this is that nanofluids directly absorb solar radiation, and the rate of absorption increases with solar intensity. Another reason is that the basin liner also transfers thermal energy to the nanofluid, resulting in an increase in temperature. Overall, the daily yield of the solar still increases with increasing concentration of Al_2O_3 nanoparticles in the base fluid.

Zhang et al. [18] studied the effects of Al_2O_3 and TiO_2 nanoparticles on reducing the energy demand within solar collectors. The investigation involved the application of two methods to facilitate the better use of solar energy. The first was a phase-change material (PCM), which was used to absorb the solar radiation, eliminating potential summer radiation problems. The second approach depended on the absorption of the solar radiation and its conversion into a source of heat to generate sanitary hot water. The findings showed that the use of nanoparticles resulted in the reduction in energy consumption within the solar collectors. In the PCM method, energy consumption was reduced by 44% on hot days, which was equal to a 267 kWh drop. On cold days, the reduction was 48%—equivalent to 2419 kWh. Year-round analysis revealed that the energy consumption was reduced by 2686 kWh with the use of the nanoparticles in solar collectors.

Farajzadeh et al. [19] conducted experimental and numerical studies on the effect of Al_2O_3 on the thermal efficiency of flat-plate solar collectors. First, they determined the maximum efficiency and thermal loss of collectors with water following the American Society of Heating, Refrigerating, and Air-Conditioning Engineers methodology. The maximum efficiency of the solar still with water was 0.9, while the thermal loss was 21.2. This was followed by another experiment in which the solar still was filled with Al_2O_3 along with water. The maximum efficiency of the solar still with this mixture was 0.9, while the thermal loss was reduced to 13.74. These findings showed that Al_2O_3 did not substantially improve the maximum efficiency of a solar still but can be beneficial in reducing thermal loss. However, the authors failed to explain the reasons for the decrease in the heat loss when Al_2O_3 nanoparticles were introduced.

Faridani and Ameri [20] analysed the possibility of using Al_2O_3 nanoparticles to enhance the performance of basin solar stills. They used γ-Al_2O_3 nanoparticles to effectively produce pure water in the presence of a mixer. Three analyses—Fourier-transform infrared spectroscopy, X-ray diffraction, and scanning electron microscopy—were used to verify the nanoparticles. The quantity of γ-Al_2O_3 nanoparticles, initial depth of water, intensity of solar energy, and temperatures of the glass, bottom, and brine were analysed. The results showed a distillate yield of approximately 60.03% with a 0.3 mass% of γ-Al_2O_3. The tests with nanoparticles also showed an increase in the glass, bottom, and brine temperatures. Overall, the application of γ-Al_2O_3 nanoparticles improved the performance of the still because of the better thermal characteristics of saline water.

Negm et al. [21] investigated the effect of Al_2O_3 on the efficiency of a thermosyphon flat-plate solar collector and found that the efficiency of solar collectors could be increased using nanofluids such as Al_2O_3 as the working fluid. They observed an increase in the efficiency when using nanofluids as the working fluid compared with that of designs that used distilled water alone. Al_2O_3–water nanofluids have been found to be suitable for improving the efficiency of solar collectors.

Shoeibi et al. [22] studied the effects of nano-enhanced PCM on the performance of solar stills. The Al_2O_3 nanoparticles used in the study were at concentrations of 0.3 wt%. Al_2O_3 was mixed in paraffin wax to enhance the thermal properties of PCM. The study indicated a 49.5% increase in the productivity of solar stills when Al_2O_3 nanoparticles were used at 0.3 wt% concentration. Moreover, the Al_2O_3 nanoparticles could reduce the melting point by 1.8 °C at a concentration of 0.1 wt%. The nano-coating also increased the rate of water production of the solar still by approximately 5.7%. Overall, the study showed an improved performance of the solar still with the addition of Al_2O_3 nanoparticles.

Chaichan and Kazem [23] investigated the productivity improvement of a single-slope solar distillator using a PCM and Al_2O_3 nanoparticles. They added nano-Al_2O_3 to the wax of one of the distillates used in the study to enhance the thermal conductivity of paraffin wax. The addition of Al_2O_3 to paraffin wax resulted in a substantial increase in the rate of heat transfer and enhanced the distillate yield to approximately 60.53% compared with that of the simple distiller yield recorded after sunset. Muraleedharan et al. [24] reported the design and construction of a modified active-solar-distillation system (MSDS) and compared its performance parameters with those of a conventional solar still. The heat-transfer fluid was an Al_2O_3 Therminol-55 nanofluid (nHTF), and different parameters—including the temperature of the saline water, hourly yield, and total yield—were compared. The experiment showed that the hourly yield of the MSDS with an nHTF of 0.1% was 45–250.27% more than that of the conventional solar still. The total yield of the MSDS with 0.1% nHTF was much higher at 12.190 $L/m^2/day$ compared with the 3.48 $L/m^2/day$ reported for the conventional solar still. Daily efficiency of the MSDS varied depending on the concentration of the nanofluid, but the maximum efficiency was 53.33% for an nHTF concentration of 0.1%. Thus, an MSDS system using a nanofluid showed higher productivity and better cost-effectiveness than those of a conventional solar still using only water.

Rashidi et al. [25] numerically tested the significance of a nanofluid used in stepped solar stills. The glass cover and bottom surface had constant temperatures of 30 °C and 40 °C, respectively. An unstable Al_2O_3–water nanofluid flow was used in the simulation. The nanoparticles were then added to the base fluid. Employing higher concentrations of the nanofluid led to higher rates of evaporation and condensation and quantities of water generated by the device. The results showed an increase in hourly productivity because of increasing the solid volume fraction of nanoparticles. Elevating the percentage concentration of Al_2O_3 from 0% to 5% resulted in a 22% increase in the hourly productivity.

Choudhary and Subudhi [26] reported turbulent natural convection in an enclosure full of a water-based Al_2O_3 nanofluid. The nanoparticles were spherical and had a mean diameter of 40 nm, and they were mixed with distilled water to prepare the nanofluid at a concentration of 0.01 and 0.1 vol%. The resulting nanofluids remained stable for >24 h. There was an increase in Ra, suggesting an increase in heat transfer because of the use of nanomaterials in the enclosure. Bellila et al. [27] used an Al_2O_3 nanofluid to enhance the productivity of a hemispherical solar still. The improvement in the yield of the solar distiller ranged from 105.8% to 121% across different volume concentrations of the nanoparticles. Tuly et al. [28] evaluated the use of Al_2O_3 in a modified DSSS and found a 21.5% increase in the augmented productivity.

The effects of Al_2O_3 on the performance of solar-still desalination systems is summarised in Table 2.

Table 2. Summary of the effects of Al_2O_3 on the performance of a solar-still desalination system.

