Materials Advances

REVIEW

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Mater. Adv.*, 2026, 7, 4037

The role of copper oxide nanomaterials in solar desalination: a systematic review of integration strategies

A. S. Abdullah,[a] Abanob Joseph,[b] Wissam H. Alawee,*[c] Mohamed Elashmawy,[d] Mohammed El Hadi Attia,[e] Swellam W. Sharshir [b] and Ahmed El-Harairy *[fg]

Low freshwater productivity and the intermittent nature of operation remain the major limitations of conventional solar still (SS) desalination systems, restricting their large-scale and long-term applicability despite their simplicity and low environmental impact. This review comprehensively analyzes the role of copper oxide nanoparticles (CuO NPs) as an effective multifunctional enhancement agent for overcoming these limitations. CuO NPs can be used as a nanofluid in the water basin and as a nanocoating on absorber surfaces to enhance the absorption of solar radiation and, consequently, increase evaporation rates and freshwater productivity. CuO NPs can also be employed as an additive for phase change materials (PCMs) to improve heat charging and discharging characteristics and to modify melting and solidification temperatures, thereby extending SS operation for several hours after sunset. The dual application of CuO NPs as a PCM additive and as an absorber surface coating provides up to 80.20% enhancement in freshwater productivity, achieves a thermal efficiency of 63.71%, and reduces the cost per liter of distilled water by up to 75% compared to conventional SSs. CuO NPs have been applied in both passive and active SS configurations, either individually or in hybrid arrangements. This review critically examines the effects of CuO nanofluid concentration, hybrid CuO-based nanofluids with other nanomaterials, and CuO nanocomposites, highlighting the superior performance of CuO NPs compared to alternative nanoparticles in terms of yield, thermal performance, and economic feasibility. In addition to experimental investigations, relevant theoretical and numerical modeling studies are integrated to provide design-oriented insights and optimization pathways for high-performance SSs.

Received 25th December 2025,
Accepted 24th March 2026

DOI: 10.1039/d5ma01512j

rsc.li/materials-advances

1. Introduction

Water is the fundamental medium sustaining life; however, access to safe freshwater remains one of the most critical challenges worldwide, affecting public health, economic development, and environmental sustainability. Water resources suffer from multiple global challenges, including scarcity, contamination, and unequal geographical distribution.[1,2] Although water covers the majority of the Earth's surface, more than 97% of it is saline, rendering it unsuitable for direct human consumption. Therefore, converting seawater and brackish water into freshwater has become an essential necessity rather than an option. The process of removing salts from saline water is known as desalination.[3]

Desalination technologies can be broadly classified into membrane-based desalination, which involves the use of selective membranes that allow only water molecules to pass through,[4] and thermal-based desalination, which relies on the evaporation of saline water followed by condensation of freshwater vapor.[5] Despite their high efficiency, membrane-based systems suffer from major operational challenges, particularly membrane fouling, high maintenance requirements, and limited lifespan, which significantly increase operational expenses.[6] Thermal desalination processes, although energy-intensive, offer higher robustness and reliability, especially in harsh operating environments.

[a] Department of Mechanical Engineering, College of Engineering in Al-Kharj, Prince Sattam bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia
[b] Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33516, Egypt
[c] College of Artificial Intelligence Engineering, University of Technology, Baghdad, Iraq. E-mail: wissam.h.alawee@uotechnology.edu.iq
[d] Department of Mechanical Engineering, Faculty of Engineering, Suez University, P.O. Box: 43221, Suez, Egypt
[e] Department of Physics, Faculty of Science, University of El Oued, 39000 El Oued, Algeria
[f] Department of Chemical and Biomolecular Engineering, College of Engineering, University of Nebraska-Lincoln, Lincoln, NE 68588, USA. E-mail: ael-harairy2@huskers.unl.edu, ael-harairy2@nebraska.edu
[g] Department of Soils and Water, Faculty of Agriculture, Damietta University, New Damietta, Damietta 34517, Egypt

Thermal desalination systems require a heat source to generate water vapour; however, the ongoing reliance on conventional fuels has contributed to the escalating emissions of greenhouse gases and environmental deterioration.[7] Consequently, the international research efforts have been increasingly focused on the integration of renewable energy sources, especially solar radiation, into desalination technologies. Solar still (SS) technology is one of the simplest and most environmentally benign solar driven desalination technologies.[8] SSs are characterised by low capital cost, simple construction and zero carbon emissions, making them suitable for remote and arid regions. However, the freshwater productivity of conventional SSs remains relatively low, limiting their large-scale deployment.

To overcome this limitation, a large number of modification techniques have been proposed to improve the productivity of SSs, which can be broadly classified as active and passive modifications.[9–11] Active SS systems include external devices such as heaters, condensers, solar collectors or pumps to supplement the heat and mass transfer processes.[10] In contrast, passive SS systems do not require external power input and enhance productivity through thermal energy storage using phase change materials (PCMs), addition of absorbing materials to basin water, surface modification and optimisation of glass cover geometry.[12]

Recent progress in nanotechnology has opened new possibilities for enhancing the performance of SSs. Owing to their outstanding thermal, optical and physicochemical properties, nanomaterials have been increasingly used in solar desalination systems.[13] Within SSs, nanomaterials can be used in three main ways: nanofluids dispersed in basin water, nanocoatings applied to absorber surfaces and nano-additives integrated within PCMs.[14,15] Nanofluids and nanocoatings promote increased solar radiation absorption, heat transfer, and basin water temperature, which leads to increased evaporation rates and freshwater productivity.[16] Likewise, nano-enhanced PCMs enhance thermal energy storage by speeding up heat charging and discharging processes, which extends the operation of SSs beyond sunset.[17]

Among the different nanomaterials studied, copper oxide nanoparticles (CuO NPs) have become a highly promising candidate in recent years, due to their excellent solar absorptivity, thermal conductivity, chemical stability and cost-effectiveness. Experimental and theoretical studies have repeatedly shown that CuO nanoparticles are superior to many other metal-oxide nanomaterials, making them a favorable choice for increasing heat transfer and evaporation rates and freshwater productivity in SS systems. Beyond individual performance metrics, the emerging scientific focus on CuO-based enhancement strategies is also well reflected in the bibliometric structure of the field. To objectively map this research evolution and justify the organisation of the present review, a comprehensive bibliometric analysis was conducted.

The keyword co-occurrence analysis, Fig. 1, enables the classification of CuO-based SS enhancement strategies into three dominant research strategies, which are represented as different colour-coded clusters in the network, Fig. 1(a). The green cluster mainly corresponds to nanofluid-based enhancement, wherein strong co-occurrence between CuO nanoparticles, nanofluids, thermal conductivity, solar power, and exergy and energy efficiencies reveals that CuO is mostly used as a basin water additive for enhancing heat transfer, evaporation rate and freshwater productivity. The red cluster refers to absorber surface modification and distillation performance and is characterised by keywords such as copper oxide, nanoparticles, solar still, distillation, productivity, efficiency, glass, and water depth, thereby emphasising the application of CuO-based nanocoatings on the basin liners or the absorber surfaces for enhanced absorption of solar radiation and efficiency at the system level. The blue cluster is primarily related to thermal storage and PCM-related enhancement, dominated by phase change materials, heat storage, thermal efficiency, solar desalination and thermal conductivity, in which CuO nanoparticles are increasingly used as a PCM additive to enhance charging and discharging behaviour and extend SS operation beyond sunset. These colour-coded clusters illustrate the multifunctional role of CuO nanoparticles in fluid, surface, and storage enhancement strategies, providing a clear bibliometric rationale for the organisation of this review into sections on nanofluids, absorber coatings, and PCM-enhanced thermal storage. In addition, Fig. 1(a) presents the bibliometric grouping of the main keywords, while Fig. 1(b) illustrates their time evolution, highlighting how the research focus has gradually shifted from nanofluid-based studies to absorber coatings and PCM integration. The overlay map shows a clear time evolution from nanofluid focused studies to absorber coatings and PCM integration, which can be seen as a maturation of the field and provides the rationale for organising this review into sections on nanofluids, absorber coatings and CuO enhanced PCM thermal storage as sequential and complementary development stages.

The bibliometric coupling analysis between journals, authors, and countries, Fig. 2, shows the core-periphery structure and a strong temporal evolution of research on SSs and solar desalination. At the journal level (Fig. 2(a)), desalination and water treatment, applied thermal engineering and energy conversion and management make up the intellectual core, as the main foundational outlets from earlier stages of research (represented by darker time domain colours), when studies focused primarily on thermal modelling, productivity improvement and traditional performance analysis. More recent coupling shifts to the *Journal of Cleaner Production*, *Journal of Energy Storage*, *Environmental Science and Pollution Research*, and *Separation and Purification Technology*, signalling a transition after 2021 towards sustainability assessment, PCM based thermal storage and purification-oriented frameworks. In Fig. 2(b), author coupling identifies Kabeel A. E., Omara Z. M., Abdullah A. A., Essa F. A. and Abdelgaied M. as the core research group, characterised by strong mutual coupling, sustained productivity and thematic continuity across nanofluids, absorber coatings and PCM enhanced SSs, whereas earlier foundational contributions are associated with authors such as Sathyamurthy R., Arun Kumar T. and Sahota L. whose work established baseline designs and performance metrics. More recent and emerging authors, such as Omara Z. M., Essa F. A., Abdullah A. A., Alawée W. H., and Shanmugan S., have lighter time-overlap

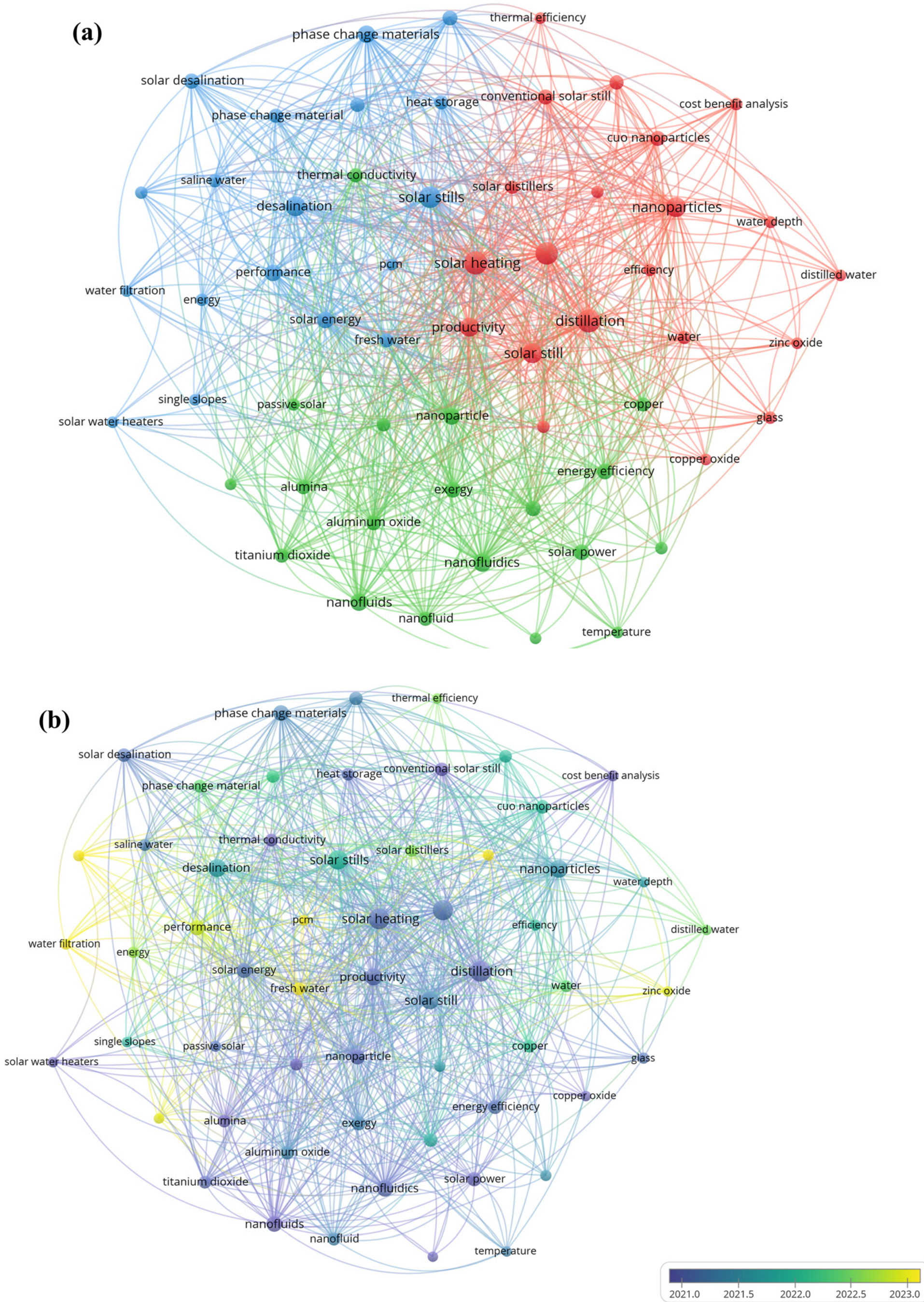

Fig. 1 The keyword co-occurrence analysis in terms of (a) bibliometric grouping and (b) time evolution.

colours and centrality, indicating a shift towards hybrid enhancement strategies and integrated system optimisation. At the country level (Fig. 2(c)), India leads the core contribution over the study period, followed by Egypt and Saudi Arabia, which constitute a strong collaborative center in line with the desalination needs of arid regions; China and the United Kingdom are earlier methodological contributors. In contrast, Algeria, Iran, Iraq, and Jordan are more recent, reflecting the rapid growth of research activity driven by water scarcity in the region. Overall, the coupling patterns reflect a clear progression from early thermally focused studies to recent, integrated separation and purification strategies that incorporate nanomaterials, thermal storage, and sustainability considerations.

This review systematically synthesizes and critically analyzes the full spectrum of copper oxide nanoparticle (CuO NP) integration strategies for SS desalination systems, encompassing the application of CuO NPs as a basin nanofluid, absorber surface nanocoating, and nano-enhanced phase change material (NanoPCM). In contrast to previous reviews that address nanomaterial applications in a fragmented manner, the

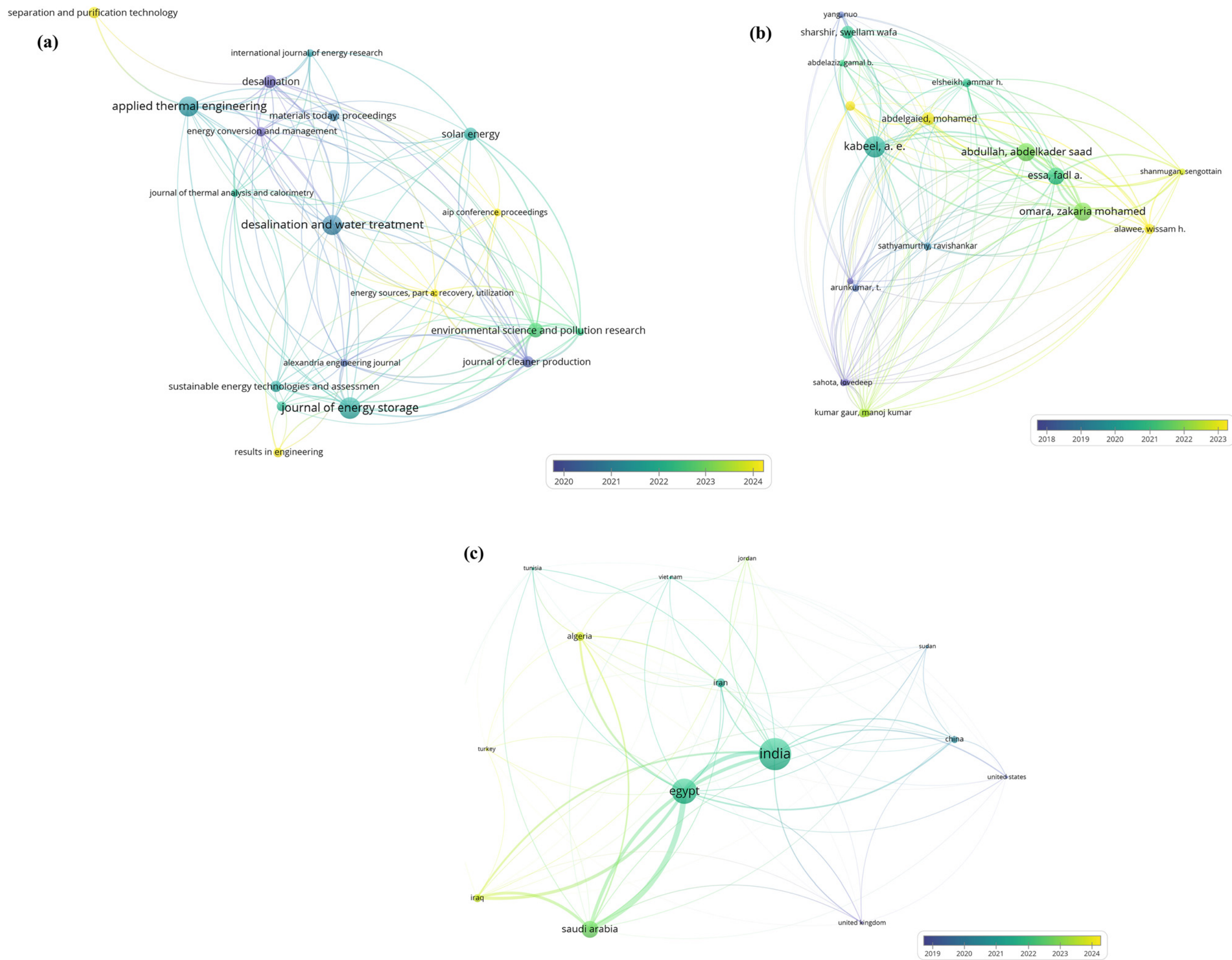

Fig. 2 The bibliometric coupling analysis between (a) journals, (b) authors, and (c) countries.

present study provides a unified framework linking material functionality with thermal mechanisms, system configuration, and freshwater productivity enhancement. This review is structured into three main sections: (1) copper oxide as a nanofluid (NF) in SSs, (2) copper oxide as a coating and surface modifier, and (3) copper oxide with phase change materials (NanoPCMs), with each section covering both passive and active SS configurations. Furthermore, comparative performance tables are developed to quantitatively assess productivity, energy and exergy efficiencies, and economic indicators across different enhancement strategies, enabling clear benchmarking and practical design guidance. This structured and bibliometrically supported synthesis highlights the multifunctional role of CuO nanoparticles and identifies optimal integration pathways for high-efficiency, cost-effective solar desalination systems.

