ISSN:2828-6235
Impact factor:13.77

International Journal of Literature and Language Studies(IJLLS)

CURRENT STATE, TECHNOLOGICAL DEVELOPMENT AND PROSPECTS OF SOLAR WATER STILLS: A CRITICAL REVIEW

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doi:https://doi.org/10.5281/zenodo.23239236

Abstract. This article critically reviews the current state, design solutions, heat and mass transfer mechanisms, and prospective development directions of solar-powered water desalination systems. In addition to conventional solar stills, the review covers phase change materials (PCMs), nanofluids, nano-enhanced PCMs, photovoltaic/thermal (PV/T) systems, external collectors, evacuated-tube heaters, thermoelectric modules, and hybrid desalination technologies. The literature indicates that the main advantages of conventional solar stills are their simplicity, low operating cost, and limited dependence on the electrical grid, whereas their principal limitations are relatively low productivity and strong dependence on solar radiation. Recent studies have achieved substantial productivity improvements through thermal energy storage, enlargement of the evaporation surface, enhanced condensation, and hybridization of energy sources. However, transferring high laboratory-scale performance to real operating conditions remains challenging because of the long-term stability of PCMs, environmental risks associated with nanomaterials, salt deposition, fouling, maintenance requirements, and the lack of comprehensive life-cycle assessment. For future systems, the article identifies the 4E approach—energy, exergy, economic, and environmental analysis—together with digital modeling and artificial-intelligence-based optimization as priority directions [1–8].

Keywords: solar still, desalination, solar energy, PCM, nanofluid, nano-PCM, PV/T, exergy, 4E analysis, water productivity, hybrid system, optimization.

1. Introduction

The uneven geographical distribution of freshwater resources, climate change, population growth, and expanding economic activity are making water security a strategic issue. According to UN-Water, global water stress reached 18.6% in 2021, with particularly high pressure in Southern and Central Asia, Northern Africa, and Western Asia [9]. Therefore, desalination of saline and brackish water is becoming an important means of diversifying water supply.

Desalination lies directly at the intersection of water and energy systems. IEA analyses report that energy demand for desalination has increased substantially since 2010 and that high-efficiency electricity-based technologies, especially reverse osmosis, are accounting for an increasing share of new capacity [10,11]. Under these conditions, solar-powered desalination systems offer an opportunity to address the water–energy–management nexus simultaneously, particularly for small-scale and decentralized users.

A solar still converts solar radiation directly into heat, evaporates saline water, and condenses the generated vapor. Although structural simplicity is its main advantage, the water productivity of conventional units generally remains within 2–5 L/m²·day [6]. Consequently, research over the last decade has focused on energy storage, intensified heat transfer, improved condensation, and hybridization [2–8].

The aim of this article is to critically evaluate recent scientific developments in solar water stills not only in terms of productivity, but also according to energy, exergy, economic, and environmental criteria, and to identify the most promising directions for commercial and region-specific application.

2. Technological Classification of Solar Water Stills

According to their operating mechanism and energy supply, solar stills can be classified as passive, active, and hybrid systems. In passive systems, solar radiation directly heats the water in the absorber basin. In active systems, the energy flow is controlled through an auxiliary solar collector, PV/T module, electric heater, heat pump, or another device. Hybrid systems combine several heat- and mass-transfer mechanisms [1,3,5].

Single-slope and double-slope solar stills are among the simplest configurations from a structural standpoint. Pyramid, wick-type, stepped-basin, tubular, and multi-effect configurations have been developed to increase the evaporation area and temperature gradient. However, greater geometric complexity does not automatically improve overall system efficiency; additional material, maintenance, and cleaning requirements may reduce the economic benefit [1,3,4].

Technology	Main advantage	Main limitation	Typical improvement	Prospects
Conventional solar still	Simple, reliable, low electricity demand	Low productivity; reduced performance at night	Cover cooling, wick, reflector	Small autonomous systems
PCM-integrated	Can supply heat at night	PCM cost; thermal resistance	Nano-PCM, encapsulation, fins	High
Nanofluid-based	Improved heat transfer and absorber properties	Stability and environmental risk	Hybrid nanofluid, nano-coating	Medium–high
PV/T or PV-integrated	Provides electricity and heat simultaneously	High initial capital cost	Smart control, storage	High
Solar collector / evacuated tube	Achieves high water temperature	Additional components and maintenance	ETC, evacuated tube	High, especially in hot climates
Membrane /	Scalable to larger	Complexity and	RO/MD + solar	High at industrial

hybrid	capacities	fouling	PV/T	scale

3. Energy and Exergy Analysis

Evaluating solar stills solely by daily distillate yield is methodologically insufficient. Energy efficiency expresses the ratio of useful evaporation heat to the solar energy supplied to the system, whereas exergy efficiency also accounts for the work potential of energy. In solar stills, exergy efficiency is generally much lower than energy efficiency because a large share of heat is transferred to the surroundings at relatively low temperature [6,8].