Author	Type of Study	Type of Nanofluids	Type of Solar Device	Concentration (%)	Results
Sahota and Tiwari [15]	Experimental	Al_2O_3	Passive double slope solar still (DSSS)	0.04, 0.08, and 0.12	At 0.12% concentration, the yield was enhanced by 12.2% and 8.4% for 35 kg and 80 kg base fluids, respectively.
Zhang et al. [18]	Experimental	Al_2O_3	Solar collectors	-	Energy consumption reduced by 44% and 48% on hot and cold days, respectively.
Farajzadeh et al. [19]	Experimental	Al_2O_3	Flat plate solar collector	-	No major reduction in maximum efficiency. Use of nanoparticles reduced thermal loss from 21.2 to 13.74.
Faridani and Ameri [20]	Experimental	γ-Al_2O_3	Basin solar still	0.3	Distillate yield of about 60.03%.
Negm et al. [21]	Experimental	Al_2O_3	Thermosyphon flat-plate solar collector	-	Increase in efficiency when using nanofluid.
Shoeibi et al. [22]	Experimental	Al_2O_3	Conventional solar still	0.3	49.5% increase in the productivity. Melting point reduced by 1.8 °C at a concentration of 0.1 wt%. Rate of water production increased by 5.7%.
Chaichan and Kazem [23]	Experimental	Al_2O_3	Single-slope solar distillatory	-	Yield of distillate enhanced to 60.53%
Muraleedharan et al. [24]	Experimental	Al_2O_3	Modified active-solar-distillation system (MSDS)	0.1	Hourly yield ranged between 45 and 250.27%. Total yield much higher at 12.190 $L/m^2/day$.
Rashidi et al. [25]	Experimental	Al_2O_3	Stepped solar still	0–5	22% increase in the hourly productivity.
Choudhary and Subudhi [26]	Numerical	Al_2O_3		0.01 and 0.1	Increase in Ra, suggesting an increase in heat transfer.
Bellila et al. [27]	Experimental	Al_2O_3	Hemispherical solar still	0.1, 0.2, and 0.3	Yield improved between 105.8% and 121%.
Tuly et al. [28]	Experimental	Al_2O_3	Modified DSSS	3	21.5% increase in augmented productivity.

5.2. Effects of CuO Nanofluid on Solar-Still Performance

CuO nanoparticles have been increasingly used at different concentrations to increase the thermal conductivity of the fluid, increase the water temperature, and reduce particle precipitation at the bottom of the solar still. Dawood et al. [29] investigated approaches to increasing the productivity of freshwater in a solar-still system incorporating CuO nanofluids. A wet-chemistry approach was used to synthesise CuO nanoparticles. During the preparation process, Cu $(NO_3)_2$, NaOH, and acetic acid were used to obtain a fine CuO nanopowder. At 1.5% nanofluid volume concentration, the daily efficiency increased by 54%, 43%, and 36%, compared with that of the conventional solar still at water depths of 10, 20, and 30 mm, respectively.

Arunkumar et al. [30] studied the effect of nano-coated CuO absorbers with polyvinyl alcohol (PVA) sponges within a single-slope solar-still (SSSS) desalination system. Four configurations were used in the experiment, two of which featured an SSSS with CuO-nano-coated absorber plates (NCAPs) and an SSSS with CuO-NCAPs with PVA sponges. The efficiency and productivity of the SSSS with CuO-NCAPs were 53% and 2995 mL/m^2/day, respectively, while those of the SSSS with CuO-NCAPs with PVA sponges were 41% and 2318 mL/m^2/day, respectively. Thus, the addition of CuO-NCAPs substantially enhanced the productivity of the solar-still system. In a different study, Arunkumar et al. [31] investigated the use of sensible thermal-storage materials in solar-still systems. CuO-NCAPs were assessed within the solar still. The productivity of the SSSS with CuO-NCAPs was 2.9 L/m^2/day, while the cost of the water distilled was USD 0.0077/L. Sharma et al. [32] evaluated the effect of copper fins on the freshwater production within a pyramid solar still. The experiment featured two sets of absorber plates—one with copper fins. The study showed that the incorporation of copper tubes which functioned as fins on a black absorber plate resulted in an increase in daily freshwater production, with a maximum value of 1.95 L/m^2. The distilled water output for the absorber plate with copper tubes was approximately 60% higher than that for the smooth absorber plate. In another study, Sharma et al. [33] investigated the performance analysis of an active solar still in the colder Indian Himalayan region and used CuO-NCAPs in one of the experiments. The productivity of the system with pebbles was 2.80 L/m^2/day, while a CuO-NCAP-augmented solar still showed a higher rate of productivity of 2.90 L/m^2/day. The minimum productivity levels recorded from the system with the pebbles and from the CuO-NCAP-augmented solar still were 2.60 L/m^2/day and 1.90 L/m^2/day, respectively. Hence, the productivity with NCAPs was much higher, and the minimum productivity was much lower.

Rufuss et al. [34] studied the effects of nano-enhanced PCMs in a solar-still system. CuO was among the nanoparticles used to enhance the PCM properties at 0.3 wt% in paraffin to form paraffin–CuO (SSNPCM-2). The findings showed an increase in the thermal conductivity and a decrease in the melting and solidification temperatures with nano-enhanced PCM similar to that of the PCM. The yield of paraffin–CuO was 5.28 L/m^2/day, corresponding to a 35% increase in productivity. An economic analysis also revealed that the cost per litre of water for paraffin–CuO was USD 0.026. With the noted advantages in productivity, the authors recommended SSNPCM-2 as the best solar still compared with those using other nanoparticles, as it provides clean water at almost half the cost of bottled water. Thakur et al. [35] conducted a performance analysis of passive solar stills with and without nanoparticles. They included CuO among other nanoparticles in basin water and compared the performance of solar stills. Observations showed that the solar still with CuO nanofluids achieved 41.60% higher productivity than that of the solar still without nanofluids. CuO also showed a higher thermal conductivity than that of ZnO. The solar still with CuO also generated 2025 mL/day of distilled water, compared with the solar still without nanoparticles, which generated 1430 mL/day. Therefore, the productivity of the solar stills with CuO was found to be much higher.

Abdullah et al. [36] studied the use of reflectors along with nano-enhanced PCM to improve the performance of solar stills. The authors attempted to assess the role of coating solar-still surfaces with black paint and CuO nanoparticles. The nanoparticles were hypothesised to enhance the heat-transfer characteristics between the water and the basin surface. Paraffin wax mixed with CuO nanoparticles was used as a PCM. The results showed an improvement in the freshwater yield by 108% when using the PCM with CuO nanoparticles compared with that of the reference. While conventional solar stills produced 2400 mL/m^2/day, those coated with CuO produced approximately 5000 mL/m^2/day. The thermal efficiency of the PCM-coated materials was 51.5%. Attia et al. [37] experimentally assessed the methods to improve the yield of hemispherical distillers using CuO nanoparticles. The nanoparticles were used at concentrations of 0.1%, 0.2%, and 0.3%. The results showed that CuO nanoparticles at 0.3% concentration improved the freshwater productivity to 7.9 L/m^2/day compared with 3.85 L/m^2/day for the normal distiller, suggesting a 105.2% improvement. Essa et al. [38] attempted to improve the thermal performance of stepped solar stills. Among the assessed methods, they applied CuO–paraffin wax on the step liner of the basin and found that the application enhanced the freshwater productivity of the distiller by 127%. The freshwater productivity of the modified stepped solar still was substantially higher at 7000 mL/m^2/day compared with that of 2600 mL/m^2/day for the conventional still.