2. Solar still performance descriptors

2.1. Energy efficiency

Energy efficiency indicates how effectively a solar still converts the energy supplied into useful energy for water evaporation. It is defined as the ratio of useful output energy to total input energy. For solar stills, the useful energy is the latent heat required to evaporate the produced distillate, while the input energy is mainly the incident solar radiation and, for active systems, any auxiliary electrical power. In general, higher energy efficiency means that a larger share of the supplied energy is utilized for evaporation, which usually improves freshwater production.

The hourly and daily energy efficiencies are expressed as:[18,19]

$$\eta_{\mathrm{hr}} = \frac{\dot{m}_{\mathrm{w}} \times h_{\mathrm{l}}}{\left[\left(I(t) \times A_{\mathrm{g}}\right) + W_{\mathrm{d}}\right] \times 3600} \tag{1}$$

$$\eta_{\mathrm{d}} = \frac{\sum\left(\dot{m}_{\mathrm{w}} \times h_{\mathrm{l}}\right)}{\sum\left[\left(I(t) \times A_{\mathrm{g}}\right) \times 3600\right] + \left(W_{\mathrm{d}} \times \tau\right)} \tag{2}$$

$$h_{\mathrm{l}} = 2.5019 \times 10^{6} - 2.40706 \times 10^{3} \times T_{\mathrm{w}} + 1.192217 \times {T_{\mathrm{w}}}^{2} - 1.5863 \times 10^{-4} \times {T_{\mathrm{w}}}^{3} \tag{3}$$

where $\dot{m}_w$ is the hourly distillate productivity, h_l is the latent heat of vaporization, A_g is the glass area, $I(t)$ is the solar radiation intensity, W_d is the rated power of active devices, τ is the operating duration, and T_w is the basin water temperature.

2.2. Exergy efficiency

Exergy efficiency represents the quality of energy utilization and reflects how effectively the available energy is converted into useful work potential. Unlike energy efficiency, exergy efficiency accounts for thermodynamic irreversibilities during heat transfer, evaporation, and condensation. Thus, it provides a deeper assessment of solar still performance. A higher exergy efficiency indicates lower useful energy destruction and better thermodynamic performance. Although higher productivity often accompanies higher energy efficiency, exergy efficiency is needed to evaluate how effectively the system uses the available solar energy.

The hourly and daily exergy efficiencies are given by:[18,19]

$$\eta_{\text{hr-Ex}} = \frac{\mathrm{Ex}_{\text{out}}(t)}{\mathrm{Ex}_{\text{in}}(t)} \tag{4}$$

$$\eta_{\text{d-Ex}} = \frac{\sum \mathrm{Ex}_{\text{out}}(t)}{\sum \mathrm{Ex}_{\text{in}}(t)} \tag{5}$$

$$\mathrm{Ex}_{\text{out}}(t) = \frac{\dot{m}_w \times h_l}{3600}\left(1\frac{T_a}{T_w + 273}\right) \tag{6}$$

$$\mathrm{Ex}_{\text{in}}(t) = \left(I(t) \times A_g\right)\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] + W_d \tag{7}$$

where $\mathrm{Ex}_{\text{out}}(t)$ and $\mathrm{Ex}_{\text{in}}(t)$ are the output and input exergies, respectively, T_a is the ambient temperature, and T_s is the sun temperature in Kelvin.

3. Copper oxide as a nanofluid in solar stills

Enhancing solar radiation absorption and heat transfer within the basin water is a key strategy for improving SS performance. Among various nanomaterials, copper oxide nanoparticles (CuO NPs) have been extensively employed as nanofluids, where their dispersion in basin water increases thermal conductivity, elevates water temperature, and accelerates evaporation, thereby enhancing freshwater productivity.[20] CuO nanofluids have been successfully implemented in both passive and active SS configurations, demonstrating consistent performance improvements under different climatic and operational conditions. It is necessary to clarify the key mechanisms through which CuO nanoparticles improve the performance of nanofluids in solar stills before the reported productivity improvements are reviewed. By adding CuO NPs to the base fluid, it will be possible to enhance the effective thermal conductivity of the basin water, thus enhancing the ability of the system to transport heat to the bulk fluid and leading to a faster increase in the water temperature. Moreover, suspended CuO nanoparticles are able to increase the absorption of solar energy and increase the evenness of the heat diffusion in the water layer, thus increasing the rate of evaporation. Nevertheless, the intensity of such effects is highly dependent on the concentration of nanoparticles, the thermophysical characteristics of the base fluid and the solar still setup. Thermal transport as well as absorptivity can become enhanced at low to moderate levels, but overload can enhance agglomeration, viscosity and sedimentation potential and undermine the advantage of heat transfer. Similarly, the effect of the CuO nanofluids can be different depending on the basin geometry, depth of water and the existence of other auxiliary machineries like condensers, collectors or cooling systems. Consequently, the impact of CuO nanofluids may be explained as the consequence of the combined thermal and optical processes, which are vulnerable to the material loading and the design of the system.[21]

3.1. Passive systems

A passive system in an SS is the one where evaporation and condensation occur naturally, without mechanical pumps or additional equipment, using only the sun's energy to drive the process.[9] Megahed and El Mahallawy[22] prepared CuO NPs and CoCuMnOx NPs using the sol–gel method to be used as nanofluids; a 1% fraction of volume (VF) of each NP type is added to the water basin of single-basin SSs. The aim of these nanomaterial additives is to increase the vaporization rate of water within the SS. CoCuMnOx nanofluids significantly increased the vaporization rate by 65.33% in contrast to pure water, whereas CuO nanofluids established a 33.24% rise, according to the experimental data. In addition to these experimental results, numerical models indicate that under certain design and environmental conditions, adding 1% Vf of CuO nanofluid to an SS can result in a total productivity of 13 liters during an 8-hour period. According to Attia *et al.*,[23] copper oxide micro- and nanoparticles (MP/NP) in different ratios (1, 2, and 3%) were used in a hemispherical SS (HSS). According to the experimental results, when NPs of CuO were applied at ratios of 1, 2, and 3%, the HSS produced 5.28, 5.92, and 6.75 L m^{-2} day^{-1}, while when MPs of CuO were used, the modified HSS (MHSS) yield was equal to 4.38, 4.82, and 5.43 kg m^{-2} day^{-1} for ratios equal to 1, 2, and 3%, respectively. The results demonstrate the significant impact of CuO nanoparticles compared to microparticles. The highest production of the classical HSS without modifications was 2.98 L m^{-2} day^{-1}.

Thakur and Gaur[24] analyzed the passive SS's performance in the winter and summer with and without CuO NPs. The experimental investigation is carried out at water depths of 4 cm and condensing cover tilt angles of 11°, 26°, and 41° with and without nanoparticles. The CuO-containing SS performs better than the pure water SS without NP additives. In comparison to water without nanoparticles, there has been an improvement of 139.44% and 127.98% in the evaporative heat transfer coefficient with CuO NFs at 11° and 41° cover tilt angles in winter and summer, respectively. In winter, CuO nanofluids and traditional SSs without nanofluids have been found to provide a maximum output of 2.03 and 1.53 L m^{-2} of freshwater per day at 41° tilt angles, respectively; in summer, SSs with CuO nanofluids and traditional SSs without nanofluids achieved a maximum of 4.02 and 2.38 L m^{-2} day^{-1} of freshwater at 11°, respectively. At a 41° tilt angle in winter, a similar study was conducted by Thakur *et al.*,[25] but with the addition of ZnO and CuO NPs in the water basin as nanofluids individually and a comparison of their influence on the SS system efficiency. It is evidenced that ZnO and CuO NPs provide 11.11% and 41.60% enhancement in the yield compared to that in the absence of nanofluids, and they also show that SSs with CuO achieved 2025 ml day^{-1}, ZnO achieved 1590 ml day^{-1}, and without nanofluids, 1430 ml day^{-1} of distilled water was achieved. Hamdan *et al.*[26] compared the efficiency of both CuO and Al_2O_3 as nanofluids in the SS to that of the classical SS without nanoparticle additives, and they noticed that the efficiency of the SS increases by 7.8% and 9.62%, respectively, when 0.4% Al_2O_3 and 0.6% CuO are added. Although the amount of water generated rose when nanoparticles were added, the cost of the freshwater produced per liter was higher than that with the classical setup. Thakur and Gaur[27] studied the effect of various parameters of SS in the presence of CuO and ZnO NPs. Three SSs with tilt angles of 41°, 26°, and 11° are constructed, and their performance is evaluated at various water depths (10, 5, and 4 cm) as well as in the presence of CuO and ZnO NPs. It was found that the maximum performance of the SS was with 4 cm depth and a 41° tilt angle. CuO NPs achieved the higher productivity of 2.03 L m^{-2} d^{-1} while ZnO NPs and the conventional SS achieved 1.54 and 1.43 L m^{-2} d^{-1} respectively. When CuO nanoparticles are added to an SS, the predicted internal heat transfer coefficient is 155.2% higher than that of a traditional SS, and when ZnO nanoparticles are added, it is 64.8% more than that of a conventional SS.

Alhendal *et al.*[28] examined the influence of using various concentrations of CuO NPs in the saline water of the SS on the evaporation rate and yield of distilled water. Through the series of CuO NP concentrations, it is found that saline water with 0.1% of weight shows the optimal yield with an enhancement in efficiency and productivity by 110% and 100%, respectively. Madhu *et al.*[29] examined how Al_2O_3, CuO, and TiO_2 NPs can be dissolved in water in three distinct concentration ratios (0.2, 0.1, and 0.05% VF) to be used as NFs in a SS. For a maximum concentration of 0.2%, the highest output from an SS using TiO_2, CuO, and Al_2O_3 NFs was determined to be 2.17, 2.25, and 4.03 L m^{-2}, respectively. With the Al_2O_3 nanofluid, the system's highest exergy efficiency is found to be 11.12%. Madhu *et al.*[30] also did the same experiment but on a stepped SS. The results demonstrated that the Al_2O_3 nanofluid also shows the highest efficiency in increasing the yield of distilled water from stepped and conventional SSs by 67% and 50%, respectively, by adding nanoparticles to the base fluid.

Regarding theoretical studies, Dhindsa *et al.*[31] used CuO, SiC, Al_2O_3, Ag, and Fe_2O_3 at different VFs (0.2, 0.12, 0.08, 0.05, and 0.02) in a theoretical investigation of a single-slope passive SS. Experiments conducted in Patiala, India were found to be in good agreement with the characteristic equation's theoretical formulation utilizing Runge–Kutta ODEs. For a single day, the total deviation for a still's theoretical and experimental distillate output was determined to be 12.24%. It was discovered that the daily output of the Al_2O_3–water-based nanofluid was 14.22% greater than that of a simple SS without a nanofluid. Next were SiC (7.61%), Fe_2O_3 (7.63%), Ag (8.11%), and CuO (10.82%). The theoretical model was validated against experimental data obtained in Patiala, India, and the predicted daily distillate yield showed a total deviation of only 12.24%, indicating acceptable agreement between the numerical formulation and practical observations. Zabour *et al.*[32] performed a numerical study on the use of Cu_2O, TiO_2, and Al_2O_3 nanofluids in a single-slope passive SS. The findings indicate that the SS employing Al_2O_3, TiO_2, and Cu_2O NPs has a productivity of 7.064, 7.1, and 7.38 L m^{-2} day^{-1}, respectively. By employing cuprous oxide NPs, it is discovered that the SS's maximum efficiency is 55.27%. Additionally, dispersing 1%, 3%, and 5% VFs of Cu_2O NPs in water resulted in an increase in the SS productivity of 6.36%, 19.54%, and 33.25%, respectively, when compared to the traditional solar still. Based on the numerical findings of Hafs *et al.*,[33] incorporating fins into the basin liner improved the daily productivity by 12.6% compared to the conventional solar still, while combining the finned basin liner with a Cu_2O/brackish-water nanofluid increased the productivity by 20%. According to Thakur *et al.*,[34] several thermal models were used to predict the distillate production and heat transfer coefficients of a single-slope SS both in and out of nanoparticles (CuO and ZnO NPs) for a 41° cover angle and a 4 cm water level. SSs with ZnO nanofluids, CuO nanofluids, and no nanoparticles had yield percentage variation, at 8.41, 9.52, and 9.89%, respectively. The model demonstrated superior agreement with the experimental results. Compared to water without nanoparticles, the distillate produced by CuO and ZnO nanofluids is approximately 41.11% and 9.75% greater, respectively. The experimental yield confirms the yield anticipated by various thermal models. The model showed a stronger correlation with the experimental findings. For a glass cover tilt angle of 41° and a water depth of 4 cm, the distillate water generated by ZnO and CuO NFs is around 9.75% and 41.11% higher than the water without NPs. The results show that CuO overcomes ZnO NPs in productivity enhancement. The proposed thermal models were also compared with the corresponding experimental measurements, and the predicted distillate productivity showed good agreement with the experimental results, confirming the reliability of the modelling approach for CuO- and ZnO-based nanofluid solar stills.

Elzemzmi *et al.*[35] integrated Al_2O_3, CuO, and TiO_2 nanofluids for two different configurations of SSs and hybrid SSs. The results demonstrate a highly cumulative yield of freshwater regardless of the different configuration compared to SSs without nanoparticles. Phukapak *et al.*[36] evaluated the effects of different nanomaterials with strip-grooved fin absorber shapes (SGFs) on the execution of a double-slope SS by developing a thermal model for it. The used nanofluids of Al_2O_3, CuO, Ag, Fe_2O_3, and ZnO combined with the fin absorber achieved output efficiencies of 36.13%, 35.58%, 34.60%, 32.44%, and

29.71%, respectively, while in the presence of fin absorber forms with strip grooves without nanofluids, it achieved only 26.93%. Modi *et al.*[37] determined the impact of nanoparticles (CuO and Al_2O_3 NPs) on the dual-slope SS's productivity by conducting an experimental study with various still glass cover orientations and basin water depths. Al_2O_3 NPs at water depths of 10 mm, 20 mm, and 30 mm for the north–south orientation resulted in an increase in distilled output of 26.59%, 28.53%, and 19.40%, respectively. At the north–south orientation, CuO NPs increased the yield by 56.31% and 58.25% at water depths of 10 mm and 20 mm, respectively, as compared to the still without nanoparticles. Using 0.1% CuO NPs for the glass covers oriented north–south resulted in 26.60% and 27.27% higher productivity at 10 mm and 20 mm water depths, respectively, compared to the SS with 0.1% Al_2O_3 NPs.

According to Kouadri *et al.*,[38] ZnO and CuO NPs were introduced individually with different masses to assess their production compared to the classical SS unit, where each metal oxide was added in varying amounts (60, 40, and 20 g) to each unit that contains the same quantity of brackish water (3.6 L). Metal oxides in this process act as photocatalysts, where concentration plays an important role; 20 g of each material show promising results. In comparison to the baseline situation, the daily yield was increased by roughly 74.76% and 79.39%, respectively, when 20 g of CuO and ZnO were added independently inside the absorber of the two distinct units. Labied *et al.*[39] also focused on using metal oxide NPs as photocatalysts in solar distillation to purify brackish water. They used CuO, ZnO, and Fe_2O_3 NPs with varying weight concentrations (0.04%, 0.08%, 0.12%, and 0.16%) to improve the yield of SSs. When compared to the traditional still, the test still's productivity rose by 13.02%, 16.64%, and 22.43% for ZnO, Fe_2O_3, and CuO, respectively, at a weight concentration of 0.16%, and a liter of distillate was expected to cost 0.0090, 0.0089, and 0.0096 dollars, respectively, as opposed to 0.0092 dollars in the baseline scenario. Patel *et al.*[40] used several semiconducting metal oxides as photocatalysts, including CuO, PbO_2, and MnO_2, in solar desalination. Metal oxides were found to significantly boost the rate of desalinated water production in addition to improving process efficiency. The various characteristics of water quality, such as pH and TDS, are examined for both raw and desalinated water.

Asadpourian and Ameri[41] focused on using the composite of CuO NPs and graphene oxide (CuO–GO nanocomposite) as a nanofluid in the still basin. In their experiments, 0.3, 0.2, 0.1, and 0 wt% of the nanocomposite were used, and the total distillate output was 6.73, 6.14, 5.08, and 3.51 kg m^{-2} h^{-1}, respectively. Freshwater yield increased by 91.7, 75.0, and 44.7%, respectively, as compared to the trial without the nanocomposite.

Alasiri *et al.*[42] investigated the thermo-economic efficiency of HSS modified with three materials: the first one with the CuO nanofluid, the second with copper chips, and the third with tests conducted on NFs and copper chips placed between the wick material. The third test demonstrated the highest productivity and thermo-economic performance. In this case, the MHSS outperformed the conventional HSS (CHSS) with a daily distillate water production and thermal efficiency of 79.11% and 79.107%, respectively. Furthermore, with a daily exergy efficiency of 2.38%, the MHSS demonstrated the greatest improvement of 167.42%, and the cost of water was reduced by 20.68% compared to the CHSS. According to Attia *et al.*,[43] CuO NPs were added to the water at three concentrations (0.3, 0.2, and 0.1%) in order to advance the thermal characteristics of the basin fluid, boost the rate at which vapor is formed within the basin, and raise the intensity of absorbed solar energy. The second modification used three distinct flow rates (2.5, 2, and 1.5 kg h^{-1}) of water film glass cooling systems to boost the rate of water vapor condensation in the HSS. The results demonstrated that the addition of CuO nanofluid of 3% concentration showed the best results, producing 6.80 L m^{-2} day^{-1}, while the second modification of the cooling system at a 2.5 kg h^{-1} flow rate produced 5.7 L m^{-2} day^{-1}, which demonstrated that the copper nanofluid showed a significant productivity compared to film glass cooling systems at a 2.5 L h^{-1} flow rate. Productivity of distilled water in winter is limited, so Attia *et al.*[44] compared the productivity in the winter and summer seasons and showed that the addition of CuO NPs to the water basin in winter enhances the productivity, yet less than that of the conventional SS in the summer season. The conventional SS was shown to be productive at 3.5 L m^{-2} in summer and 2.2 L m^{-2} in winter, while the modified SS with the CuO nanofluid used in winter produced 3 L m^{-2} per day. However, the production of the modified SS in winter is still less than that of the conventional SS in summer; the exergy of the modified SS is 2.41%, while the conventional SS in summer achieves only 1.2%. Attia *et al.*[43] studied the impact of the CuO NF and cover cooling with a sprinkler separately; Gupta *et al.*[45] studied the combined impact of both the CuO nanofluid and cover cooling technology through sprinkler attachment. It has been found that these modifications increased productivity from 2900 ml m^{-2}-day in a conventional SS to 4000 mL m^{-2} per day, and the thermal efficiency increased from 22 to 34%, respectively. Sharshir *et al.*[46] compared the efficiency of CuO NPs and graphite NPs as nanofluids using glass film cooling. The results demonstrated that the graphite nanofluid outperformed the CuO nanofluid, with the thermal efficiency reaching 49% and 46%, respectively.

3.2. Active systems

An active SS is a category of SS that uses external energy inputs or mechanical components to improve performance.[47] Eswaran *et al.*[48] used evacuated tube collectors with various nanofluids for solar desalination. They noticed that in the case of water without nanoparticles, the collected distilled water was 2275 mL after 11 h of operation, while in the case of nanofluids, the production was more than 17.4%, 15.7%, and 14.5% for CuO, Al_2O_3, and ZnO NPs. These results demonstrate the significant impact of CuO NPs compared to the other nanofluids. Dawood *et al.*[49] used the CuO nanofluid with various volume concentrations in a single-slope SS along with a vibration generator and cover cooling. The SS with 1.5% nanofluid concentration demonstrate the best results at a depth of 1 mm; the productivity and daily efficiency reached 7.13 kg day^{-1} and 54%, respectively.

El-Gazar *et al.*[50] provided a new model that analyzes the performance of an SS system with a solar panel (PV) using a hybrid NF and preheated raw water. The new model was simulated using two different fractional operators: Riemann–Liouville and Caputo–Fabrizio fractional derivatives. They used a hybrid nanofluid of CuO/Al_2O_3 at three percentages of preheating: 40, 50, and 60%. The results showed that employing the Riemann–Liouville fractional derivative yields an optimal match with the experimental findings, with an error of 3.59%. The best results were observed at a preheating of 60% with the hybrid nanofluid, where the productivity reached 7.126 kg m^{-2} day^{-1} while the energy and exergetic efficiencies reached 54.61% and 15.3%, respectively. To ensure model reliability, the fractional-order model was validated against experimental measurements, and the Riemann–Liouville formulation provided the closest agreement, with a minimum error of 3.59%, demonstrating its suitability for predicting the performance of the PV-assisted solar still using the hybrid CuO/Al_2O_3 nanofluid. Ajit *et al.*[51] examined the influence of the addition of mono- and hybrid NFs of GO and CuO NPs to the water and found that the hybrid nanofluid of GO–CuO achieved the highest productivity enhancement of 127.46%. Gaur *et al.*[52] used the hybrid nanofluid of Al_2O_3–CuO along with a PCM to enhance the yield of a pyramid SS. The daily output was around 3.89 L m^{-2} for a system using the hybrid nanofluid and PCM, while the productivity of the SS utilizing the nanofluid alone was 3.61 L m^{-2}. The results showed that the SS utilizing the hybrid nanofluid with the PCM generates 7.4% more distilled water daily than the SS using simply the nanofluid.

The efficiency of a Cu_2O NF in a single slope SS equipped with an outer thermoelectric cooling unit (TEC) as a condensing channel was shown in an experimental and theoretical investigation. According to Nazari *et al.*,[53] to provide a cool environment in the vapor flow, 4 TEC units were placed around the external channel's walls, as shown in Fig. 3(a). The exergetic and energetic efficiencies and productivity were boosted by approximately 92.6, 81.5, and 82.4%, respectively, when 0.08% of Cu_2O nanoparticles got mixed with water. The cost was reduced to 0.021 \$ per L per m^2 in a modified SS. Nazari *et al.*[54] also did the same experiment, but the TECs were installed on the sides of the exterior channel. This modification caused a significant enhancement in the exergy around 112.5%, while the productivity and energy enhancement were near to those obtained in a previous study, around 81% and 80.6%, respectively, with a little change in cost from the previous study of about 0.0218 (\$ per L per m^2). Shoeibi *et al.*[55] aimed to assess how simultaneous thermoelectric cooling and heating applications employing various nanofluids impact an SS's performance. The glass temperature was reduced as a result of the nanofluid flowing on it through the pump and decreasing with the TEC side in the cooling tank. Concurrently, the TEC hot side raises the temperature of the nanofluid in the heating tank as it enters the SS's helically coiled heat exchanger, Fig. 3(b). Al_2O_3, TiO_2, CuO, and MWCNT nanofluids were used in place of the base fluid in the heating and cooling tanks. The findings showed that, in comparison to SSs without nanofluids, the water productivity of SSs with TEC cooling and heating of Al_2O_3, CuO, TiO_2, and MWCNT NFs at 0.9% concentration was enhanced by 11.57, 7.16, 6.32, and 4.66, respectively. Naveenkumar *et al.*[56] introduced an external condenser and a vacuum fan into a double slope SS, along with ZnO, Al_2O_3, and CuO

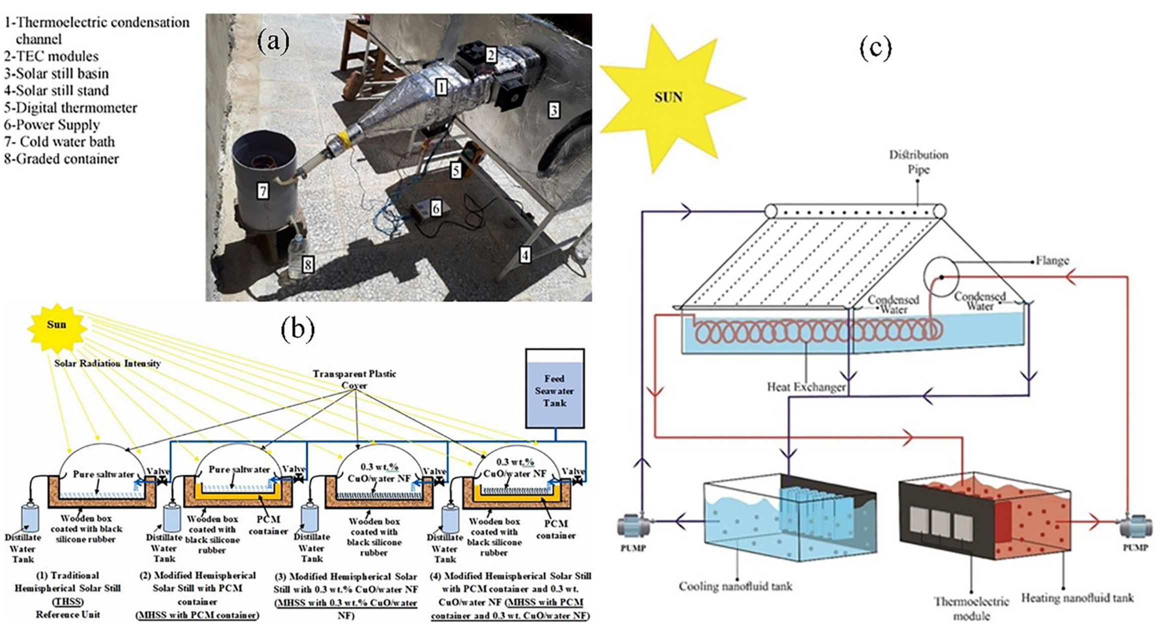

Fig. 3 (a) Thermoelectric condensation technique of a modified SS. Reproduced with permission.[53] Copyright 2018, Elsevier, (b) diagram of the thermoelectric SS. Reproduced with permission.[55] Copyright 2021, Elsevier, and (c) schematic diagram of HSSs (both conventional and modified stills). Reproduced with permission.[20] Copyright 2022, Elsevier.

nanofluids, and studied the impact of adding nanofluids. In comparison to a traditional double-slope SS, the distillate output was increased by 51.85%, 55.56%, and 59.26% and then increased to 75%, 82.14%, and 96.43% when a condenser with a vacuum fan and a 0.1% VF of the three NFs on the same order were incorporated. The copper oxide nanofluid outperformed the other two nanofluids in terms of accumulated production and energy and exergy efficiency. According to Abdelgaied *et al.*,[20] three examples of modified HSSs were examined and contrasted with a traditional HSS as shown in Fig. 3(c): incorporating 0.3 weight percent of CuO nanoparticles in water, using a PCM under the basin, and integrating a phase change material beneath the basin with the dispersion of CuO nanoparticles in water. In contrast to the CHSS, the findings indicate that the exclusive use of a pure PCM and a CuO/water NF enhanced production by 29.17% and 60.41%, respectively. In comparison to the CHSS, the synergistic use of a PCM and a CuO/water NF increased the output by 80.20% with 75% reduction in freshwater production cost. El-Gazar *et al.*[57] used a classical model and the Riemann–Liouville fractional derivative to predict the thermal performance of a traditional SS and investigate the impact of utilizing a hybrid NF of CuO and Al_2O_3 NPs on the desalination efficiency and determine the best model according to experimental investigations. The theoretical findings showed that the suggested fractional model results and the still's experimental data match perfectly, with an error percentage of 3.243% in winter and 1.486% in summer as opposed to 20.08% and 24.1% when using the classical model. The experimental results demonstrated that the hybrid nanofluid of concentration 0.025% achieved energy and exergetic efficiencies of 49.54% and 3.5325% respectively and the productivity increased to 5.5239 kg m^{-2} day^{-1}. The fractional model was further validated by comparison with experimental data under both winter and summer conditions, where the prediction errors were reduced to 3.243% in winter and 1.486% in summer, compared with 20.08% and 24.1% for the classical model, respectively. This confirms the improved predictive capability of the proposed fractional formulation.

The discussion focuses on the application of CuO as a nanofluid within a water basin system, specifically in the context of SSs. The analysis encompasses several key aspects: the influence of varying concentrations of CuO NPs on system performance, the comparative effectiveness of different nanomaterials relative to CuO NPs, and the outcomes of integrating hybrid nanofluids that combine CuO NPs with other nanomaterials. Additionally, the study examines the effects of incorporating CuO nanocomposites and the impact of external devices when used in conjunction with CuO nanofluids. These investigations aim to optimize the efficiency of the SS process through nanofluid enhancements. The summarized results of these evaluations are systematically presented in Table 1. In hybrid nanofluid-based solar stills, the reported performance enhancement is generally attributed to the combined influence of improved thermal transport and enhanced optical absorption. For example, El-Gazar *et al.*[50] reported that using a hybrid CuO/Al_2O_3 nanofluid with 60% preheating increased productivity to 7.126 kg m^{-2} day^{-1}, with energy and exergy efficiencies of 54.61% and 15.3%, respectively, while Ajit *et al.*[51] showed that a GO–CuO hybrid nanofluid achieved a productivity enhancement of 127.46%. Similarly, Gaur *et al.*[52] found that the use of a Al_2O_3–CuO hybrid nanofluid with a PCM increased daily output by 7.4% compared to the nanofluid alone. These improvements suggest that hybrid nanofluids enhance solar still performance through both better effective thermal conductivity and stronger solar absorption characteristics. However, the currently available literature does not clearly separate the individual contributions of thermal synergy and optical absorption, and therefore further dedicated mechanistic studies are needed.

4. Copper oxide as a coating and surface modifier

One of the most advantageous characteristics of nanomaterials is their high surface-area-to-volume ratio, which enables enhanced absorption of incident solar radiation and improved heat transfer. While the previous section focused on the application of copper oxide nanoparticles (CuO NPs) as a nanofluid within the basin water, CuO NPs have also been extensively utilized as an absorber surface modifier and a coating additive. When incorporated into black paint and applied to basin liners or absorber surfaces, CuO nanocoatings increase solar absorptivity, reduce thermal losses, and elevate basin water temperature, thereby enhancing evaporation and freshwater productivity. The positive contribution of the CuO nanocoatings to solar stills is directly linked to the effect of the optical and thermal properties of the absorber surface. When CuO nanoparticles are incorporated in black paint or when applied as a nanocoating, they have the potential to enhance solar absorptivity by enhancing light trapping and reducing losses due to reflection as well as to influence surface heat transfer properties. Two important controlling parameters in this case are coating thickness and roughness of the surface. An adequate thin and uniform coating can increase absorption without adding too much thermal resistance, but excessive thick coating can decrease thermal performance or change emissive properties negatively. Likewise, surface roughness can enhance incident light absorption through multiple scattering and trapping, but can also affect thermal emissivity and surface hardness. Based on this, the reported performance of the CuO-based coatings is not only related to the presence of CuO, but also to the morphological and structural properties of the coating layer, which determine the compromise between the increased solar absorption and thermal loss.

4.1. Passive systems

Yuvaperiyasamy[58] used CuO NPs (30% weight) with black paint to be applied as a coating layer on the sides of the water basin to improve heat convection and performed three experiments at 3, 5, and 7 cm of water depth for both a coated SS with the nanocoating and a traditional SS without the nanocoating.