Behura and Gupta [39] assessed the effect of PCMs embedded in nanoparticles on solar-still productivity. Paraffin wax was embedded with CuO nanoparticles at 0.1%, 0.2%, and 0.3%, and the productivity was found to be 440 mL/0.25 m^2/day, 455 mL/0.25 m^2/day, and 510 mL/0.25 m^2/day, respectively. Selimefendigil et al. [40] experimentally tested the use of CuO nanoparticles in an SSSS. The results showed that including CuO nanoparticles enhanced the productivity by 26.77% compared with that of conventional solar stills. The energy of the system was enhanced from 15.96% to 19.90%, and the energy efficiency increased from 1.25% to 2.01% when the MSS was used. Sharshir et al. [41] analysed the energy and exergy of solar stills with nanoparticles and found that the exergy of evaporation, energy efficiency, and exergy efficiency of the MSSs were substantially higher than those of traditional solar stills. For CuO, the diurnal productivity of MSSs increased by 32.35%. Gupta et al. [42] studied the performance of a passive MSS with nanoparticles of 0.12 wt% at water depths of 5 cm and 10 cm. The MSS with CuO nanoparticles produced 3445 mL/m^2/day and 3058 mL/m^2/day at water depths of 5 and 10 cm, respectively, while the conventional solar still in that study produced 2814 mL/m^2/day and 2351 mL/m^2/day for the two water depths, respectively.

Abdullah et al. [43] used a corrugated absorber with wick and nano-enhanced PCM to augment the performance of a tray solar still. The results revealed that the total freshwater yield of the corrugated-tray solar still increased by 122% when a PCM with CuO nanoparticles was used compared with that of the conventional solar still. The water-production rate improved by 180%. Abdelgaied et al. [44] compared the thermo-economic performance of a hemispherical MSS to that of a traditional hemispherical solar still (THSS). Paraffin wax was used as the PCM, and CuO nanoparticles were used. Based on these findings, the use of CuO–water nanofluid enhanced the productivity by 60.41% compared with that of the THSS. The daily energy efficiency of the system was 56.46% with CuO and 63.61% with paraffin wax and CuO. The use of both paraffin wax and CuO was found to be more effective, and producing fresh water was cheaper by 75% compared with traditional solar stills. Abdelgaied and Kabeel [45] used a novel combination of absorber surfaces coated with CuO. This combination facilitated a higher level of performance, with the cumulative yield improving to 9885–10,015 mL/m^2/day, suggesting a 140.1–142% improvement in the performance of the traditional system. The daily thermal and exergy efficiencies also improved by values ranging between 138.1% and 140.1%, and between 243.6% and 252.9%, respectively. Sharshir et al. [46] used evacuated tubes coated with nanofluids to evaluate the performance of pyramid solar stills. The augmentation with CuO improved freshwater production by approximately 27.85%. Nazari et al. [47] tested an SSSS using 0.08% CuO nanofluid—which improved the productivity, energy efficiency, and exergy efficiency by 81%, 80.6%, and 112.5%, respectively. Elsheikh et al. [48] used a copper corrugated absorber plate on a stepped solar still and found that the yield increased by 128% compared with that of the traditional solar stills. Elaziz et al. [49] found a 100% increase in yield using Cu_2O as the nanoparticle compared with that of the conventional solar stills. The effects of the CuO nanofluid on the productivity of the solar stills is shown in Table 3.

Table 3. Effects of CuO on the productivity of solar stills.

Author	Type of Study	Type of Nanofluids	Type of Solar Device	Concentration (%)	Results
Dawood et al. [29]	Experimental	CuO	Solar-still system	1.5	Daily efficiency increased by 54%, 43%, and 36% compared with that of the conventional solar still at 10, 20, and 30 mm water depths.
Arunkumar et al. [30]	Experimental	CuO	Single-slope solar still		Efficiency enhanced to 53% and productivity to 2995 mL/m^2/day.
Arunkumar et al. [31]	Numerical	CuO	Solar-still system		Productivity was 2.9 L/m^2/day.
Sharma et al. [32]	Experimental	Copper fins	Pyramid solar still	-	Increase in freshwater production with a maximum value of 1.95 L/m^2/day. Distilled water output was 60% higher.
Sharma et al. [33]	Numerical	CuO	Active solar still	-	Higher rate of productivity of 2.90 L/m^2/day.
Rufuss et al. [34]	Experimental	CuO	Solar-still system	0.3	Daily yield increased by 35%.
Thakur et al. [35]	Experimental	CuO	Passive solar still	-	41.6% higher productivity.
Abdullah et al. [36]	Experimental	CuO	Solar-still system	-	108% increase in freshwater yield.
Attia et al. [37]	Experimental	CuO	Hemispherical distiller	0.1–0.3	105.2% improvement in freshwater production.
Essa et al. [38]	Experimental	CuO	Stepped solar still	-	Enhanced freshwater production by 127%.
Behura and Gupta [39]	Experimental	CuO	Solar-still system	0.1–0.3	Productivity at 0.3% concentration was higher at 510 mL/0.25 m^2/day.
Selimefendigil et al. [40]	Experimental	CuO	Single-slope solar still	-	26.77% increase in productivity. Energy increased from 15.96% to 19.90%; energy efficiency increased from 1.25% to 2.01%.
Sharshir et al. [41]	Experimental	CuO	Modified solar-still system	-	Diurnal productivity increased by 32.35%.
Gupta et al. [42]	Experimental	CuO	Modified passive solar still	0.12	Productivity at 5 cm and 10 cm water depth was higher at 3445 mL/m^2/day and 3058 mL/m^2/day, respectively.
Abdullah et al. [43]	Experimental	CuO	Trays solar still	-	Total freshwater yield improved by 122%. Water production rate improved by 180%.
Abdelgaied et al. [44]	Experimental	CuO	Modified hemispherical solar still	-	Productivity enhanced by 60.41%.

Table 3. *Cont.*

Author	Type of Study	Type of Nanofluids	Type of Solar Device	Concentration (%)	Results
Abdelgaied and Kabeel [45]	Experimental	CuO		-	Cumulative yield improved between 140.1 and 142%.
Sharshir et al. [46]	Experimental	CuO	Pyramid solar still	-	Freshwater production improved by 27.85%.
Nazari et al. [47]	Experimental	CuO	Single-slope solar still	0.08	Productivity, energy, and exergy efficiency improved by 81%, 80.6%, and 112.5%, respectively.
Elsheikh et al. [48]	Experimental	CuO	Stepped solar still	-	Yield increased by 128%.
Elaziz et al. [49]	Experimental	Cu_2O	Active solar stills	-	100% increase in yield.

5.3. Effects of TiO_2 on Solar-Still Productivity

Parikh et al. [50] evaluated the use of TiO_2 nanoparticles to enhance the productivity of a solar-still system. TiO_2 was used alongside a black dye as the base paint at 20% and 40 wt%. The results showed higher water-depth productivity of the solar still. Compared with that of the conventional solar still, there was an 11–18% and a 20–23% increase in productivity based on a 20% and a 40% mixture, respectively. Ibrahim et al. [51] used TiO_2 nanoparticles to test the thermal performance of a wick-type solar still. Two types of solar stills were used: one with a pure PCM and the other with a PCM coated with TiO_2 nanoparticles. The inclusion of nanoparticles enhanced the thermal conductivity of the PCM by 9.6%. Parsa et al. [52] tested this effect using a 0.1 wt% TiO_2 in a DSSS using a combination of thermodynamic and environmental analyses. The findings revealed a thermal efficiency of 20.7% compared with that of the conventional system. Essa et al. [53] also tested this effect using a convex tubular solar still reliant on the nanocomposites. The use of jute cloth increased the daily distillate by 114% with nanocomposites. The highest productivity using jute cloth with nanocomposites was reported to be an output of 9000 $mL/m^2/day$ against 4200 $mL/m^2/day$ for tubular solar stills. The enhanced design enhanced the performance of solar stills.