Table 1 Comparison of using copper oxide as a nanofluid in SSs, including the type of SS, modifications, productivity enhancement, energy efficiency, exergy efficiency, and cost

SS type	Modification	Productivity enhancement (%)	Energy efficiency (%)	Exergy efficiency (%)	Cost	Ref.
Passive systems						
Hemispherical	CuO NPs at 3% concentration	126.51	50.97	4.41	60 DZD	23
Single slope	CuO NPs in the winter season at a 42° tilt angle	32.67	N/A	N/A	N/A	24
Single slope	CuO NPs in the summer season at a 11° tilt angle	68.90	N/A	N/A	N/A	
Single slope	CuO NPs	41.60	N/A	N/A	N/A	25
Single slope	ZnO NPs	11.11	N/A	N/A	N/A	
Pyramid	0.6% CuO NPs	9.62	N/A	N/A	0.0308 $ per L	26
Pyramid	0.4% Al_2O_3 NPs	7.80	N/A	N/A	N/A	
Single slope	0.1 wt% CuO in basin saline water	100.00	111.2 (enh.)	N/A	168 KD (capital cost)	28
Single slope	CuO nanofluid (0.2%)	53.54	21.67	N/A	N/A	29
Single slope	TiO_2 nanofluid (0.2%)	50.23	20.22	N/A	N/A	
Single slope	Al_2O_3 nanofluid (0.2%)	74.19	37.44	11.12	N/A	
Single slope	Cu_2O nanofluid (2%), numerical study	12.89	55.27	N/A	N/A	32
Single slope	Al_2O_3 nanofluid (2%), numerical study	7.95	N/A	N/A	N/A	
Single slope	TiO_2 nanofluid (2%), numerical study	8.51	N/A	N/A	N/A	
Single slope	Finned basin liner with a Cu_2O nanofluid, numerical study	20.00	25.00	N/A	N/A	33
Single slope	ZnO nanofluid	9.75	N/A	N/A	N/A	34
Single slope	CuO nanofluid	41.11	N/A	N/A	N/A	
Double slope	Al_2O_3 NPs + strip-grooved fins (SGFs)	34.58	36.13	N/A	0.0309 $ per L	36
Double slope	CuO NPs + SGFs	33.94	35.58	N/A	N/A	
Double slope	Ag NPs + SGFs	32.96	34.60	N/A	N/A	
Double slope	Fe_2O_3 NPs + SGFs	30.80	32.44	N/A	N/A	
Double slope	ZnO NPs + SGFs	28.07	29.71	N/A	N/A	
Double slope	Al_2O_3 NPs at a water depth of 10 mm	26.59	N/A	N/A	N/A	37
Double slope	CuO NPs at a water depth of 10 mm	56.31	N/A	N/A	N/A	
Single slope	20 g of CuO NPs	74.76	N/A	N/A	N/A	38
Single slope	20 g of ZnO NPs	79.39	N/A	N/A	N/A	
Single slope	CuO nanofluid (0.16%)	22.43	N/A	N/A	0.0090 $ per L	39
Single slope	Fe_2O_3 nanofluid (0.16%)	16.64	N/A	N/A	0.0089 $ per L	
Single slope	ZnO nanofluid (0.16%)	13.02	N/A	N/A	0.0096 $ per L	
Single slope	CuO–GO nanocomposite (0.1%)	44.70	N/A	N/A	N/A	41
Single slope	CuO–GO nanocomposite (0.2%)	75.00	N/A	N/A	N/A	
Single slope	CuO–GO nanocomposite (0.3%)	91.70	N/A	N/A	N/A	
Hemispherical	CuO nanofluid + copper chips + wick material (MHSS)	48.73	46.63	2.38	0.029 $ per L	42
Hemispherical	CuO nanofluid + copper chips + wick material + external condenser (MHSSC)	79.11	56.15	1.82	0.029 $ per L	
Hemispherical	CuO–water nanofluid (0.3 vol%)	76.60	65.20	N/A	0.0066 $ per L	43
Single slope	CuO nanofluid in winter	26.34	31.37	2.41	0.5 $ per L	44
Single slope	CuO nanofluid + cooling system	37.90	34.00	N/A	INR 0.98 per L	45
Single slope	CuO micro-flakes	44.91	N/A	N/A	N/A	46
Single slope	Graphite micro-flakes	53.95	N/A	N/A	N/A	
Single slope	CuO micro-flakes + glass-cover cooling	47.80	N/A	N/A	N/A	
Single slope	Graphite micro-flakes + glass-cover cooling	57.60	N/A	N/A	N/A	
Single slope	Hybrid nanofluid (Al_2O_3 + CuO), summer	27.20	49.54	5.12	N/A	57
Active systems						
ETC-assisted still	CuO/Al_2O_3/ZnO nanofluids + ETC	67.00	N/A	N/A	N/A	48
Single slope	CuO nanofluid (1.5%) + vibration generator + cover cooling + PV	138.00	54.00	N/A	0.027653 $ per L	49
Single slope	(Al_2O_3/CuO) hybrid nanofluid (0.025%) + PV panel + preheating saline water	10.00	54.61	15.30	0.0177 $ per L	50
Pyramid	CuO + GO hybrid nanofluid (25 : 75) + solar heater	127.46	N/A	N/A	0.015 $ per L	51
Pyramid	Al_2O_3–CuO hybrid nanofluid + PCM	6–7.4 (*vs.* nanofluid-only)	N/A	N/A	N/A	52
Single slope	0.08% Cu_2O nanofluid + external thermoelectric condensing channel	82.40	81.5 (enh.)	92.6 (enh.)	0.021 $ per L per m^2	53
Single slope	0.08% Cu_2O nanofluid + external thermoelectric condensing galvanized channel	81.00	80.6 (enh.)	112.5 (enh.)	0.0218 $ per L per m^2	54
Double slope	Simultaneous TEC cooling/heating with an Al_2O_3 nanofluid	11.57	N/A	N/A	0.098 $ per L per m^2	55
Double slope	Simultaneous TEC cooling/heating with a TiO_2 nanofluid	6.32	N/A	N/A	N/A	

Table 1 (*continued*)

SS type	Modification	Productivity enhancement (%)	Energy efficiency (%)	Exergy efficiency (%)	Cost	Ref.
Double slope	Simultaneous TEC cooling/heating with a CuO nanofluid	7.16	N/A	N/A	N/A	
Double slope	Simultaneous TEC cooling/heating with MWCNTs	4.66	N/A	N/A	N/A	
Double slope	Solar-operated vacuum fan + water-cooled condenser + 0.1% VF CuO NPs	96.43	42.71	6.89	N/A	56
Double slope	Solar-operated vacuum fan + water-cooled condenser + 0.1% VF Al_2O_3 NPs	82.14	41.67	6.28	N/A	
Double slope	Solar-operated vacuum fan + water-cooled condenser + 0.1% VF ZnO NPs	75.00	39.11	5.68	N/A	
Hemispherical	PCM + CuO–water nanofluid	80.20	63.61	4.26	75% cost reduction	20

The coated SS collected the most freshwater, with a volume of 70 ml at noon and a depth of 3 cm, whereas the traditional only collected 50 ml. At a depth of 5 cm, the coated SS gathered 80 ml of freshwater, while the traditional SS only collected 50 ml. At a depth of 7 cm, the values changed to 74 ml and 47 ml at midday, respectively. Thakur *et al.*[59] investigated the efficiency of solar desalination by doping black paint used in basins with various nanomaterials, including reduced graphene oxide (RGO), copper oxide, and titanium dioxide. The RGO-coated SS possessed the highest heat transfer coefficient due to its superior solar absorption behavior and increased thermal conductivity, producing an hourly freshwater yield of 0.88 L, CuO NPs produced 0.84 L, and TiO_2 NPs produced 0.77 L compared to a conventional SS, which produced only 0.7 L. Kabeel *et al.*[60] showed the influence of adding cuprous oxide NPs with various concentrations (10% and 40%) to the black coating on the productivity of SSs. CuO NPs were shown to increase the distilled water by 25% and 16% at weight fraction concentrations of 40% and 10%, respectively, in contrast to the classical SS.

Arunkumar *et al.*[61] examined the influence of using a CuO nano-coated absorber plate (NCAP) on the single slope SS performance compared to MoO_3 and ZnO NCAPs. They synthesized CuO NCAPs using thermal evaporation while MoO_3 and ZnO NCAPs were fabricated by a sputtering technique. The results show that the conventional single slope SS, ZnO, MoO_3, and CuO NCAPs in SSs produce 2.1, 2.6, 2.7, and 2.9 L m^{-2}, demonstrating the significant impact of CuO NPs in a single slope SS. Also, Arunkumar *et al.*[62] assessed a single-slope solar still modified using a CuO nanocoated absorber plate and PVA sponges under four distinct operating conditions. The highest efficiency, 53%, was achieved when only the CuO nanocoating was applied, yielding a daily productivity of 2995 ml m^{-2} day^{-1}. In contrast, the configuration incorporating both the CuO coating and PVA sponges reached an efficiency of 41% with a water yield of 2318 ml m^{-2} day^{-1}. The conventional SS exhibited an efficiency of 37% and produced 2144 ml m^{-2} day^{-1}, while the system containing only PVA sponges showed the lowest performance, with an efficiency of 32% and a productivity of 1970 ml m^{-2} day^{-1}. These outcomes confirm that the CuO nanocoating is the primary contributor to performance enhancement, whereas the inclusion of PVA sponges does not provide a beneficial effect.

Meena *et al.*[63] showed the absorption capacity of black paint used in a 3D pyramid SS by adding CuO, Al_2O_3, carbon powder, TiO_2 nano- and micro-powder, and activated carbon. All additives for the black paint cause a significant rise in the temperature of water, but CuO and activated carbon have the highest water temperature. As previously mentioned, adding copper oxide with different concentrations to the black paint in the absorber plate causes different results. Katekar *et al.*[64] determined the ideal type and amount of nanoparticles to add to a dull black absorber plate paint in order to improve the transfer of heat to water from the absorber. This investigation used mass percentages of 10, 20, 30, 40, and 50% for titanium dioxide, copper oxide, and aluminum oxide nanoparticles. The greatest average temperature in the open environment was 55.3 °C for the dull black paint containing 30% aluminum oxide nanoparticles and hence it shows the best efficiency for solar thermal devices.

Abdullah *et al.*[65] examined the influence of interior reflectors on the distillation execution of trays along with applying a black paint and CuO NP mixture to the SS's surfaces. They also used CuO NPs as an additive for a PCM and detected their effect. Under experimental conditions, freshwater output from the tray distiller was increased by 57% with reflectors, 14% with CuO nanoparticles in paint, 70.7% when reflectors were combined with a nano-coating, and 108% when reflectors, nano-coating, and PCM containing CuO nanoparticles were applied together. Additionally, the traditional and tray SSs gathered 2.4 and 5.0 L m^{-2} of freshwater every day, respectively. Additionally, the tray SS with a coating, reflectors and a PCM–CuO NP mixture attained a 51.5% thermal efficiency. Benghanem *et al.*[66] investigated the impact of employing unique cylindrical fins wrapped in bamboo-cotton fabric covered in black and treated with CuO-NPs. The findings showed that the modified still produced the highest daily yield of approximately 9.64 kg m^{-2} day^{-1}, which was 106.55% more than that of the traditional still. Furthermore, \$0.009 L^{-1} was the lowest manufacturing cost. The modified device produced the highest energy and exergy efficiencies, which were around 119.36 and 5.15%, respectively. Additionally, the modified distillation equipment produced maximum increases in payback time and carbon credit of almost 76.11% and 99.01%, respectively. Attia *et al.*[67] investigated the addition of CuO NPs to tubes filled with sponge in a HSS and studied the efficiency of the SS before and after adding CuO NPs. The first was the CHSS, the second was the modified SS (HSS-HCP) incorporated with honeycomb-shaped copper tubes, and the third SS (HSS-HCP&BS@CuO) incorporates additional CuO-NP-coated sponges. In comparison to the CHSS, the results showed that employing HSS-HCP&BS@CuO and HSS-HCP significantly increased daily production by 63.46% and 42.83%, respectively. Interestingly, HSS-HCP&BS@CuO containing CuO-NPs performed 14.5% better than HSS-HCP. For the economic aspects, the distillate product costs were cut by 56.41% and 35.56%, respectively. For the suggested HSS-HCP, the energy payback time decreased by 33.29% and 24.02%, respectively. Each year, the systems lowered their CO_2 emissions by 4.19 and 3.77 tons, respectively. Attia *et al.*[68] used CuO NPs as a coating to float plastic tubes in a HSS. The suggested adjustment seeks to enhance heat dispersion, boost solar absorption, and lower water surface tension, which speed up the evaporation process. They also studied three modified designs as well as a CHSS with tubes floating at 3/4, 1/2, and 1/4 of their height above the basin water level. According to the results, all modified designs outperformed the CHSS in terms of thermal performance. The HSS with a 1/4 floating tube system performed the best, increasing freshwater production by 63.26%, thermal efficiency by 65.22%, and exergy efficiency by 149.74%. Additionally, this arrangement lowered the cost of producing freshwater by 50.13%, illustrating how deeper tube immersion reduces surface tension and enhances heat transmission to the water.

Omara *et al.*[69] used convex cylinder absorbers (CCPSS) and dish-shaped absorbers (CDPSS) as alternatives to flat absorbers and applied a paint mixed with different nanomaterials (Ag, CuO, and TiO_2 NPs). Ag showed the maximum productivity of CDPSS; CuO and TiO_2 came next. The accumulated daily output of the CDPSS with Ag and jute was 6.75 L m^{-2} day^{-1}, while that of the PSS was 3800 mL m^{-2} day^{-1}. Additionally, the CDPSS without nanoparticles exhibited a CO_2 mitigation rate of about 10.17 tons per year, whereas the use of TiO_2, CuO, and Ag nanoparticles increased the mitigation to approximately 12.5, 12.7, and 13.5 tons per year, respectively. Alawee *et al.*[70] improved the performance of a pyramid SS by placing a parallel plate three centimeters above the base. There were thirty-five surface cracks on this plate in the modified cord pyramid SS. Like the study of Omara *et al.*,[69] the same three kinds of nanoparticles TiO_2, CuO, and Ag, were also mixed with black paint as a basin side coating. The production was 176% higher for the SS with Ag than that for a conventional SS, and the energy efficiency was 60.4%, according to the results. The SS with Ag showed an annual emission reduction of 28.71 tons of CO_2.

4.2. Active systems

In this subsection, the impact of adding external devices with nanocoating application to the SS is investigated. Kandeal *et al.*[71] examined three configurations of a tubular SS for the integration of different additives. An air-based solar collector with evacuated tubes and a V-corrugated basin was combined in case I. The basin surface in case II was then coated with a CuO nanocoating using the same attachments to improve heat absorption. Lastly, all the earlier enhancers were present when the CuO NF was utilized in case III as shown in Fig. 4(a). In comparison to a conventional tubular SS, a notable yield improvement of up to 49.84% (case I), 57.14% (case II), and 79.88% (case III) was achieved. Case III demonstrated an astounding 242.45% increase in exergy efficiency and an excellent 83.69% improvement in energy efficiency due to the addition of nanofluid. Selimefendigil *et al.*[72] examined the effects of using CuO NPs in both thermal storage and coatings on the performance of a single-slope SS. Four distinct SSs were developed, manufactured, and empirically tested: a conventional SS, an SS with a thermal storage unit, an SS with a latent heat storage unit embedded with CuO nanoparticles, and an SS with a thermal storage unit combined with a CuO nano-enhanced absorber coating. When the combined modifications were applied, exergy and energy efficiency values escalated from 1.25% to 2.01% and from 15.96% to 19.90%, respectively. Additionally, the output of the altered SS improved by 26.77% compared to the traditional SS, demonstrating significant enhancements in performance due to the integration of nanomaterials and thermal storage components.

This literature explored the application of CuO as a coating material, particularly when integrated with black paint on wall surfaces. The studies focused on evaluating the effectiveness of CuO nanofluids and nano-enhanced coatings in improving surface properties and functionalities. Additionally, the impact of incorporating external devices with CuO nanocoatings has been examined to assess potential enhancements in performance. Table 2 consolidates the findings from various experiments, offering clearer insights into the benefits and limitations of using CuO nanomaterials in coating applications. These investigations aim to advance understanding of the nanotechnology's role in surface modification, emphasizing durability, thermal properties, and potential antimicrobial effects of CuO-based coatings.