Rufuss et al. [54] conducted a numerical study on a solar desalination system using TiO_2. TiO_2 particles were added to paraffin and tested for different thermophysical properties—including thermal conductivity. The use of nanoparticles improved the cumulative yield to 6.6 $L/m^2/day$. Therefore, paraffin enhanced with TiO_2 yielded better productivity compared with that of the unenhanced paraffin. Sahota and Tiwari [55] investigated the effect of TiO_2 particles on the performance of a passive DSSS and observed a higher thermal-energy efficiency of 46.10% compared with that of 37.78% for the base fluid. The thermal exergy was also higher for nanofluids—such as TiO_2 (12.38%)—than that for the base fluid (4.92%). Samneang et al. [56] assessed the TiO_2 concentration in a solar-still system. TiO_2 was used in assorted sizes, e.g., 20 nm, 150 nm, and 400 nm. The results showed a highest temperature of 69.69 °C recorded for TiO_2 of 400 nm specimens; the temperature was 15.97% higher than that for the bare plate. Zabour et al. [57] attempted to improve the performance of an SSSS using various metal-oxide nanofluids—including TiO_2 and water. The productivity of the solar-still nanoparticles TiO_2 was 7.1 $kg/m^2/day$.

Kabeel et al. [58] used a novel absorber plate in a solar still and coated it with TiO_2 nano black paint to improve the performance of solar stills. TiO_2 nanoparticles enhanced the water temperature by 1.5 °C compared with that of the absorber plate without the nanoparticle coating. The coating also enhanced the yield during sunshine hours. Overall, there was a 12% improvement in the yield at the maximum water depth when the absorber plate coated with TiO_2 was used. Gandhi et al. [59] developed and assessed the efficiency of a stepped-basin solar still with TiO_2 as a nanomaterial. There was a 49.21% increase in efficiency with 20% and 30% coatings of the nanomaterial. The efficiency of the coated system was substantially higher than that of a solar-still system without nanoparticle coating. Shanmugan et al. [60] experimented with a single-basin SSSS and found that TiO_2 nanoparticles resulted in an average daily efficiency of 57.16% and 36.69% during summer and winter, respectively.

Table 4 provides a summary of the effects of TiO_2 on the performance of distinct solar-still systems, as discussed above.

Table 4. Summary of the effects of TiO_2 on the performance of several types of solar-still systems.

Author	Type of Study	Type of Nanofluids	Type of Solar Device	Concentration (%)	Results
Parikh et al. [50]	Experimental	TiO_2	Solar-still system	20 and 40	At 20% and 40% concentrations, the productivity increased by 11–18% and 20–23%, respectively.
Ibrahim et al. [51]	Experimental	TiO_2	Wick-type solar still	-	Thermal conductivity improved by 9.6%.
Parsa et al. [52]	Experimental	TiO_2	Double-slope solar still	0.1	Thermal efficiency improved by 20.7% compared to conventional system.
Essa et al. [53]	Experimental	TiO_2	Convex tubular solar still	-	Daily distillate enhanced by 114%.
Rufuss et al. [54]	Experimental	TiO_2	Solar desalination system	-	Cumulative yield improved to 6.6 $L/m^2/day$.
Sahota and Tiwari [55]	Experimental	TiO_2	Passive double-slope solar still	-	Higher thermal energy efficiency of 46.10% compared with that of 37.78% for the base fluid.
Samneang et al. [56]	Experimental	TiO_2	Solar-still system	-	400 nm TiO_2 generated the highest temperature of 69.69 °C.
Zabour et al. [57]	Experimental	TiO_2	Single-slope solar still	-	Productivity was higher at 7.1 $kg/m^2/day$.
Kabeel et al. [58]	Experimental	TiO_2	Solar-still system	-	Enhanced water temperature by 1.5 °C. Overall, 12% increase in yield at maximum water depth.
Gandhi et al. [59]	Experimental	TiO_2	Stepped-basin solar still	20 and 30	49.21% increase in efficiency.
Shanmugan et al. [60]	Experimental	TiO_2	Single-slope-basin solar still	-	Average daily efficiency was higher at 57.16% during summer and 36.69% during winter.

5.4. Effects of Other Nanomaterials on Solar-Still Productivity

ZnO is prominent among the nanomaterials proposed to increase solar-still productivity. Kumar et al. [61] studied a solar-still system incorporating a nano disbanded PCM. ZnO nanoparticles were used on the crude wax. The results indicated that the addition of ZnO enhanced the output of clean water by 65.17%. Saleh et al. [62] used ZnO nanoparticles to enhance the distillation capacity of a solar-still system. The use of these nanoparticles increased the productivity and efficiency of the solar still by 30% and 38%, respectively, compared with that of the system without nanomaterials. Attia et al. [63] experimented with a hemispherical solar still using a series of nanomaterials including zinc trays. The modification resulted in a major increase in the rate of evaporation of the saltwater owing to better heat-transfer characteristics. The cumulative yield resulting from the use of zinc trays was 6.3 kg/m^2/day. The use of Zn also caused a 31.25% increase in productivity compared with that of the conventional solar stills. Panchal and Sadasivuni [64] conducted an experiment on a modified solar still using ZnO nanoparticles and reported a 52.5% overall efficiency.

SiO_2 is another material that has been extensively considered by researchers. Arani et al. [65] used SiO_2 nanoparticles on an absorber plate of a tubular solar still and showed that the basin and water temperatures increased by 10.49% and 10.88%, respectively, when using SiO_2 nanoparticles at 20% concentration along with black paint. Water production was enhanced by 55.18%. Sathyamurthy et al. [66] used fumed-silica nanoparticles to boost the yield of stepped solar stills. The fumed silicon oxide concentration ranged from 10% to 40%. The total yield improved by 27.2%, 34.2%, 18.3%, and 18.4% at 10%, 20%, 30%, and 40% concentrations, respectively. Kumar et al. [67] also used silica nanoparticles along with paraffin and noted a 67.07% increase in freshwater production. Thakur et al. [68] used a nanosilicon-coated cover to augment the performance of a solar desalination unit. Augmenting the system with a silicon coating increased the water yield by 15.6% compared with that of the conventional solar stills.

Sharshir et al. [69] used carbon black nanoparticles to enhance the thermal performances of a solar-still system in an economical and environmental-friendly approach. The accumulated yield in the system improved by 59.33%, while the average energy efficiency and exergy efficiency improved by 75.12% and 142.7%, respectively. In another study, Sharshir et al. [70] used carbon black nanoparticles on a stepped DSSS. The addition of nanoparticles increased freshwater productivity by 80.57% and energy efficiency by 110.5% compared with those of the traditional solar stills.

Rasachak et al. [71] evaluated the capability of SnO_2 in enhancing solar-still productivity. SnO_2 concentrations of 15 wt% resulted in the highest surface temperature of 101.61 °C—which was 53.67% higher than that of the conventional solar still. Kabeel et al. [72] added graphite nanoparticles to paraffin wax in a solar-still system. The distillate production of the system ranged between 7.123 and 8.52 L/m^2/day across different concentrations. The percentage improvement in the water production ranged between 62.62% and 94.52% across different graphite-nanoparticle mass concentrations. Alqsair et al. [73] used a PCM–Ag mixture to experimentally test a solar desalination system. The nanoparticles improved the production of the system by approximately 320%, with an efficiency of 72%. Gupta et al. [74] tested the effectiveness of Cu_2O on an MSS and noted an efficiency of 34% compared with that of 22% recorded for the conventional still. Lawrence et al. [75] used NiO on a wick-type SSSS and reported an increased yield of 5.8 L/m^2/day.