5. Copper oxide with phase change materials (NanoPCM)

While the previous sections addressed the application of copper oxide nanoparticles (CuO NPs) as a nanofluid and an absorber surface nanocoating, the integration of CuO NPs as an additive within phase change materials (PCMs) represents an additional and highly effective enhancement strategy for SS desalination systems. In this approach, CuO NPs are incorporated into PCMs to improve thermal conductivity, modify melting and solidification temperatures, and enhance heat storage and release characteristics. As a result, nano-enhanced PCMs (NanoPCMs) enable extended operation of SSs during low-irradiance periods and after sunset, leading to improved freshwater productivity and overall system efficiency. This section systematically reviews experimental and theoretical studies that evaluate the performance of CuO-enhanced PCMs in both passive and active SS configurations and compares their effectiveness

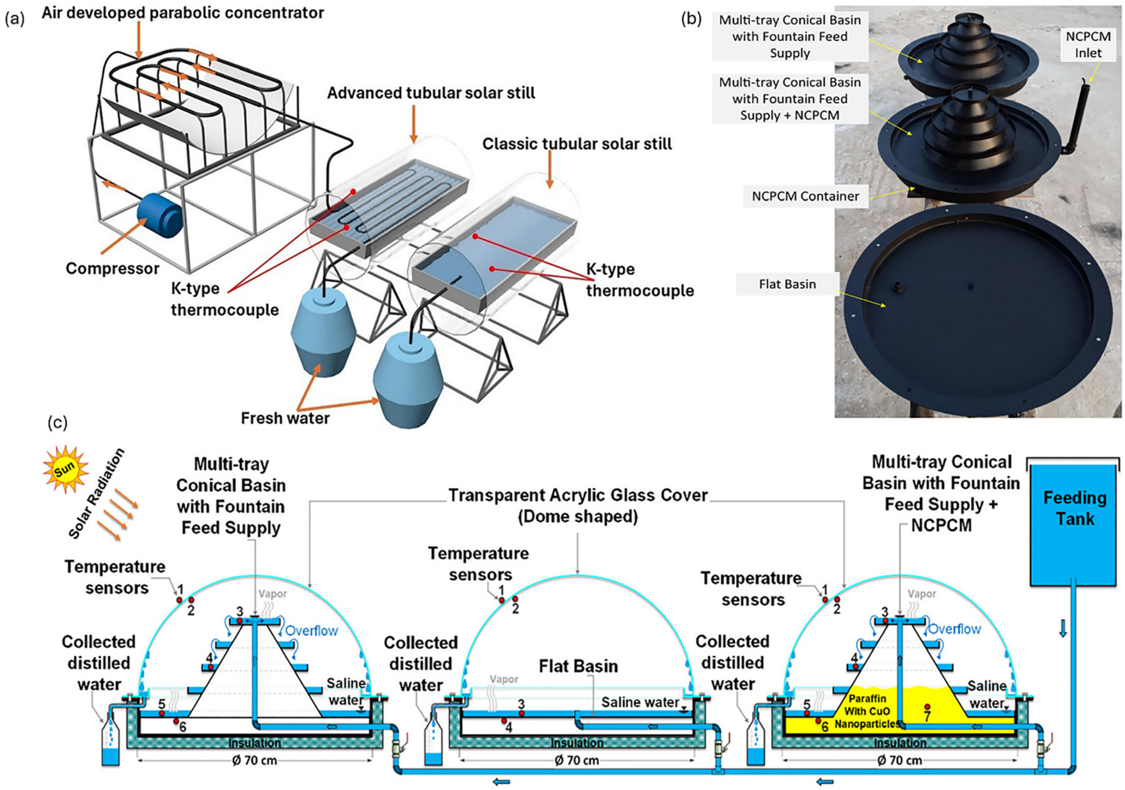

Fig. 4 (a) Representation diagram of a tubular SS with an air PTC. Reproduced with permission[71] Copyright 2024, Elsevier, (b) the various shapes of the basin and (c) the experimental setup test ring. Reproduced with permission.[75] Copyright 2024, Elsevier.

Table 2 Comparison of using copper oxide as a nanocoating in SSs, including the type of SS, modifications, productivity enhancement, energy efficiency, exergy efficiency, and cost

SS type	Modification	Productivity enhancement (%)	Energy efficiency (%)	Exergy efficiency (%)	Cost	Ref.
Single slope	30 wt% CuO-coated floated absorber + CuO-coated basin walls, 5 cm water depth	71.00	N/A	N/A	N/A	58
Single slope	CuO nanoparticle-doped black paint coated absorber (5 wt%), max hourly yield basis	20.00	N/A	N/A	N/A	59
Single slope	CuO nanoparticles mixed with black paint on still walls, 10 wt%	16.00	N/A	N/A	Payback: 96 days	60
Single slope	CuO nanoparticles mixed with black paint on still walls, 40 wt%	25.00	N/A	N/A	N/A	
Single slope	ZnO NCAPs	N/A	28.90	N/A	0.0085 $ per L	61
Single slope	MoO_3 NCAPs	N/A	30.50	N/A	0.0085 $ per L	
Single slope	CuO NCAPs	38.10	32.10	N/A	0.0080 $ per L	
Single slope	CuO–NCAP–PVA sponges	28.40	41.00	N/A	N/A	62
Trays	Reflectors + nano-coating + PCM with CuO NPs	108.00	51.50	N/A	N/A	65
Hemispherical	Cylindrical fins wrapped with bamboo-cotton wick impregnated with CuO-NPs, 3 cm spacing (MCSD-SF3&W3)	106.55	119.36	5.15	0.009 $ per L	66
Hemispherical	Honeycomb copper tubes + black sponges coated with CuO-NPs (HSS-HCP&BS@CuO)	63.46	77.05	4.38	0.039 $ per L	67
Hemispherical	Floating plastic pipes coated with CuO nanoparticles, 1/4 tube height above water (HSS&1/4FPP)	63.26	78.11	17.68	0.0028 $ per L	68
Tubular	Air PTC with evacuated tubes + V-corrugated basin + CuO nanocoating + CuO nanofluid	79.88	83.69 (improvement)	242.45 (improvement)	0.032 $ per L	71
Single slope	Combined use of CuO NPs in the PCM and absorber coating	26.77	19.90	2.01	N/A	72

with other nano-additives. Incorporation of CuO nanoparticles into phase change materials alters the thermal characteristics of PCMs in multiples of a correlation effect. Due to their good thermal conductivity, CuO nanoparticles are capable of enhancing heat diffusion in the PCM, increasing the speed of charging and discharging, and minimizing the thermal resistance of the melting and solidification processes. This results in quicker heat storage during daytime operations and heat release when the radiation is low and after the sun has set. Meanwhile, the introduction of CuO NPs can possibly change the observed melting-solidification properties and enhance temperature homogeneity in the storage medium. Nevertheless, these advantages have a significant trade-off, namely, the higher the nanoparticle loading, the smaller can be the latent heat storage capacity of the composite PCM, as the volume of a solid PCM can be substituted by solid nanoparticles. Thus the performance improvement of CuO–NanoPCM is determined by striking a balance between high thermal conductivity and maintaining adequate latent heat capacity and therefore nanoparticle concentration is a critical design value in solar still thermal storage.

5.1. Passive systems

Vijayaraghavan *et al.*[73] employed CuO NPs as a medium for energy storage in an experimental investigation to increase the effectiveness of a pyramid SS. The main goal was to enhance thermal energy absorption and storage by incorporating CuO NPs into the PCM in an effort to improve the output of water and hence enhance the system efficiency. The modified pyramid SS achieves the highest water temperature of 72 °C, while the traditional pyramid SS achieves 61.5 °C; this increase in water temperature causes an enhancement in the distilled water output by 89.19%. Kumaravel *et al.*[74] studied three types of stills: PCM, copper plates, and a mixture of PCM and three percent weight of CuO NPs. The study demonstrated how adding 3 weight percent of CuO NPs to a PCM in a copper plate-attached SS greatly increased distillate production, reaching roughly 6.85 kg m^{-2} day^{-1}. This reflected an increase of roughly 23.42% over the still with a PCM and a copper plate and 69.14% over the conventional SS. In order to improve the evaporation and exposure areas, Hammad *et al.*[75] employed a new design of a stepped conical basin in a dome-shaped SS with many trays rather than the conventional flat basin SSs as shown in Fig. 4(b). To extend the distiller's nighttime yield, a PCM enhanced with CuO NPs was also placed within the hollow multiple-tray inside the stepped conical basin and compared to the baseline dome SS as shown in Fig. 4(c). The findings demonstrated that the daily output of the modified SS with a PCM was 7.21 kg day^{-1} m^{-2} and 6.84 kg day^{-1} m^{-2} for the SS without a PCM. The exergy and energy efficiencies of the SS with a PCM were found to be 4.16 and 62.42%, respectively, while the cost was reduced by 18.48% compared to the traditional SS.

Patel *et al.*[76] studied the effectiveness of CuO NPs along with other nanomaterials used in a PCM (including paraffin wax and fatty acid). For performance investigation, the traditional single slope SS (TSSS) was mixed with various nanoparticles (TSSS + nanoparticles) and (TSSS + PCM), as well as their combination (TSSS + nanoparticle + PCM). In comparison to the TSSS, which produced 3.15 L m^{-2} day^{-1}, the best production was achieved in the case of TSSS + paraffin wax + TiO_2 + GO + Al_2O_3, which produced 5.21 L m^{-2} day^{-1}, boosting the daily output by 65%. When replacing paraffin wax with fatty acids with the same experiment, the daily output is 5.09 L m^{-2} day^{-1}, leading to a 61% increase in productivity. According to Gupta and Kumar,[77] CuO and TiO_2 NPs were combined with PCMs $CH_3(CH_2)_{16}COOH$, $C_{31}H_{64}$, and $CH_3(CH_2)_{10}COOH$ and used in an SS connected to a solar heater for water heating. When compared to a simple SS, the new system attained better results, such as 25.23% efficiency for stearic acid, 40.12% efficiency for paraffin wax, and 36.81% efficiency for lauric acid. When PCMs like stearic acid, paraffin wax, and lauric acid were used, productivity increased also by 25.23%, 40.18%, and 36.61%, respectively. Ajdari and Ameri[78] used CuO NPs and GO NPs and their nanocomposite as nanoadditives into paraffin wax as PCMs within an inclined stepped SS. According to the findings, the freshwater production was enhanced by 81.59% and 48.12%, respectively, by 0.03% weight GO and CuO. Distilled water volume was raised by 81.59% using a nanocomposite with a VF of 30/70 for CuO/GO.

To enhance the rate of heat transfer, improve the solar rays that fall on the water basin and prolong the operation for a few hours after sunset within a stepped SS, Abdelgaied *et al.*[79] performed experimental research aimed at attaining the maximum efficiency of a stepped SS by utilizing three successful hybrid design modifications: PCMs beneath the steps, internal mirrors, and an absorber surface covered with CuO NPs. Their result demonstrated that the modified stepped SS produced 9.79 L m^{-2} day^{-1}, while the classical SS produced 4.15 L m^{-2} day^{-1}, achieving a 135.9% enhancement in the production of freshwater, with daily energy and exergetic efficiencies of the modified SS being 78.8% and 7.96%. According to Sonker *et al.*,[80] CuO NPs were mixed with paraffin and kept in a copper tube to improve the solar distillation unit's thermal conductivity and boost its daily output. A simple SS (SSS), an SS with a PCM (SSPCM), and an SS with a PCM doped with nanoparticles (SSNPCM) all were compared through experiments. The thermophysical characteristics of the SSPCM undergo a paradigm shift due to the mixing of NPs. For the SSNPCM, both the greatest and average temperatures for the water basin and NPCM were considerably improved. In comparison to the SSS, the daily production of the SSNPCM and the SSPCM was grown by 94.19% and 40.5%, respectively. Rufuss *et al.*[81] used three types of NPs as additives for a PCM in a single slope SS. The experiment was performed using the following systems: PCM SS, PCM–CuO SS, PCM–GO SS, and PCM–TiO_2 SS. The findings demonstrate that regardless of the type of NP used, the PCM was shown to possess lower solidifying and melting temperatures and greater heat conductivity compared to the nanoparticle-free PCM. The results also demonstrated that the PCM–CuO SS attained the maximum output of 5.28 l m^{-2} day^{-1}, while the PCM–GO SS, PCM–TiO_2SS and PCM SS produced 3.66 l, 4.94, 3.92, and 3.66 l m^{-2} day^{-1}, respectively. Singh and Kumar[82] investigated the thermo-economic performance of a single-slope SS modified with a PCM enhanced with CuO/TiO_2 NPs. Different weight contents (1–6) of NPs (CuO/TiO_2) and PCMs were examined. PCM-3 has the largest yield of 3.26 l m^{-2} day^{-1}. When compared to the absence of PCM, it represents a 100.89% improvement. A payback period of 129 days and a water cost of \$0.012 per liter were obtained alongside 10.67% exergy efficiency and 46.23% energy efficiency, while the evaporation heat transfer coefficient ranged from 26.79 to 14.74 W m^{-2} K^{-1} at an optimal nanomaterial loading of 1.5%.

Shoeibi *et al.*[16] used porous media, a nano-enhanced PCM, and a nanocoating to improve solar desalination performance. The productivity of the SS was enhanced by 55.8% when paraffin wax was combined with CuO and Al_2O_3 nanoparticles at a concentration of 0.3 wt% and injected into twelve copper pipes placed over anthracite. In comparison, applying CuO nanoparticles mixed with black paint as a coating on the copper pipes resulted in a 49.5% increase in output. In this approach, nanoparticle loadings of 0.1 and 0.3 wt% were examined to improve the thermal behavior of the phase change material. According to Behura and Gupta,[83] incorporating nanoparticles into a PCM used in an SS can shorten PCM's charging and discharging times. SS experiments were conducted using varying weight fractions of nanoparticles (0.1, 0.2, and 0.3%) in paraffin wax. Among these three weight fractions, productivity was higher, around 510 ml/0.25 m^2 day^{-1}, for 0.3% concentration of CuO NPs. Rufuss *et al.*[84] focused on the theoretical examination of latent thermal energy storage using nanoparticles. In this study, paraffin wax containing 0.3 weight percent of NPs such as TiO_2, CuO, and GO is chosen as an additive for the PCM. Graphene oxide combined with paraffin is shown to produce better results than other nanoparticles. Essa *et al.*[85] enhanced the efficiency of a stepped SS by using a corrugated liner, applying vapor suction, and using a wick and PCM enhanced with CuO NPs. CuO/paraffin was inserted into a groove that extended parallel to the liner of the basin steps. The daily productivity of freshwater from a modified SS and a classical SS was found to be 7 and 2.6 L m^{-2} day^{-1}, and the thermal efficiency attained 35% and 59%, respectively. The price of water yield decreased from 0.023 to 0.014 \$ per L. To enhance the performance of the tray SS, an experimental study was performed by incorporating internal reflectors, wick materials, and 3 heaters along with the PCM doped with CuO NPs, which enhanced the productivity by 196% and achieved a thermal energy of 63%, according to Abdullah *et al.*[86] Younes *et al.*[87] showed that finned discs are superior for SS performance in contrast to corrugated and flat discs. For further enhancement, a PCM such as paraffin wax mixed with copper oxide NPs is used, which increases the productivity by 149% compared to a conventional SS. For further augmentation, exterior reflectors are also used along with PCM + CuO NPs + finned discs, causing a 184% improvement compared to a conventional SS. For the final modification, the thermal energy efficiency reached 51.3%, and the cost of produced freshwater per liter was reduced to \$0.014. Khanmohammadi *et al.*[88] introduced various nanomaterials within a PCM (paraffin wax): PCM + CuO, PCM + TiO_2, and PCM + GO and applied different brackish water mass flow rates to a weir-style cascade SS. The best results were observed at a flow rate of 0.07 kg (m^{-2} min^{-1}) for the PCM + CuO NP SS, which produced 9.28 kg m^{-2} h^{-1} and achieved exergy and energy efficiencies of 63.55% and 6.4181%, respectively.

5.2. Active systems

In this subsection, the impact of adding external devices with nano-enhanced PCM application to the SS is investigated. Abdelgaied *et al.*[20] studied the dual use of CuO NPs as a nanofluid and PCM enhancer within the HSS. In the first instance, 0.3 weight percent CuO NPs were dispersed in water; secondly, the pure PCM was integrated beneath the basin; and thirdly, they combined the CuO-enhanced PCM beneath the basin and CuO nanofluid (CuO NPs–PCM + CuO/water NF). These modifications in the third case increase the productivity and energy by 60.41% and 79.08% respectively and reduce the cost by 75% compared to the traditional HSS, which provides superior performance for the modified SS. Selimefendigil *et al.*[72] applied the same procedure of Abdelgaied *et al.*[20] but on a single slope SS, not on a HSS. According to experimental findings, the combined use of NPs increased accumulated production by 26.77% as compared to a traditional SS. Additionally, the combined adjustment also improved exergy and energy efficiency values from 1.25 to 2.01% and 15.96 to 19.90%, respectively.

Bamasag *et al.*[89] suggested the usage of a convex dish absorber with a circular stepping surface with wick, which was utilized as a wetting substance for assisting the vaporization process within the SS. Additionally, the impact of varying water levels was examined. Lastly, the area underneath the absorber was packed with a PCM comprising paraffin wax combined with CuO NPs. At 1.50 cm with all these modifications, the conductivity increased by 178% compared to the conventional SS, and the thermal efficiency reached 67.62%. Abdullah *et al.*[90] investigated the impact of various tray SSs, including a flat tray SS (FTSS), a corrugated tray SS (CTSS), and a conventional SS. The wick facilitates the gradual upward movement of feed water through the porous material, and this wick material has been used to cover the corrugated tray, which yields superior results compared to flat trays. The PCM combined with CuO NPs has been utilized for testing the CTSS in order to further improve the performance of tray SSs. The water was also heated using three electric heaters. Using electrical heaters, the PCM mixed with CuO NPs, and corrugated absorbers increased the CTSS's overall water production by 180% in comparison to the baseline SS. Dawood *et al.*[91] combined an under-basin PCM with a heat exchanger serpentine and a PTC. Water, oil, and nano-oil (mineral oil with 3% CuO by volume concentration) were the working fluids in the proposed SS that flowed within the PTC and the heat exchanger at various flow rates. The results show that nano-oil (mineral oil with 3% CuO) at a flow rate of 0.5 L min^{-1} shows the best performance, achieving an efficiency of 34% and a productivity of 11.14 L m^{-2} day^{-1}.

The current literature focus extends to examining the effects of incorporating CuO nanofluids and CuO nanocoatings, in addition to CuO nano-enhanced PCMs. Furthermore, the influence of integrating external devices with nano-enhanced PCMs

Table 3 Comparison of using copper oxide as an additive for a PCM in an SS, including SS type, modifications, productivity enhancement, energy efficiency, exergy efficiency, and cost

SS type	Modification	Productivity enhancement	Energy efficiency	Exergy efficiency	Cost	Ref.
Pyramid	CuO–paraffin wax PCM blend as an energy storage material	89.19%	N/A	N/A	N/A	73
Conventional/single slope	3 wt% CuO NPs combined with a PCM and a copper plate	69.14%	74.23%	9.75%	$0.03 per kg	74
Dome-shaped	DSSD-FFS + NanoPCM	62.38%	62.42%	4.16%	18.48% reduction	75
Single slope	Paraffin wax + TiO_2 + GO + Al_2O_3 NPs	65.00%	55.20%	2.50%	₹1.51 per L	76
Inclined stepped	0.03 wt% CuO NPs in brine	48.12%	N/A	N/A	N/A	78
Inclined stepped	0.03 wt% GO NPs in brine	81.59%	N/A	N/A	N/A	
Inclined stepped	0.03 wt% CuO/GO nanocomposite in brine	53.85–69.04%	N/A	N/A	N/A	
Inclined stepped	Best CuO/GO nanocomposite case + paraffin wax PCM under the steps	32.80%	N/A	N/A	N/A	
Inclined stepped	CuO-coated absorber surface + internal mirrors + PCMs beneath steps	135.90%	78.80%	7.96%	N/A	79
Single slope	CuO NPs mixed with paraffin wax PCM and stored in copper cylinders	94.19%	N/A	N/A	N/A	80
Single slope	CuO NPs + PCM	43.20%	N/A	N/A	0.026 per L	81
Single slope	TiO_2 NPs + PCM	39.27%	N/A	N/A	$0.028 per L	
Single slope	GO NPs + PCM	18.03%	N/A	N/A	$0.13 per L	
Single slope	CuO/TiO_2 + PCM	100.89%	46.23%	10.67%	$0.012 per L	82
Pyramid	CuO–PCM + CuO nanocoating on pipes containing CuO–PCM	55.80%	17.41%	N/A	$0.013 per L	16
Pyramid	Al_2O_3–PCM + CuO nanocoating on pipes containing Al_2O_3–PCM	49.50%	16.70%	N/A	$0.013 per L	
Single slope	Different CuO-NP concentrations added to paraffin wax (0.1, 0.2, 0.3%)	62.74%	N/A	N/A	N/A	83
Stepped	Corrugated liner + wick + CuO/paraffin wax + vapor suction	170.00%	59.00%	N/A	$0.014 per L	85
Rotating discs	PCM + CuO NPs + finned discs + external reflectors	184.00%	51.30%	N/A	$0.014 per L	87
Weir-type cascade	CuO NPs + PCM (paraffin wax), mass flow rate 0.07 kg (m^{-2} min^{-1})	9.28 kg (m^{-2} h^{-1})	63.55%	6.4181%	N/A	88
Hemispherical	Dual use of CuO NPs with PCM and CuO-NP absorber coating	80.20%	63.61%	N/A	75% reduction *vs.* baseline	20
Single slope	Dual use of CuO NPs with PCM and CuO-NP absorber coating	26.77%	19.90%	2.01%	N/A	72
Stepped dish	Wick + paraffin-wax PCM mixed with CuO NPs	178.00%	67.62%	N/A	$0.01 per L	89
Trays	PCM with CuO NPs + 3 electric heaters + PV panel + jute wick + reflecting mirrors	196.00%	63.00%	N/A	N/A	86
Trays	PCM enhanced with CuO + PV module + heater	180.00%	57.00%	N/A	$0.025 per L	90
Single slope	Mineral oil with 3% CuO + PTC + serpentine heat exchanger	250.00%	34.00%	N/A	$0.0154 per L	91

is also analyzed. To facilitate a clearer understanding of these studies, Table 3 summarizes the key results, highlighting the comparative impacts and potential advantages of each modification. This systematic overview aims to provide a detailed insight into how nanotechnology can optimize thermal energy storage systems, improve efficiency, and expand application possibilities in various industries.

6. Summary and comparison

The current review systematically discussed the use of copper oxide nanoparticles in solar driven SS desalination systems, with a focus on three main enhancement strategies: nanofluids, absorber surface nanocoatings and nano-enhanced phase change materials (NanoPCMs). The collated experimental, numerical and theoretical investigations consistently show that CuO NPs play a multifunctional role in enhancing heat transfer, solar radiation absorption, thermal storage and evaporation–condensation processes, which in turn results in significant enhancement of freshwater productivity and overall system efficiency.

When used as nanofluids, CuO NPs increase the thermal conductivity and absorptivity of basin water, leading to high water temperature and high evaporation rates. Comparative analyses between passive and active configurations have shown that CuO nanofluids generally outperform many other metal oxide nanofluids (*e.g.* ZnO, TiO_2, and Fe_2O_3) in terms of productivity enhancement; however, optimal performance is strongly dependent on nanoparticle concentration, water depth, basin geometry and climatic conditions. Hybrid nanofluids and CuO-based nanocomposites expand these advantages, particularly for active systems with external condensers, cover cooling or auxiliary heating devices.

Regarding CuO-based absorber coatings, the addition of CuO NPs in black paint or nano-coating of absorber plates is found to significantly enhance solar absorptivity and to decrease thermal losses from the basin. Compared to nanofluid approaches, the use of nanocoatings provides a more stable and maintenance-free enhancement strategy because they eliminate problems associated with nanoparticle sedimentation and long-term fluid stability. The reviewed studies show that the use of CuO nanocoatings is an effective way to enhance basin temperature, evaporation intensity, and daily freshwater yield, especially when in combination with advanced absorber geometries, fins, wicks, or reflectors.

The addition of CuO NPs into phase change materials (NanoPCMs) offers an additional mechanism by increasing the thermal energy storage capacity and extending the duration of heat release. CuO-enriched PCMs offer the benefits of enhanced thermal conductivity, reduced charging/discharging time, and SS operation beyond sunset to overcome the inherent intermittency of solar desalination. Comparative results indicate that the productivity losses during nighttime and the overall daily efficiency of NanoPCM-based systems are generally lower than those of systems based only on nanofluids or coatings.

The CuO-specific contribution is more clearly observed in comparative studies, such as ref. 23, where CuO nanoparticles produced 5.28–6.75 L m^{-2} day^{-1} compared with 4.38–5.43 L m^{-2} day^{-1} for CuO microparticles and 2.98 L m^{-2} day^{-1} for the conventional still, and[25] where the CuO nanofluid achieved 2025 mL day^{-1} compared with 1590 mL day^{-1} for ZnO and 1430 mL day^{-1} without a nanofluid. By contrast, in integrated configurations, as reported in ref. 65, productivity increased by 57% with reflectors alone, 14% with the CuO nano-coating alone, 70.7% with reflectors plus nano-coating, and 108% with reflectors, nano-coating, and CuO-enhanced PCM together; the observed gain should be interpreted as the cumulative effect of both CuO and the accompanying modifications.

A detailed comparison of these three enhancement strategies, summarized in Tables 1–3, shows that the best performance improvements are obtained using hybrid configurations, especially those that use CuO nanofluids, CuO nanocoatings, and CuO enhanced PCMs in the same system. The results of such integrated methods demonstrate higher productivity improvements, enhanced energy and exergy efficiencies, and decrease in cost per liter of distilled water significantly. However, material cost, operational stability and complexity of the system must be taken into consideration during the selection of the most appropriate strategy of enhancement. Fig. 5 shows a schematic comparison of the three CuO integration strategies for solar stills.

Altogether, the comparative analysis proves the high versatility and the high efficiency of CuO nanoparticles in the context of the SS performance enhancement, where the role and impact of nanoparticles lie in the modes of integration and system organization. This synthesis gives a clear foundation on the identification of optimal configurations on the basis of CuO and will facilitate informed decision making on the development of the solar desalination systems in the future.

7. Research gaps and current limitations

Although the nanofluids of CuO, nanocoatings, and nano-enhanced phase change materials (NanoPCMs) have shown promising thermo-economic benefits in solar still (SS) systems, there are a number of critical research gaps that are still uncovered before these enhancement strategies can be regarded as mature enough to be practiced and implemented on a large scale. Although the reviewed studies exhibit consistent

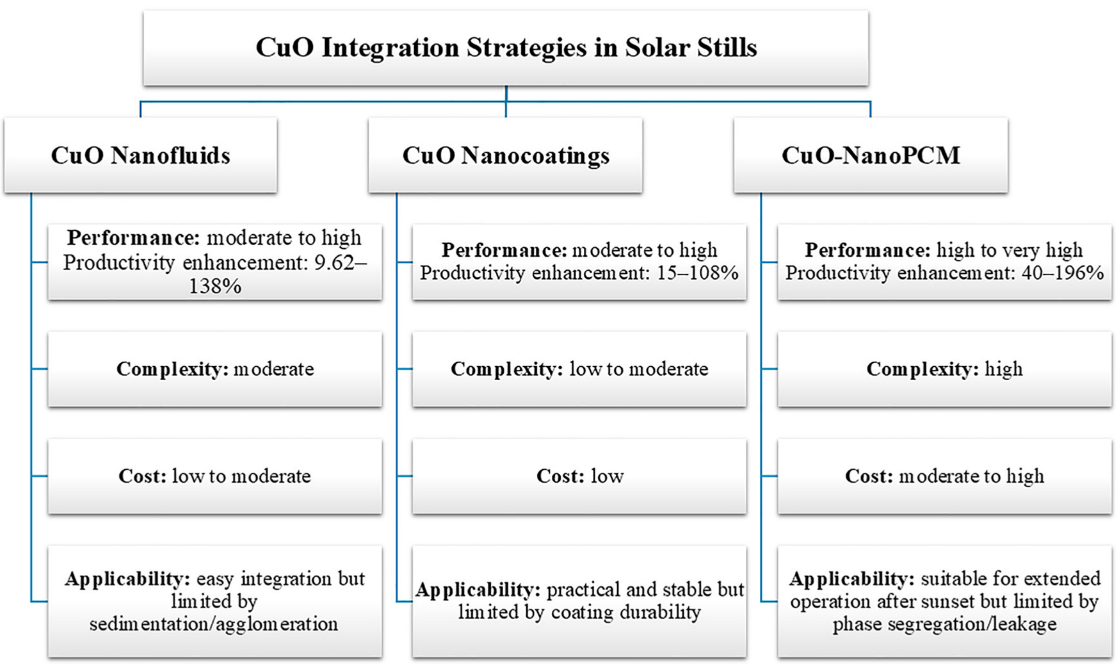

Fig. 5 Schematic comparison of the three CuO integration strategies in solar stills.

improvements in freshwater productivity, energy efficiency, and exergy efficiency, the current body of literature remains characterized by short-term, laboratory-scale investigations with limited standardization of methodology, limited mechanistic explanation, and limited long-term durability and environmental performance.

A key gap in the literature is the lack of a standard model for assessing and comparing CuO-based improvements across the various SS configurations. The studied articles evaluate the expression of the nanoparticle concentration in various ways, such as weight fraction, volume fraction, and fixed mass loading, so it is challenging to compare them directly. Besides this, the operating conditions of an individual study relative to another are highly different in regard to basin geometry, water depth, solar radiation intensity, climatic conditions, and test duration. In spite of the tendency of most studies to compare the modified still with a conventional still under the same local experimental conditions, which allows normalizing the relative improvement in each study, the cross-comparison between independent studies is not easy. It can thus be concluded that future research must use more standardized reporting guidelines in the loading of nanoparticles, thermophysical characterization, productivity, energy efficiency, exergy efficiency and cost analysis with the aim of enhancing the comparability and reproducibility of scientific studies using CuO nanoparticles.

A second gap is related to the lack of mechanistic knowledge of the way in which CuO nanoparticles enhance the performance of SSs. The majority of reviewed publications present general productivity and efficiency improvement, yet very few of them cover the relevant physical mechanisms in detail. Specifically, the contributions of improved optical absorption, increased thermal conductivity, decreased thermal resistance, and altered evaporation–condensation behavior are not well isolated in a majority of the cases. This weakness is more pronounced in hybrid nanofluids, where the performance improvements that have been observed are usually ascribed to the increased ability to absorb solar energy as well as to synergistic thermal processes, but rarely has the contribution of each effect been quantified. Indicatively, hybrid CuO/Al_2O_3 and GO–CuO nanofluids exhibited significant productivity improvement, yet the literature does not clearly differentiate between the optical effects, thermal transport improvement, or a combination of the two. Consequently, further experimental and numerical research ought to aim at isolating these coupled mechanisms and developing a more vivid structure–property–performance relationship.

The other significant gap in research relates to the characteristics of the CuO nanoparticles such as particle size, shape, morphology, and surface treatment. The existing reviews demonstrate that the existing literature on solar stills is indirectly evidence-based regarding the effect of the particle-size. As an illustration, ref. 23 revealed that nanoparticles of CuO yielded 5.28–6.75 L m^{-1} day^{-1} at room temperature, compared to 2.98 L m^{-1} day^{-1} in a conventional still, which is superior. But none of the systematic solar still studies, which have been identified, investigated the influence of the variation of nanoscale size, shape of particles, and surface functionalization on optical absorption, dispersion stability, agglomeration resistance, interfacial thermal resistance, and heat transfer performance. As these parameters are identified to have a strong effect on nanomaterial behavior, future research must systematically study them with the view to enhancing the mechanistic richness and design-inspiration of the CuO-based SS enhancement strategies.

Another important limitation is the long-term sustainability and durability of CuO-based enhancement techniques. A majority of studies are on the concept of short-term productivity improvement based on the controlled laboratory conditions, with the long-term operational reliability inadequately covered. With CuO nanofluids, agglomeration and sedimentation growth of nanoparticles, as well as stability changes with time duration, could decrease the thermal performance and optical changes. On the particle of CuO nanocoatings, the issues are raised on coating adhesion, surface loss, cracking, foul, erosion and repeated outdoor exposure at dust, humidity, saltiness and varying solar radiation levels. In analogous cases to CuO-based NanoPCMs, multiple melting-solidification steps can lead to phase separation, clustering of nanoparticles, leakage, decrease in the latent heat properties, or thermal conductivity decay. As these problems can be exacerbated during long-term operation, future research should include extended cyclic tests, outdoor test cases, and post-operational materials analysis to determine the stability of the CuO-based systems under realistic service cycles.

In addition to durability, the scalability of CuO nanocoating and NanoPCM technologies from laboratory prototypes to field-scale systems remains uncertain. The majority of the reviewed papers were conducted on small test units under controlled conditions, whereas real-field solar desalination units might be associated with large surface areas, changing weather conditions, dust deposition, biofouling, and maintenance limitations. The process of scaling up CuO nanocoatings might entail the maintenance of the same thickness of coating, good adhesion, and constant optical characteristics across extended absorber substrates, which can prove to be technologically difficult and expensive to do. Similarly, NanoPCM system scaling might need regular nanoparticles for uniform nanoparticle dispersion, leakage prevention measures, repeated thermal reliability and uniformity of the charging–discharging dynamics over larger thermal storage capacities. Thus, the next steps are to explore the techniques of large-area fabrication, the field durability, and the manufacturing feasibility to identify whether the advantages of the laboratory-scale can be preserved under the conditions of actual operations.