Table 5 provides a summary of the reviewed studies on different nanofluids and their effects on the performance of solar stills.

Table 5. Summary of the effects of other nanomaterials on solar-still productivity.

Author	Type of Study	Type of Nanofluids	Type of Solar Device	Concentration (%)	Results
Kumar et al. [61]	Experimental	ZnO	Solar-still system	-	Output of clean water enhanced by 65.17%.
Saleh et al. [62]	Experimental	ZnO	Solar-still system	-	Productivity and efficiency increased by 30% and 38%, respectively.
Attia et al. [63]	Experimental	Zinc trays	Hemispherical solar still		31.25% increase in productivity.
Panchal and Sadasivuni [64]	Experimental	ZnO	Modified solar still		52.5% increase in overall efficiency.

Table 5. *Cont.*

Author	Type of Study	Type of Nanofluids	Type of Solar Device	Concentration (%)	Results
Arani et al. [65]	Experimental	SiO_2	Tubular solar still	20	Basin and water temperatures increased by 10.49% and 10.88%, respectively. Water production enhanced by 55.18%.
Sathyamurthy et al. [66]	Experimental	Fumed silica	Stepped solar still	10–40	Total yield improved by 27.2%, 34.2%, 18.3%, and 18.4% for 10%, 20%, 30%, and 40% concentrations, respectively.
Kumar et al. [67]	Experimental	Silica	Solar-still system	-	67.07% increase in freshwater production.
Thakur et al. [68]	Experimental	SiO_2	Solar desalination unit	-	Water yield increased by 15.6%.
Sharshir et al. [69]	Experimental	Carbon	Solar-still system	-	Accumulated yield in the system improved by 59.33%. Average energy efficiency and the exergy efficiency improved by 75.12% and 142.7%, respectively.
Sharshir et al. [70]	Experimental	Carbon	Stepped DSSS	-	Freshwater productivity and energy efficiency increased by 80.57% and 110.5%, respectively.
Rasachak et al. [71]	Experimental	SnO_2	Solar-still system	15	Surface temperature was 53.67% higher than that of conventional system.
Kabeel et al. [72]	Analytical	Graphite	Solar-still system	-	The percentage improvement in water production ranged between 62.62% and 94.52%.
Alqsair et al. [73]	Experimental	Ag	Solar desalination system	-	Production and efficiency improved by 320% and 72%, respectively.
Gupta et al. [74]	Experimental	Cu_2O	Modified solar still	-	Efficiency was higher at 34% compared with that of 22% for the conventional still.
Lawrence et al. [75]	Experimental	NiO	Single-slope wick-type solar still	-	Increase in the yield of 5.8 $L/m^2/day$.

6. Economic and Environmental Analysis

Two types of analysis were conducted for solar-still systems using non-metallic nanofluids—economic and environmental analysis. From an economic perspective, the initial setup costs for the solar stills using nanofluids would entail the procurement of materials, such as solar collectors, the still structure, and the components required to prepare and circulate the nanofluid. Other factors that contribute to economic costs include the cost of acquiring high-quality non-metallic nanoparticles as well as the development of nanofluid-synthesis processes that are efficient. Maintenance expenses are also likely to be crucial in the economic analysis of these solar stills. Regular costs of maintenance might arise from cleaning the glass cover, replacing the components, and ensuring that they are functioning properly. Operational costs are also likely to arise due to the energy used to pump and circulate the nanofluid, and any other additional energy requirements needed for the system to operate.

Concerning the environmental impact, energy consumption is a major factor that would need to be considered. Since solar stills are powered using renewable solar energy, they have lower greenhouse-gas emissions in comparison to conventional desalination methods that are highly dependent on fossil fuels. Despite this benefit, the energy needed to facilitate nanofluid circulation and the operation of the system needs to be evaluated to guarantee minimal environmental impacts. Water usage is another major environmental factor to consider. Solar stills can be useful in areas with limited freshwater resources since they rely on saltwater or brackish water sources. However, it is necessary to analyse the water-usage efficiency of the system and the losses resulting from evaporation, leakage, and other related factors.

7. Conclusions

This review identified some of the non-metallic nanofluids used to augment the performance of different types of solar stills. The main findings were as follows:

- The review concluded that the addition of various nanoparticles—such as Al_2O_3, CuO, ZnO, TiO_2, SiO_2, and Ag—in the base fluid in a traditional solar still or MSS resulted in a significant yield increase.
- The efficiency and output of the solar still were clearly improved after modifying the experimental setup. Thus, the inclusion of nanomaterials while considering other design parameters can enhance the effectiveness and output of a solar still.
- A review of different studies adding Al_2O_3 in a solar-still desalination system resulted in an increase in distillate yield, better efficiency, reduced energy consumption, reduced thermal loss, and better productivity.
- The incorporation of CuO in a solar-still desalination system led to major improvements in performance. These included enhanced daily efficiency, better productivity, improved production of freshwater, and higher energy and exergy efficiency.
- The incorporation of TiO_2 in a solar-still desalination system resulted in increased productivity, better thermal conductivity, better thermal efficiency, higher daily distillate output, and high levels of water temperature.
- It was also evident that the incorporation of ZnO in a solar-still desalination system resulted in a substantial increase in the output of clean water and occasioned improvements in productivity and overall efficiency.
- Together, these findings demonstrated the potential of these nanomaterials to significantly enhance the performance of solar-still desalination systems.

The inclusion of nanofluids in solar stills presented some limitations and challenges. The studies acknowledged these limitations and addressed them to different extents. A key challenge was nanoparticle agglomeration, or the settling of nanoparticles in the nanofluid. This had the potential to affect the stability and the functioning of the solar still. The reviewed studies dealt with this issue using techniques such as ultrasonication, adding surfactants to increase the dispersion and stability of nanoparticles in the base fluid, and magnetic stirring. Another major challenge was clogging and fouling of the solar-still system. Most of the studies dealt with this by implementing filtration or pre-treatment methods to eradicate larger particles before introducing the nanofluid into the system.

The findings of this review study have major implications and potential applications in different fields. The study provides useful insights for the design and optimisation of solar-still systems. This enables better production of freshwater in arid and remote areas where there is limited access to clean water. The better performance achieved by using non-metallic nanofluids provides practical solutions for decentralised desalination and water purification. This not only benefits communities but also industries and agriculture in regions experiencing water challenges.

There are various avenues for future research. Studies could examine the long-term durability and stability of non-metallic nanofluids in solar-still applications. An understanding of their possible interactions with system components is necessary for ensuring strong performance over long operational periods. Furthermore, additional studies could focus on optimising nanofluid formulations. Optimisation could be achieved by considering factors like concentration of the nanoparticle, size, and modification of the surface. Moreover, future research could explore the integration of advanced technologies, such as phase-change materials or solar concentrators, when using non-metallic nanofluid-based solar stills.