The other one is the economic assessment methodology applied in the literature. Most studies have given a report on the reduced cost per liter of distilled water, but the assumptions applied to the economic calculations do not always support each other. Some material prices, lifetime assumptions, replacement periods, maintenance costs, and nanoparticle preparation costs vary in different studies and this could result in the lack of comparability of the reported thermo-economic benefits. The same is true of exergy-based economic analysis where most research has compared modified and conventional systems in the same experimental setting, but the assumptions are not always balanced through the publications. Future studies will thus need to come up with more standardized techno-economic and exergo-economic evaluation procedures such as sensitivity analysis on the cost of nanoparticles, the lifespan of the system and its stability in operation and the maintenance needs of the field.

The environmental effects of the CuO based enhancements in the long term are also not well studied. Although CuO nanoparticles enhance the use of SSs, there is minimal literature on the environmental aspects related to the production, handling, leakage, disposal, or end-of-life of nanoparticles. In the case of nanofluids, the potential release of nanoparticles into the water streams or the surrounding soil can pose a problem to the environment unless the containment and disposal are done effectively. In the case of nanocoatings and NanoPCMs, release of nanoparticles may also occur due to the degradation of materials during service life or disposal. In addition, life-cycle assessment, ecotoxicological analysis or the environmental risk assessment of the CuO based SS systems is not frequently covered in the reviewed literature. This is the gap of particular importance to the technologies that are aimed at sustainable water production. Thus, the environmental life-cycle assessment, recycling and disposal, nanoparticle release analysis, and ecotoxicity research have to be incorporated into the work in the future under real operating conditions.

Finally, more studies on multi-parameter optimization should be integrated. The majority of the literature in the field are focused on single or two adjustments at a time, including, but not confined to, the concentration of the CuO nanofluids, the addition of a coating, or the incorporation of CuO into the PCM instead of giving a full optimization of the interactions between thermal storage, optical absorption, basin geometry, water depth, condenser design, and climatic variability. Whereas the hybrid configurations have been proved to show the best performance, the optimum gain of productivity, complexity, cost and reliability of operation of the systems have not yet been clearly determined. Subsequent research should thus utilize a combination of experimental and numerical and optimization designs to determine robust design windows for CuO-based solar stills under various environmental and operational conditions.

The literature review confirms that CuO nanoparticles have high potential as solar still desalination enhancers; nevertheless, numerous gaps remain in standardization, mechanistic explanation, nanoparticle engineering, modelling support, stability, scale-up, economic reliability, and long-term ecological safety. These gaps will also be critical to translating the promising lab results of CuO-based improvements into reliable, scalable, and sustainable real-world solar desalination technologies.

8. Conclusions and future directions

Overall, the reviewed literature confirms that copper oxide nanoparticles (CuO NPs) are highly effective and versatile enhancement media for SS desalination systems. When incorporated into nanofluids, absorber surface coatings, or nano-enhanced phase change materials, CuO NPs dramatically enhance solar energy absorption, heat transfer, thermal storage, and evaporation–condensation processes. The magnitude of performance enhancement depends on nanoparticle concentration, mode of integration, system geometry, and operating conditions; however, consistent performance improvements in freshwater productivity, thermal efficiency, and economic feasibility are reported for both passive and active SS configurations. The most pronounced improvements are obtained when CuO NPs are used in hybrid or combined enhancement approaches, which shows their high potential to overcome the inherent limitations of conventional SSs, especially low productivity and intermittent operation. Key findings are summarized as follows:

- CuO nanofluids increase freshwater productivity by 30–80% in passive SSs, with reported maximum enhancements exceeding 100% at optimized concentrations ($\approx$0.1–0.3 wt%); in active systems, productivity gains of 90–140% and daily yields of 6–7 L m^{-2} day^{-1} are commonly reported.
- The use of CuO nanofluids leads to thermal efficiency improvements of 30–65% and exergy efficiency values up to 4–6%, depending on system configuration and auxiliary enhancements.
- CuO-based absorber surface coatings typically enhance freshwater productivity by 15–70% in passive systems, while advanced geometries and hybrid coating designs have demonstrated productivity increases exceeding 100% and energy efficiency improvements up to 80%.
- CuO-enhanced phase change materials (NanoPCMs) improve PCM thermal conductivity by 150–180%, shorten charging–discharging times, and extend SS operation beyond sunset, resulting in productivity enhancements ranging from 40% to over 180%.
- SSs incorporating NanoPCMs have achieved daily freshwater yields above 9 L m^{-2} day^{-1}, with energy efficiencies of 78–80% and exergy efficiencies of 8–10%.
- Hybrid systems combining CuO nanofluids, nanocoatings, and NanoPCMs deliver the highest overall performance, with the highest reported results in the cited studies indicating productivity enhancements of 80–196% and reduction in water production costs of up to 75% compared to conventional SSs.

Recommendations for future work:

- Establish standardized testing and reporting protocols for CuO-based solar still studies, including nanoparticle concentration expression, thermophysical characterization, energy/exergy analysis, uncertainty analysis, repeatability testing, and cost evaluation.
- Conduct more mechanistic studies to distinguish the relative contributions of optical absorption, thermal conductivity enhancement, reduction in interfacial thermal resistance, and intensification of evaporation–condensation.
- Investigate the influence of CuO nanoparticle size, shape, morphology, and surface treatment, as these parameters

remain insufficiently addressed in the available solar still literature.

• Examine the effects of nanocoating thickness, surface roughness, and coating durability on solar absorptivity, thermal emissivity, and long-term performance.

• Optimize CuO–NanoPCM loading to balance improved thermal conductivity with possible reduction in latent heat storage capacity at high nanoparticle concentrations.

• Perform more long-term durability and cycling stability studies for CuO nanofluids, nanocoatings, and NanoPCM systems under realistic outdoor conditions.

• Expand research from laboratory-scale prototypes to pilot-scale and field-scale systems in order to assess scalability, manufacturability, and real operating performance.

• Assess the environmental and freshwater safety impacts of CuO-based enhancements, including possible nanoparticle release, leaching, disposal risks, and ecotoxicological effects.

• Develop integrated optimization studies that combine material properties, still geometry, thermal storage, condenser design, and climatic conditions to identify robust and practical design configurations.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

CDPSS	Convex dish pyramid solar still
CHSS	Conventional hemispherical solar still
CCPSS	Convex cylinder pyramid solar still
CTSS	Corrugated tray solar still
CuO NPs	Copper oxide nanoparticles
DSSD-FFS	Dome-shaped solar distiller with fountain-shaped basin
DSSS	Double-slope solar still
EDX	Energy-dispersive X-ray spectroscopy
ETC	Evacuated tube collector
FTSS	Flat tray solar still
GO	Graphene oxide
HSS	Hemispherical solar still
HSS&1/4FPP	Hemispherical solar still with floating plastic pipes at a one-quarter immersion level
HSS-HCP	Hemispherical solar still with honeycomb copper pipes
HSS-HCP&BS@CuO	Hemispherical solar still with honeycomb copper pipes and black sponges coated with CuO nanoparticles
MCSD-SF3&W3	Multi-effect cylindrical solar distiller with fin spacing and wick configuration
MHSS	Modified hemispherical solar still
MHSSC	Modified hemispherical solar still with an external condenser
MWCNTs	Multi-walled carbon nanotubes
NanoPCM	Nano-enhanced phase change material
NCAP	Nano-coated absorber plate
NF	Nanofluid
PCM	Phase change material
PCM SS	Solar still integrated with a PCM
PCM–CuO SS	Solar still integrated with a PCM enhanced by CuO nanoparticles
PCM–GO SS	Solar still integrated with a PCM enhanced by graphene oxide
PCM–TiO_2SS	Solar still integrated with a PCM enhanced by TiO_2 nanoparticles
PEL	Process engineering laboratory
PSS	Pyramid solar still
PTC	Parabolic trough collector
PV	Photovoltaic
PV/T	Photovoltaic/thermal
PVA	Polyvinyl alcohol
RGO	Reduced graphene oxide
SBDS	Single-basin dual-slope
SEM	Scanning electron microscopy
SGFs	Strip-grooved fins
SS	Solar still
SSSS	Single-slope solar still
SSNPCM	Solar still with nanoparticle-enhanced PCM
SSPCM	Solar still with phase change material
SSs	Solar stills
TEC	Thermoelectric cooler/thermoelectric cooling
TDS	Total dissolved solids
TSSS	Traditional single-slope solar still
VF	Volume fraction
WHO	World Health Organization

Symbols

A_g	Glass cover area
DZD	Algerian dinar
$Ex_{in}(t)$	Input exergy at time t
$Ex_{out}(t)$	Output exergy at time t
h_l	Latent heat of vaporization
$I(t)$	Solar radiation intensity at time t
INR	Indian rupee
KD	Kuwaiti dinar
T_a	Ambient temperature
T_s	Sun temperature
T_w	Basin water temperature
W_d	Rated power of active devices
wt%	Weight percentage
VF	Volume fraction of nanoparticles
$\dot{m}_w$	Hourly distillate productivity

Greek letters

η_d	Daily energy efficiency
$\eta_{d\text{-Ex}}$	Daily exergy efficiency
η_{hr}	Hourly energy efficiency
$\eta_{hr\text{-Ex}}$	Hourly exergy efficiency
τ	Operating duration

Data availability

This review article does not report new experimental or computational data. All data discussed are derived from the previously published literature, which is cited within the article.

Acknowledgements

The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/RV/1).

References

1 A. Biswas, S. Sarkar, S. Das, S. Dutta, M. Roy Choudhury, A. Giri, B. Bera, K. Bag, B. Mukherjee, K. Banerjee, D. Gupta and D. Paul, Water scarcity: A global hindrance to sustainable development and agricultural production – A critical review of the impacts and adaptation strategies, *Cambridge Prisms: Water*, 2025, vol. 3, p. e4.

2 F. A. Essa, Z. Omara and H. Y. Gadallah, Enhancing the performance of the stepped distiller in conjunction with the finned wick absorber and vertical wick distiller, *J. Contemp. Technol. Appl. Eng.*, 2025, **3**, 47–54.

3 J. Djuansjah, A. Joseph, M. Abdelgaied, S. Ataya and S. W. Sharshir, Techno-economic investigation of the solar-powered innovative small-scale hybrid HDH-RO-SD desalination unit incorporated with a shell and tube nano-enhanced energy storage reservoir, *Sep. Purif. Technol.*, 2026, **390**, 136966.

4 M. K. Shahid, B. Mainali, P. R. Rout, J. W. Lim, M. Aslam, A. E. Al-Rawajfeh and Y. Choi, A Review of Membrane-Based Desalination Systems Powered by Renewable Energy Sources, *Water*, 2023, p. 534.

5 T. Liu and M. S. Mauter, Heat transfer innovations and their application in thermal desalination processes, *Joule*, 2022, **6**, 1199–1229.

6 M. A. Ahmed, S. Amin and A. A. Mohamed, Fouling in reverse osmosis membranes: monitoring, characterization, mitigation strategies and future directions, *Heliyon*, 2023, **9**, e14908.

7 J. Wang and W. Azam, Natural resource scarcity, fossil fuel energy consumption, and total greenhouse gas emissions in top emitting countries, *Geosci. Front.*, 2024, **15**, 101757.

8 M. A. Tony and H. A. Nabwey, Recent advances in solar still technology for solar water desalination, *Appl. Water Sci.*, 2024, **14**, 147.

9 Z. Y. Ho, R. Bahar and C. H. Koo, A comprehensive review on small-scale passive solar stills for desalination, *Environ. Technol. Rev.*, 2021, **10**, 188–212.

10 A. H. Mohammed, A. N. Shmroukh, N. M. Ghazaly and A. E. Kabeel, Active solar still with solar concentrating systems, Review, *J. Therm. Anal. Calorim.*, 2023, **148**, 8777–8792.

11 S. R. Akkala and A. Kumar Kaviti, Advanced design techniques in passive and active tubular solar stills: a review, *Environ. Sci. Pollut. Res.*, 2022, **29**, 48020–48056.

12 F. T. Jodah, W. H. Alawee, H. A. Dhahad and Z. Omara, Evaluating the performance of spherical, hemispherical, and tubular solar stills with various configurations – A detailed review, *Proc. Inst. Mech. Eng. Part A J. Power Eng.*, 2024, **238**, 1261–1296.

13 T. S. Gajbhiye, S. N. Waghmare, P. M. Sirsat, P. Borkar and S. M. Awatade, Role of nanomaterials on solar desalination systems: A review, *Mater. Today: Proc.*, 2024, **100**, 37–44.

14 A. S. Abdullah, W. H. Alawee, S. A. Mohammed, U. F. Alqsair, H. A. Dhahad, F. A. Essa and Z. M. Omara, Performance improvement of tubular solar still via tilting glass cylinder, nano-coating, and nano-PCM: experimental approach, *Environ. Sci. Pollut. Res.*, 2022, **29**, 65088–65099.

15 A. K. Hussein, F. L. Rashid, M. K. Rasul, A. Basem, O. Younis, R. Z. Homod, M. E. H. Attia, M. Al-Obaidi, Z. T. Al-Sharify, N. M. Al-Dabooni, B. Ali and S. K. Rout, Enhancing hemispherical solar stills thermal performance by using nanotechnologies – recent advances and overview, *Environ. Technol. Rev.*, 2025, **14**, 127–141.

16 S. Shoeibi, H. Kargarsharifabad and N. Rahbar, Effects of nano-enhanced phase change material and nano-coated on the performance of solar stills, *J. Energy Storage*, 2021, **42**, 103061.

17 A. Sathishkumar and M. Cheralathan, Charging and discharging processes of low capacity nano-PCM based cool thermal energy storage system: An experimental study, *Energy*, 2023, **263**, 125700.

18 J. Djuansjah, M. M. Younes, A. Joseph, M. Abdelgaied, S. Ataya, S.-H. Jang and S. W. Sharshir, Thermal performance improvement of solar desalination system integrated with a heat pump, evacuated tube, hanging wick, reflector, and cover cooling, *Int. Commun. Heat Mass Transfer*, 2026, **172**, 110591.

19 A. S. Abdullah, A. Joseph, M. Aljaghtham and S. W. Sharshir, Performance assessment of an innovative multi-enhanced tubular solar still using local materials: 4E evaluation, *Sol. Energy Mater. Sol. Cells*, 2026, **294**, 113913.

20 M. Abdelgaied, M. E. H. Attia, A. E. Kabeel and M. E. Zayed, 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.

21 U. F. Alqsair, A. Joseph, A. S. Abdullah and S. W. Sharshir, High-efficiency desalination of hemispherical solar still incorporating dish collector, hanging wick, nanofluids, back reflector, and external condenser: A 4E perspective, *Appl. Therm. Eng.*, 2026, **288**, 129550.

22 H. Megahed and N. El Mahallawy, Nano-advancements: Leveraging CoCuMnOx and CuO in solar stills for sustainable water solutions, *Next Mater.*, 2025, **8**, 100770.

23 M. E. H. A. Attia, M. S. Murshitha Shajahan, S. Vembu, A. E. Kabeel, M. Abdelgaied and S. Shaik, Improving the Evaporation Rate of Hemispherical Solar Still Yield Using

Micro/Nano-Particles of Copper Oxide: Energy, Exergy, and Cost-Effective Analysis, *Iran. J. Chem. Chem. Eng.*, 2024, **43**, 1731–1747.

24 V. K. Thakur and M. K. Gaur, Study the effect of CuO nanoparticles on the performance of passive solar still in winter and summer season, *Mater. Today: Proc.*, 2022, **57**, 2009–2017.

25 V. K. Thakur, M. K. Gaur, A. K. Dhamneya and M. K. Sagar, Performance analysis of passive solar still with and without nanoparticles, *Mater. Today: Proc.*, 2021, **47**, 6309–6316.

26 M. A. Hamdan, A. M. Al Momani, O. Ayadi, A. H. Sakhrieh and F. Manzano-Agugliaro, Enhancement of solar water desalination using copper and aluminum oxide nanoparticles, *Water*, 2021, **13**, 1914.

27 V. K. Thakur and M. K. Gaur, Heat and mass transfer analysis of passive solar still with nanoparticles, operating at different water depth and various slope of glass cover, *Desalin. Water Treat.*, 2021, **235**, 1–25.

28 Y. Alhendal, A. Kulaib, S. Hussain, A. Kalendar, A. Alenzi and R. El Shiaty, Improving solar stills productivity by using nanofluids technology, *JP J. Heat Mass Transfer*, 2020, **19**, 73–96.

29 B. Madhu, E. Bala Subramanian, P. K. Nagarajan, R. Sathyamurthy and D. Mageshbabu, Improving the yield of freshwater and exergy analysis of conventional solar still with different nanofluids, *FME Trans.*, 2017, **45**, 524–530.