Author Contributions: Conceptualisation, A.A.; investigation, Y.A.; resources, Y.A.; supervision, A.A.; validation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, A.A. and Y.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, A.A., upon request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. UNICEF. Billions of People will Lack Access to Safe Water, Sanitation and Hygiene in 2030 unless Progress Quadruples—Warn WHO, UNICEF. 2021. Available online: https://www.unicef.org/press-releases/billions-people-will-lack-access-safe-water-sanitation-and-hygiene-2030-unless (accessed on 16 November 2022).
2. Koigi, B. Is Desalination the Answer to Global Water Shortage? *Fairplanet*. 2022. Available online: https://www.fairplanet.org/story/is-desalination-the-answer-to-global-water-shortage/ (accessed on 17 November 2022).
3. Curto, D.; Franzitta, V.; Guercio, A. A review of the water desalination technologies. *Appl. Sci.* **2021**, *11*, 670. [CrossRef]
4. Habibullah, A. Sustainable Strategies for Urban Water Management for Arid Region: The Case Study of Jeddah City Saudi Arabia. Master's Thesis, University of Illinois, Urbana-Champaign, IL, USA, 2014. Available online: https://hdl.handle.net/2142/49442 (accessed on 17 November 2022).
5. Ayaz, M.; Namazi, M.; Din, M.A.U.; Ershath, M.M.; Mansour, A.; Aggoune, E.-H.M. Sustainable seawater desalination: Current status, environmental implications and future expectations. *Desalination* **2022**, *540*, 116022. [CrossRef]
6. Nair, M.; Kumar, D. Water desalination and challenges: The Middle East perspective: A review. *Desalin. Water Treat.* **2013**, *51*, 2030–2040. [CrossRef]
7. Alwan, N.T.; Shcheklein, S.E.; Ali, O.M. Evaluation of distilled water quality and production costs from a modified solar still integrated with an outdoor solar water heater. *Case Stud. Therm. Eng.* **2021**, *27*, 101216. [CrossRef]
8. Alwan, N.T.; Shcheklein, S.E.; Ali, O.M.; Majeed, M.H.; Agyekum, E.B. Experimental and theoretical investigations of a modified single-slope solar still with an external solar water heater. *Sustainability* **2021**, *13*, 12414. [CrossRef]
9. Arunkumar, T.; Vinothkumar, K.; Ahsan, A.; Jayaprakash, R.; Kumar, S. Experimental study on various solar still designs. *ISRN Renew. Energy* **2012**, *2012*, 569381. [CrossRef]
10. Kabeel, A.E.; Khairat Dawood, M.M.; Ramzy, K.; Nabil, T.; Elnaghi, B.; Elkassar, A. Enhancement of single solar still integrated with solar dishes: An experimental approach. *Energy Convers. Manag.* **2019**, *196*, 165–174. [CrossRef]
11. Gude, V.G.; Nirmalakhandan, N.; Deng, S.; Maganti, A. Feasibility study of a new two-stage low temperature desalination process. *Energy Convers. Manag.* **2012**, *56*, 192–198. [CrossRef]
12. Ghaffour, N.; Lattemann, S.; Missimer, T.; Ng, K.C.; Sinha, S.; Amy, G. Renewable energy-driven innovative energy-efficient desalination technologies. *Appl. Energy* **2014**, *136*, 1155–1165. [CrossRef]
13. Kapoor, V.; Dsilva Winfred Rufuss, D.; Arulvel, S.; Akinaga, T.; Davies, P. Nanoparticles-enhanced energy storage materials in solar thermal desalination. In *Energy Storage Multigeneration*; Academic Press: Cambridge, MA, USA, 2023; pp. 197–220. [CrossRef]
14. Kabeel, A.E.; Omara, Z.M.; Essa, F.A.; Abdullah, A.S.; Arunkumar, T.; Sathyamurthy, R. Augmentation of a solar still distillate yield via absorber plate coated with black nanoparticles. *Alex. Eng. J.* **2017**, *56*, 433–438. [CrossRef]
15. Sahota, L.; Tiwari, G.N. Effect of Al_2O_3 nanoparticles on the performance of passive double slope solar still. *Sol. Energy* **2016**, *130*, 260–272. [CrossRef]
16. Naveenkumar, R.; Gurumoorthy, G.; Kunjithapatham, G.; Anbu Chellappan, R.A.; Bharath, A.; Ravichandran, M. Impact of adding various nano materials in the efficiency of single slope solar still: A review. *Mater. Today Proc.* **2020**, *33*, 3942–3946. [CrossRef]

17. Balachandran, G.B.; David, P.W.; Mariappan, R.K.; Kabeel, A.E.; Athikesavan, M.M.; Sathyamurthy, R. Improvising the efficiency of single-sloped solar still using thermally conductive nano-ferric oxide. *Environ. Sci. Pollut. Res. Int.* **2020**, *27*, 32191–32204. [CrossRef] [PubMed]
18. Zhang, J.; Sajadi, S.M.; Chen, Y.; Tlili, I.; Fagiry, M.A. Effects of Al_2O_3 and TiO_2 nanoparticles in order to reduce the energy demand in the conventional buildings by integrating the solar collectors and phase change materials. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102114. [CrossRef]
19. Farajzadeh, E.; Movahed, S.; Hosseini, R. Experimental and numerical investigations on the effect of Al_2O_3/TiO_2H_2O nanofluids on thermal efficiency of the flat plate solar collector. *Renew. Energy* **2018**, *118*, 122–130. [CrossRef]
20. Hasanianpour Faridani, Z.; Ameri, A. Performance enhancement of a basin solar still using γ-Al2O3 nanoparticles and a mixer: An experimental approach. *J. Therm. Anal. Calorim.* **2022**, *147*, 1919–1931. [CrossRef]
21. Negm, M.N.A.; Abdel-Rehim, A.A.; Attia, A.A.A. Investigating the effect of Al_2O_3/water nanofluid on the efficiency of a thermosyphon flat-plate solar collector. In Proceedings of the ASME 2016 International Mechanical Engineering Congress and Exposition, Phoenix, AZ, USA, 11–17 November 2017. [CrossRef]
22. Shoeibi, S.; Kargarsharifabad, H.; Rahbar, N. Effects of nano-enhanced phase change material and nano-coated on the performance of solar stills. *J. Energy Storage* **2021**, *42*, 103061. [CrossRef]
23. Chaichan, M.T.; Kazem, H.A. Single slope solar distillator productivity improvement using phase change material and Al_2O_3 nanoparticle. *Sol. Energy* **2018**, *164*, 370–381. [CrossRef]
24. Muraleedharan, M.; Singh, H.; Udayakumar, M.; Suresh, S. Modified active solar distillation system employing directly absorbing Therminol 55–Al_2O_3 Nano heat transfer fluid and Fresnel lens concentrator. *Desalination* **2019**, *457*, 32–38. [CrossRef]
25. Rashidi, S.; Bovand, M.; Rahbar, N.; Esfahani, J.A. Steps optimization and productivity enhancement in a nanofluid cascade solar still. *Renew. Energy* **2018**, *118*, 536–545. [CrossRef]
26. Choudhary, R.; Subudhi, S. Aspect ratio dependence of turbulent natural convection in Al_2O_3/water nanofluids. *Appl. Therm. Eng.* **2016**, *108*, 1095–1104. [CrossRef]
27. Bellila, A.; Attia, M.E.H.; Kabeel, A.E.; Abdelgaied, M.; Harby, K.; Soli, J. Productivity enhancement of hemispherical solar still using Al_2O_3-water-based nanofluid and cooling the glass cover. *Appl. Nanosci.* **2021**, *11*, 1127–1139. [CrossRef]
28. Tuly, S.S.; Islam, M.S.; Hassan, R.; Das, B.K.; Sarker, M.R.I. Investigation of a modified double slope solar still integrated with nanoparticle-mixed phase change materials: Energy, exergy, exergo-economic, environmental, and sustainability analyses. *Case Stud. Therm. Eng.* **2022**, *37*, 102256. [CrossRef]
29. Khairat Dawood, M.M.; Shehata, A.I.; Kabeel, A.E.; Elharidi, A.M.; Abdelsalam Taha, A.; Bayoumi, S.; Abdalla, A.M. Increasing the freshwater productivity of a solar still loaded with CuO nanofluids using vibration motion and cover cooling techniques. *Int. J. Energy Res.* **2021**, *45*, 9099–9115. [CrossRef]
30. Arunkumar, T.; Murugesan, D.; Raj, K.; Denkenberger, D.; Viswanathan, C.; Rufuss, D.D.W.; Velraj, R. Effect of nano-coated CuO absorbers with PVA sponges in solar water desalting system. *Appl. Therm. Eng.* **2019**, *148*, 1416–1424. [CrossRef]
31. Arunkumar, T.; Wang, J.; Dsilva Winfred Rufuss, D.; Denkenberger, D.; Kabeel, A.E. Sensible desalting: Investigation of sensible thermal storage materials in solar stills. *J. Energy Storage* **2020**, *32*, 101824. [CrossRef]
32. Sharma, N.; Noushad, S.; Ram, G.S.; Reddy, K. Effect of copper fins on fresh water productivity of pyramid solar still. In *Recent Trends in Thermal Engineering*; Springer: Singapore, 2022; pp. 83–91. [CrossRef]
33. Sharma, S.; Sinha, S.; Raina, G.; Malik, P.; Katoch, S.S. Investigation and performance analysis of active solar still in colder Indian Himalayan region. *Groundwater Sustain. Dev.* **2022**, *19*, 100850. [CrossRef]
34. Dsilva Winfred Rufuss, D.; Suganthi, L.; Iniyan, S.; Davies, P.A. Effects of nanoparticle-enhanced phase change material (NPCM) on solar still productivity. *J. Clean. Prod.* **2018**, *192*, 9–29. [CrossRef]
35. Thakur, V.K.; Gaur, M.K.; Dhamneya, A.K.; Sagar, M.K. Performance analysis of passive solar still with and without nanoparticles. *Mater. Today Proc.* **2021**, *47*, 6309–6316. [CrossRef]
36. Abdullah, A.S.; Essa, F.A.; Bacha, H.B.; Omara, Z.M. Improving the trays solar still performance using reflectors and phase change material with nanoparticles. *J. Energy Storage* **2020**, *31*, 101744. [CrossRef]
37. Attia, M.E.H.; Kabeel, A.E.; Elaloui, E.; Abdelgaied, M.; Abdullah, A. Experimental study on improving the yield of hemispherical distillers using CuO nanoparticles and cooling the glass cover. *Sol. Energy Mater. Sol. Cells* **2022**, *235*, 111482. [CrossRef]
38. Essa, F.A.; Omara, Z.; Abdullah, A.; Shanmugan, S.; Panchal, H.; Kabeel, A.E.; Sathyamurthy, R.; Athikesavan, M.M.; Elsheikh, A.; Abdelgaied, M.; et al. Augmenting the productivity of stepped distiller by corrugated and curved liners, CuO/paraffin wax, wick, and vapor suctioning. *Environ. Sci. Pollut. Res. Int.* **2021**, *28*, 56955–56965. [CrossRef]
39. Behura, A.; Gupta, H.K. Use of nanoparticle-embedded phase change material in solar still for productivity enhancement. *Mater. Today Proc.* **2021**, *45*, 3904–3907. [CrossRef]
40. Selimefendigil, F.; Şirin, C.; Öztop, H.F. Experimental analysis of combined utilization of CuO nanoparticles in latent heat storage unit and absorber coating in a single-slope solar desalination system. *Sol. Energy* **2022**, *233*, 278–286. [CrossRef]
41. Sharshir, S.W.; Peng, G.; Elsheikh, A.H.; Edreis, E.M.A.; Eltawil, M.A.; Abdelhamid, T.; Kabeel, A.E.; Zang, J.; Yang, N. Energy and exergy analysis of solar stills with micro/Nano particles: A comparative study. *Energy Convers. Manag.* **2018**, *177*, 363–375. [CrossRef]
42. Gupta, B.; Shankar, P.; Sharma, R.; Baredar, P. Performance enhancement using Nano particles in modified passive solar still. *Procedia Technol.* **2016**, *25*, 1209–1216. [CrossRef]