30 B. Madhu, E. Balasubramanian, P. K. Nagarajan, R. Sathyamurthy, A. E. Kabeel, T. Arunkumar and D. Mageshbabu, Improving the yield of fresh water from conventional and stepped solar still with different nanofluids, *Desalin. Water Treat.*, 2017, **100**, 243–249.

31 G. S. Dhindsa, V. Kumar, M. K. Mittal, G. S. Sokhal, N. Khalilpoor, M. Sharifpur, A. Issakhov and R. Tonk, Performance Comparison of single-slope solar still loaded with various nanofluids, *Energy Sci. Eng.*, 2022, **10**, 4318–4331.

32 K. Zabour, M. B. Feddaoui and H. Meftah, Effect of metal oxide nanofluids on the performance of passive solar still single slope for two different absorbent plates, *Heat Transfer*, 2022, **51**, 3675–3695.

33 H. Hafs, A. Zaaoumi, Z. Bouramdane, O. Ansari, A. Bah, M. Asbik and M. Malha, A performance analysis study of a single slope solar still with integrating fins and nanofluid for productivity enhancement, in: Proceedings of the 1st International Conference of Computer Science and Renewable Energies, ICCSRE, 2018, pp. 342–348.

34 V. K. Thakur, M. K. Gaur, A. K. Dhamneya and P. K. Chaurasiya, Validation of thermal models to predict the productivity and heat transfer coefficients for passive solar still with different nanoparticles, *Energy Sources, Part A*, 2025, **47**, 10916–10936.

35 I. Elzemzmi, K. Hidouri, B. Chaouachi and H. Akrout, Integration of Al2O3, CuO, and TiO2 nanofluids for efficient solar desalination, *Desalin. Water Treat.*, 2021, **239**, 41–53.

36 C. Phukapak, S. Phukapak and N. Pawaree, Experimental investigation of the effects of different nanoparticles on the performance of single basin double-slope solar stills, *Clean Energy*, 2024, **8**, 96–119.

37 K. V. Modi, H. K. Jani and I. D. Gamit, Impact of orientation and water depth on productivity of single-basin dual-slope solar still with Al2O3 and CuO nanoparticles, *J. Therm. Anal. Calorim.*, 2021, **143**, 899–913.

38 M. R. Kouadri, N. Chennouf, M. H. Sellami, M. N. Raache and A. Benarima, The effective behavior of ZnO and CuO during the solar desalination of brackish water in southern Algeria, *Desalin. Water Treat.*, 2021, **218**, 126–134.

39 A. Labied, M. H. Sellami and R. Cherraye, Experimental study to improve the performance of a conventional single-slope solar still using the photo-catalytic effect of three different metal oxides, *Desalin. Water Treat.*, 2020, **208**, 9–16.

40 S. G. Patel, S. Bhatnagar, J. Vardia and S. C. Ameta, Use of photocatalysts in solar desalination, *Desalination*, 2006, **189**, 287–291.

41 E. Asadpourian and A. Ameri, Enhancement of solar still productivity using CuO–GO nanocomposite: An experimental approach, *J. Taiwan Inst. Chem. Eng.*, 2021, **124**, 41–52.

42 A. Alasiri, S. W. Sharshir, L. A. Lotfy, M. Ahmadein and A. H. Elsheikh, Improvement of the performance of hemispherical distillers through passive and active techniques, *Sol. Energy*, 2024, **271**, 112409.

43 M. E. H. Attia, A. E. Kabeel, M. Abdelgaied and G. B. Abdelaziz, A comparative study of hemispherical solar stills with various modifications to obtain modified and inexpensive still models, *Environ. Sci. Pollut. Res.*, 2021, **28**, 55667–55677.

44 M. E. H. Attia, A. Karthick, A. M. Manokar, Z. Driss, A. E. Kabeel, R. Sathyamurthy and M. Sharifpur, Sustainable potable water production from conventional solar still during the winter season at Algerian dry areas: energy and exergy analysis, *J. Therm. Anal. Calorim.*, 2021, **145**, 1215–1225.

45 B. Gupta, A. Kumar and P. V. Baredar, Experimental investigation on modified solar still using nanoparticles and water sprinkler attachment, *Front. Mater.*, 2017, **4**, 23.

46 S. W. Sharshir, G. Peng, L. Wu, N. Yang, F. A. Essa, A. H. Elsheikh, S. I. T. Mohamed and A. E. Kabeel, Enhancing the solar still performance using nanofluids and glass cover cooling: Experimental study, *Appl. Therm. Eng.*, 2017, **113**, 684–693.

47 A. Muthu Manokar, D. Prince Winston, A. E. Kabeel, S. Ravishankar and T. Arunkumar, Different parameter and technique affecting the rate of evaporation on active solar still -a review, *Heat Mass Transfer*, 2018, **54**, 593–630.

48 V. Eswaran, B. S. K. Subrananiam and M. M. Athikesavan, Performance evaluation of solar still using evacuated tube collector with and without nanoparticles, *Environ. Sci. Pollut. Res.*, 2023, **30**, 113002–113014.

49 M. M. Khairat Dawood, A. I. Shehata, A. E. Kabeel, A. M. Elharidi, A. Abdelsalam Taha, S. Bayoumi and A. M. Abdalla, 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.

50 E. F. El-Gazar, H. Hassan, S. I. Rabia and W. K. Zahra, Study of the impact of using hybrid nanofluid and saline water preheating on the performance of both integrated solar still and photovoltaic panel using fractional modeling, *Eur. Phys. J. Plus*, 2021, **136**, 717.
51 A. Ajit, H. Pandey and N. K. Gupta, Analysis of solar water desalination using hybrid nanofluids: An experimental study, *J. Therm. Eng.*, 2023, **9**, 1502–1515.
52 K. Gaur, S. Chauhan, Ajit and G. Kajal, *Productivity Analysis of Pyramid Solar Still Using Phase Change Material and Hybrid Nanofluid,* Springer Nature Singapore, Singapore, 2023, pp. 621–634.
53 S. Nazari, H. Safarzadeh and M. Bahiraei, Experimental and analytical investigations of productivity, energy and exergy efficiency of a single slope solar still enhanced with thermoelectric channel and nanofluid, *Renewable Energy*, 2019, **135**, 729–744.
54 S. Nazari, H. Safarzadeh and M. Bahiraei, Performance improvement of a single slope solar still by employing thermoelectric cooling channel and copper oxide nanofluid: An experimental study, *J. Cleaner Prod.*, 2019, **208**, 1041–1052.
55 S. Shoeibi, N. Rahbar, A. Abedini Esfahlani and H. Kargarsharifabad, Improving the thermoelectric solar still performance by using nanofluids– Experimental study, thermodynamic modeling and energy matrices analysis, *Sustainable Energy Technol. Assess.*, 2021, **47**, 101339.
56 R. Naveenkumar, S. Shanmugam and A. Veerappan, Performance and exergy analysis of solar-operated vacuum fan and external condenser integrated double-slope solar still using various nanofluids, *Environ. Sci. Pollut. Res.*, 2023, **30**, 12883–12902.
57 E. F. El-Gazar, W. K. Zahra, H. Hassan and S. I. Rabia, Fractional modeling for enhancing the thermal performance of conventional solar still using hybrid nanofluid: Energy and exergy analysis, *Desalination*, 2021, **503**, 114847.
58 M. Yuvaperiyasamy, Experimental investigation focuses on the desalination productivity and water quality using a Nano CuO-coated floated absorber in a solar still, *Turk. J. Eng.*, 2025, **9**, 791–800.
59 A. K. Thakur, R. Sathyamurthy and P. Ganesh Kumar, A comparative investigation of energy storage potential of nanoparticles doped in black paint coated absorber for solar desalination application, in: Composite Materials for Extreme Loading: Proceedings of the Indo-Korean workshop on Multi Functional Materials for Extreme Loading 2021, Springer, 2021, pp. 35–50.
60 A. E. Kabeel, Z. M. Omara, F. A. Essa, A. S. Abdullah, T. Arunkumar and R. Sathyamurthy, Augmentation of a solar still distillate yield via absorber plate coated with black nanoparticles, *Alexandria Eng. J.*, 2017, **56**, 433–438.
61 T. Arunkumar, D. Murugesan, C. Viswanathan, G. Neri and D. Denkenberger, Effect of CuO, MoO_3 and ZnO nanomaterial coated absorbers for clean water production, *SN Appl. Sci.*, 2020, **2**, 1709.
62 T. Arunkumar, D. Murugesan, K. Raj, D. Denkenberger, C. Viswanathan, D. D. W. Rufuss and R. Velraj, Effect of nano-coated CuO absorbers with PVA sponges in solar water desalting system, *Appl. Therm. Eng.*, 2019, **148**, 1416–1424.
63 P. K. Meena, S. Sharma and N. Sengar, *Development of Pyramid-Shaped Solar Distillation System and Experiments with Different Absorber Coating Materials,* Springer Singapore, Singapore, 2021, pp. 285–294.
64 V. P. Katekar, A. B. Rao and V. R. Sardeshpande, *An Experimental Investigation to Determine the Optimal Nanomaterial for Coating a Solar Thermal Absorber Panel,* Springer Nature Singapore, Singapore, 2024, pp. 535–552.
65 A. S. Abdullah, F. A. Essa, H. B. Bacha and Z. M. Omara, Improving the trays solar still performance using reflectors and phase change material with nanoparticles, *J. Energy Storage*, 2020, **31**, 101744.
66 M. Benghanem, M. E. Hadi Attia, K. Harby, S. J. Almalowi and M. Abdelgaied, A comparative study of multi-effect designs using cylindrical fins coated with bamboo-cotton fabric impregnated with nanomaterials to improve the efficiency of hemispherical solar distillers, *Sep. Purif. Technol.*, 2025, **379**, 135103.
67 M. E. Hadi Attia, K. Harby, M. Amin and M. Abdelgaied, Improving the performance of hemispherical solar stills using innovative copper tubes arranged in a honeycomb structure with natural sponges coated with nanoparticles, *Appl. Therm. Eng.*, 2025, **269**, 126130.
68 M. E. Hadi Attia, M. K. M. Handawy, K. Harby, M. Benghanem and M. Abdelgaied, Performance improvement and optimization of hemispherical solar stills using different buoyancy levels of plastic pipes in water basins: surface tension optimization, *Sep. Purif. Technol.*, 2025, **378**, 134823.
69 Z. M. Omara, W. H. Alawee, S. A. Mohammed, H. A. Dhahad, A. S. Abdullah and F. A. Essa, Experimental study on the performance of pyramid solar still with novel convex and dish absorbers and wick materials, *J. Cleaner Prod.*, 2022, **373**, 133835.
70 W. H. Alawee, A. S. Abdullah, S. A. Mohammed, H. A. Dhahad, Z. M. Omara and F. A. Essa, Augmenting the distillate yield of cords pyramid distiller with baffles within compartments, *J. Cleaner Prod.*, 2022, **356**, 131761.
71 A. W. Kandeal, A. A. El-Naggar, M. R. Sharaby, S. W. Sharshir, A. Swidan, G. B. Abdelaziz, A. S. Abdullah, A. M. Elsaid, N. M. Ghazaly and M. O. A. El-Samadony, Augmentation of the tubular distiller performance via hot air injection from a parabolic trough collector, nanocoating, and nanofluid, *Sol. Energy*, 2024, **277**, 112743.
72 F. Selimefendigil, C. Şirin and H. F. Öztop, 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.
73 G. Vijayaraghavan, K. Velavan, K. Babu, M. Yuvaperiyasamy and M. Mohanraj, Investigation of a Pyramid Solar Still with CuO Nanoparticles-Paraffin Wax Blend as Energy Storage Material, *J. Environ. Nanotechnol.*, 2025, **14**, 1–6.
74 S. Kumaravel, M. S. Nagaraj and G. Bharathiraja, Improved Thermal Performance and Distillate of Conventional Solar

Still *via* Copper Plate, Phase Change Material and CuO Nanoparticles, *Recent Pat. Nanotechnol.*, 2025, **19**, 483–497.

75 F. A. Hammad, M. E. Zayed, E. El-Bialy, K. Irshad, Z. Lu and S. M. Shalaby, Performance assessment of a novel solar distiller with a fountain-shaped basin design embedded with phase change materials enriched with copper oxide nano-additives: A detailed experimental investigation, *J. Energy Storage*, 2024, **82**, 110555.

76 P. Patel, Z. N. Ansari, M. M. A. Zahra, G. G. Tejani, S. Singh, D. Varshney and M. A. Shah, Experimental analysis of corrugated solar still using nano-enhanced phase change material, *Multidiscip. Sci. J.*, 2025, **7**, e2025471.

77 S. K. Gupta and D. Kumar, Thermal and exergy efficiency optimisation in hybrid solar stills with nano-enhanced PCM as thermal storage, *Int. J. Ambient Energy*, 2025, **46**, 2507137.

78 H. Ajdari and A. Ameri, Performance assessment of an inclined stepped solar still integrated with PCM and CuO/GO nanocomposite as a nanofluid, *J. Build. Eng.*, 2022, **49**, 104090.

79 M. Abdelgaied, A. S. Abdulla, G. B. Abdelaziz and A. E. Kabeel, Performance improvement of modified stepped solar distillers using three effective hybrid optimization modifications, *Sustainable Energy Technol. Assess.*, 2022, **51**, 101936.

80 V. K. Sonker, R. K. Singh, J. P. Chakraborty and A. Sarkar, Performance assessment of a passive solar still integrated with thermal energy storage and nanoparticle stored in copper cylinders, *Int. J. Energy Res.*, 2021, **45**, 2856–2869.

81 D. Dsilva Winfred Rufuss, L. Suganthi, S. Iniyan and P. A. Davies, Effects of nanoparticle-enhanced phase change material (NPCM) on solar still productivity, *J. Cleaner Prod.*, 2018, **192**, 9–29.

82 V. K. Singh and D. Kumar, An experimental investigation and thermo-economic performance analysis of solar desalination system by using nano-enhanced PCM, *Mater. Today Sustainability*, 2024, **27**, 100884.

83 A. Behura and H. K. Gupta, Use of nanoparticle-embedded phase change material in solar still for productivity enhancement, *Mater. Today: Proc.*, 2021, **45**, 3904–3907.

84 D. D. W. Rufuss, S. Iniyan, L. Suganthi, P. Davies and T. Akinaga, Analysis of solar still with nanoparticle incorporated phase change material for solar desalination application, in: ISES Solar World Congress 2015, Conference Proceedings, International Solar Energy Society, 2015, pp. 1271–1280.

85 F. A. Essa, Z. Omara, A. Abdullah, S. Shanmugan, H. Panchal, A. E. Kabeel, R. Sathyamurthy, M. M. Athikesavan, A. Elsheikh, M. Abdelgaied and B. Saleh, Augmenting the productivity of stepped distiller by corrugated and curved liners, CuO/paraffin wax, wick, and vapor suctioning, *Environ. Sci. Pollut. Res.*, 2021, **28**, 56955–56965.

86 A. S. Abdullah, Z. M. Omara, F. A. Essa, U. F. Alqsair, M. Aljaghtham, I. B. Mansir, S. Shanmugan and W. H. Alawee, Enhancing trays solar still performance using wick finned absorber, nano- enhanced PCM, *Alexandria Eng. J.*, 2022, **61**, 12417–12430.

87 M. M. Younes, A. S. Abdullah, Z. M. Omara and F. A. Essa, Enhancement of discs' solar still performance using thermal energy storage unit and reflectors: An experimental approach, *Alexandria Eng. J.*, 2022, **61**, 7477–7487.

88 S. Khanmohammadi and M. Sabzpooshani, Theoretical assessment of a solar still system equipped with Nanophase change materials, *Int. J. Green Energy*, 2021, **18**, 111–127.

89 A. Bamasag, F. A. Essa, Z. M. Omara, E. Bahgat, A. O. Alsaiari, H. Abulkhair, R. A. Alsulami and A. H. Elsheikh, Machine learning-based prediction and augmentation of dish solar distiller performance using an innovative convex stepped absorber and phase change material with nanoadditives, *Process Saf. Environ. Prot.*, 2022, **162**, 112–123.

90 A. S. Abdullah, Z. M. Omara, F. A. Essa, M. M. Younes, S. Shanmugan, M. Abdelgaied, M. I. Amro, A. E. Kabeel and W. M. Farouk, 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.

91 M. M. Khairat Dawood, T. Nabil, A. E. Kabeel, A. I. Shehata, A. M. Abdalla and B. E. Elnaghi, Experimental study of productivity progress for a solar still integrated with parabolic trough collectors with a phase change material in the receiver evacuated tubes and in the still, *J. Energy Storage*, 2020, **32**, 102007.