43. Abdullah, A.S.; Omara, Z.M.; Essa, F.A.; Younes, M.M.; Shanmugan, S.; Abdelgaied, M.; Amro, M.I.; Kabeel, A.E.; Farouk, W.M. Improving the performance of trays solar still using wick corrugated absorber, nano-enhanced phase change material and photovoltaics-powered heaters. *J. Energy Storage* **2021**, *40*, 102782. [CrossRef]
44. Abdelgaied, M.; Attia, M.E.H.; Kabeel, A.E.; Zayed, M.E. Improving the thermo-economic performance of hemispherical solar distiller using copper oxide nanofluids and phase change materials: Experimental and theoretical investigation. *Sol. Energy Mater. Sol. Cells* **2022**, *238*, 111596. [CrossRef]
45. Abdelgaied, M.; Kabeel, A.E. Performance improvement of pyramid solar distillers using a novel combination of absorber surface coated with CuO Nano black paint, reflective mirrors, and PCM with pin fins. *Renew. Energy* **2021**, *180*, 494–501. [CrossRef]
46. Sharshir, S.W.; Kandeal, A.W.; Ismail, M.; Abdelaziz, G.B.; Kabeel, A.E.; Yang, N. Augmentation of a pyramid solar still performance using evacuated tubes and nanofluid: Experimental approach. *Appl. Therm. Eng.* **2019**, *160*, 113997. [CrossRef]
47. Nazari, S.; Safarzadeh, H.; Bahiraei, M. Performance improvement of a single slope solar still by employing thermoelectric cooling channel and copper oxide nanofluid: An experimental study. *J. Clean. Prod.* **2019**, *208*, 1041–1052. [CrossRef]
48. Elsheikh, A.H.; Katekar, V.P.; Muskens, O.L.; Deshmukh, S.S.; Elaziz, M.A.; Dabour, S.M. Utilization of LSTM neural network for water production forecasting of a stepped solar still with a corrugated absorber plate. *Process Saf. Environ. Prot.* **2021**, *148*, 273–282. [CrossRef]
49. Abd Elaziz, M.; Essa, F.A.; Elsheikh, A.H. Utilization of ensemble random vector functional link network for freshwater prediction of active solar stills with nanoparticles. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101405. [CrossRef]
50. Parikh, R.; Patdiwala, U.; Parikh, S.; Panchal, H.; Sadasivuni, K.K. Performance enhancement using TiO_2 Nano particles in solar still at variable water depth. *Int. J. Ambient Energy* **2022**, *43*, 4037–4044. [CrossRef]
51. Ibrahim, A.; El-Sebaii, A.; Aboul-Enein, S.; Hegazy, M.; Fleafl, A.; El-Monem Khallaf, A. Thermal performance enhancement of the wick-type solar still using titanium dioxide nanoparticles embedded in paraffin wax as a phase change material. *Environ. Sci. Pollut. Res. Int.* **2022**, 1–10. [CrossRef]
52. Parsa, S.M.; Yazdani, A.; Dhahad, H.; Alawee, W.H.; Hesabi, S.; Norozpour, F.; Javadi, Y.D.; Ali, H.M.; Afrand, M. Effect of Ag, Au, TiO2 metallic/metal oxide nanoparticles in double-slope solar stills via thermodynamic and environmental analysis. *J. Clean. Prod.* **2021**, *311*, 127689. [CrossRef]
53. Essa, F.A.; Alawee, W.H.; Mohammed, S.A.; Dhahad, H.A.; Abdullah, A.S.; Omara, Z.M. Experimental investigation of convex tubular solar still performance using wick and nanocomposites. *Case Stud. Therm. Eng.* **2021**, *27*, 101368. [CrossRef]
54. Dsilva Winfred Rufuss, D.; Arulvel, S.; Iniyan, S.; Suganthi, L. Numerical study of titanium oxide nanoparticle enhanced energy storage material in solar desalination. *Mater. Today Proc.* **2021**, *43*, 805–808. [CrossRef]
55. Sahota, L.; Tiwari, G.N. Effect of nanofluids on the performance of passive double slope solar still: A comparative study using characteristic curve. *Desalination* **2016**, *388*, 9–21. [CrossRef]
56. Samneang, H.; Kumar, L.; Zafar, A.; Ali, M.U.; Zahid, T.; Bibi, S.; Ahmad, M.S.; Ghafoor, U.; Selvaraj, J. A systematic indoor and outdoor study of the effect of particle size and concentration of TiO_2 in improving solar absorption for solar still application. *Front. Mater.* **2021**, *8*, 683490. [CrossRef]
57. Zabour, K.; Feddaoui, M.; Meftah, H. Effect of metal oxide nanofluids on the performance of passive solar still single slope for two different absorbent plates. *Heat Trans.* **2022**, *51*, 3675–3695. [CrossRef]
58. Kabeel, A.E.; Sathyamurthy, R.; Sharshir, S.W.; Muthumanokar, A.; Panchal, H.; Prakash, N.; Prasad, C.; Nandakumar, S.; El Kady, M.S. Effect of water depth on a novel absorber plate of pyramid solar still coated with TiO_2 Nano black paint. *J. Clean. Prod.* **2019**, *213*, 185–191. [CrossRef]
59. Gandhi, A.M.; Shanmugan, S.; Gorjian, S.; Pruncu, C.I.; Sivakumar, S.; Elsheikh, A.H.; Essa, F.A.; Omara, Z.M.; Panchal, H. Performance enhancement of stepped basin solar still based on OSELM with traversal tree for higher energy adaptive control. *Desalination* **2021**, *502*, 114926. [CrossRef]
60. Shanmugan, S.; Essa, F.A.; Gorjian, S.; Kabeel, A.E.; Sathyamurthy, R.; Muthu Manokar, A. Experimental study on single slope single basin solar still using TiO2 Nano layer for natural clean water invention. *J. Energy Storage* **2020**, *30*, 101522. [CrossRef]
61. Manoj Kumar, P.M.; Chauhan, P.; Sharma, A.K.; Rinawa, M.L.; Rahul, A.J.; Srinivas, M.; Tamilarasan, A. Performance study on solar still using Nano disbanded phase change material (NDPCM). *Mater. Today Proc.* **2022**, *62*, 1894–1897. [CrossRef]
62. Saleh, S.M.; Soliman, A.M.; Sharaf, M.A.; Kale, V.; Gadgil, B. Influence of solvent in the synthesis of nano-structured ZnO by hydrothermal method and their application in solar-still. *J. Environ. Chem. Eng.* **2017**, *5*, 1219–1226. [CrossRef]
63. Attia, M.E.H.; Kabeel, A.E.; Abdelgaied, M.; Essa, F.A.; Omara, Z.M. Enhancement of hemispherical solar still productivity using iron, zinc and copper trays. *Sol. Energy* **2021**, *216*, 295–302. [CrossRef]
64. Panchal, H.; Sadasivuni, K.K. Experimental investigation on solar still with nanomaterial and dripping arrangement. *Energy Sources A* **2020**, 1–11. [CrossRef]
65. Arani, R.P.; Sathyamurthy, R.; Chamkha, A.; Kabeel, A.E.; Deverajan, M.; Kamalakannan, K.; Balasubramanian, M.; Manokar, A.M.; Essa, F.; Saravanan, A. Effect of fins and silicon dioxide nanoparticle black paint on the absorber plate for augmenting yield from tubular solar still. *Environ. Sci. Pollut. Res. Int.* **2021**, *28*, 35102–35112. [CrossRef]
66. Sathyamurthy, R.; Kabeel, A.E.; Balasubramanian, M.; Devarajan, M.; Sharshir, S.W.; Manokar, A.M. Experimental study on enhancing the yield from stepped solar still coated using fumed silica nanoparticle in black paint. *Mater. Lett.* **2020**, *272*, 127873. [CrossRef]

67. Manoj Kumar, P.M.; Sudarvizhi, D.; Prakash, K.B.; Anupradeepa, A.M.; Boomiha Raj, S.; Shanmathi, S.; Sumithra, K.; Surya, S. Investigating a single slope solar still with a nano-phase change material. *Mater. Today Proc.* **2021**, *45*, 7922–7925. [CrossRef]
68. Thakur, A.K.; Sathyamurthy, R.; Velraj, R.; Saidur, R.; Hwang, J.-Y. Augmented performance of solar desalination unit by utilization of nano-silicon coated glass cover for promoting drop-wise condensation. *Desalination* **2021**, *515*, 115191. [CrossRef]
69. Sharshir, S.W.; Ismail, M.; Kandeal, A.W.; Baz, F.B.; Eldesoukey, A.; Younes, M.M. Improving thermal, economic, and environmental performance of solar still using floating coal, cotton fabric, and carbon black nanoparticles. *Sustain. Energy Technol. Assess.* **2021**, *48*, 101563. [CrossRef]
70. Sharshir, S.W.; Eltawil, M.A.; Algazzar, A.M.; Sathyamurthy, R.; Kandeal, A.W. Performance enhancement of stepped double slope solar still by using nanoparticles and linen wicks: Energy, exergy and economic analysis. *Appl. Therm. Eng.* **2020**, *174*, 115278. [CrossRef]
71. Rasachak, S.; Khan, R.S.U.; Kumar, L.; Zahid, T.; Ghafoor, U.; Selvaraj, J.; Nasrin, R.; Ahmad, M.S. Effect of tin oxide/black paint coating on absorber plate temperature for improved solar still production: A controlled indoor and outdoor investigation. *Int. J. Photoenergy* **2022**, *2022*, 6902783. [CrossRef]
72. Kabeel, A.E.; Abdelgaied, M.; Eisa, A. Effect of graphite mass concentrations in a mixture of graphite nanoparticles and paraffin wax as hybrid storage materials on performances of solar still. *Renew. Energy* **2019**, *132*, 119–128. [CrossRef]
73. Alqsair, U.F.; Abdullah, A.S.; Omara, Z.M. Enhancement the productivity of drum solar still utilizing parabolic solar concentrator, phase change material and nanoparticles' coating. *J. Energy Storage* **2022**, *55*, 105477. [CrossRef]
74. Gupta, B.; Kumar, A.; Baredar, P.V. Experimental investigation on modified solar still using nanoparticles and water sprinkler attachment. *Front. Mater.* **2017**, *4*, 23. [CrossRef]
75. Lawrence, A.; Hariharan, C.; Nagamani Prabu, A.; Janarthanan, B. Influence of nickel oxide nanoparticles on the absorption enhancement of solar radiation for effective distillation by single slope wick-type solar still. *Mater. Today Proc.* **2021**, *45*, 2357–2363. [CrossRef]