In simplified form, thermal efficiency can be expressed as $\eta_{th} = m_d \cdot h_{fg}/(A \cdot I_t)$, where m_d is the mass of distillate, h_{fg} is the latent heat of vaporization, A is the active area, and I_t is the accumulated solar irradiation. Exergy analysis additionally considers the high exergy of the solar source, the temperature difference between the absorber and water, heat rejection from the condenser to the environment, and irreversibilities.

Studies published in 2024–2026 show the growing importance of the 4E approach. For example, a pyramid solar still integrating nano-PCM, fins, porous material, and black sand demonstrated simultaneous improvements in water productivity, exergy efficiency, and economic indicators compared with a conventional configuration [8]. This result leads to an important methodological conclusion: optimal design should seek a Pareto balance among productivity, exergy, cost, and environmental impact rather than merely maximizing distillate output.

4. PCM and Thermal Energy Storage Technologies

One of the major challenges of solar stills is the temporal variability of solar radiation. PCM technology mitigates this problem through latent heat storage. During sunny periods, the PCM melts and stores heat; in the evening and at night, it releases the stored heat back to the system during solidification. Reviews published in 2024 identify the combination of PCM and nano-PCM as a promising direction [7,8].

PCM selection should jointly consider melting temperature, latent heat capacity, thermal conductivity, cyclic stability, corrosion effects, encapsulation feasibility, and cost. Selecting a material solely because of its high latent heat is insufficient: if the PCM melting temperature does not match the operating range of the solar still, the stored heat cannot be effectively utilized in practice.

A 2026 critical review synthesized 4E analyses of PCM, sensible heat storage, and nano-enhanced systems, reporting that productivity in PCM-integrated solar stills may increase by 30–100%. At the same time, PCM leakage, nanoparticle stability, and the lack of comprehensive life-cycle assessment were identified as major unresolved issues [6].

5. Nanofluids and Nano-Enhanced Materials

Nanofluids are used to intensify heat flow from the absorber to the water by improving thermal conductivity and convective heat transfer. Reviews published in 2024 systematically examined the effects of nanofluids, nano-coatings, and nano-PCMs on solar still productivity [12]. A 2025 review reported productivity increases of 20–80% in certain configurations using nanomaterials [13].

Nevertheless, direct comparison of nanofluid results requires caution. Particle concentration and size, base fluid, ultrasonic dispersion method, radiation intensity, water depth, and experimental climate conditions vary considerably among studies. Higher concentration may

improve thermal conductivity, but increased viscosity can weaken natural convection and raise costs.

From an environmental perspective, nanoparticles cannot be assessed solely by performance indicators. Nanomaterial production, disposal, and the possibility of nanoparticle transfer into the distillate should be included in life-cycle assessment. Therefore, future experiments should measure water quality, nanoparticle migration, and recyclability alongside productivity [6,13].

6. Hybridization with PV/T Systems and Solar Collectors

Integrating a solar still with a PV or PV/T system makes it possible to manage energy flows simultaneously. PV electricity can power pumps, sensors, automation, or membrane processes, while the thermal component preheats saline water. A comprehensive 2025 review emphasized PV and PV/T integration as one of the key pathways for improving the energy efficiency and scalability of solar desalination [2].

The use of evacuated-tube solar collectors enhances the evaporation rate by increasing water temperature. A 2024 review reported high productivity values for several solar-heated configurations [14]. However, adding a collector requires the overall economic performance of the system to be evaluated not only in terms of distillate yield, but also with respect to capital cost per unit of product and energy storage.

A promising concept is the PV/T + PCM + solar still combination. In this configuration, electricity and heat are generated simultaneously during the daytime, while the PCM shifts thermal energy into the evening period. Such systems may be especially important for rural areas with weak electrical grids and for small island or desert settlements.

7. Economic and Environmental Assessment

The commercial prospects of solar stills are determined not only by water productivity, but also by the life-cycle cost of a unit volume of freshwater (LCOW or cost per liter), maintenance requirements, service life, and the extent to which local materials are used. In one experimental study published in 2024, the combination of nano-PCM, fins, and porous materials significantly reduced the cost of water compared with a conventional still [8]. However, transferring such results to other climatic conditions requires recalculation of solar radiation, material prices, and labor costs.

Environmental assessment should account not only for avoided CO_2 emissions, but also for brine management, material life cycles, and the disposal of PCMs and nanomaterials. Solar energy can reduce emissions during the operational stage; however, the embodied energy and material consumption associated with manufacturing the system itself should not be neglected.

Another important aspect of economic optimization in small solar stills is the level of automation. Sensors, microcontrollers, and remote monitoring can improve productivity, but excessive electronics may create reliability and repair problems for small systems. Therefore, the principle of “minimum necessary automation” is appropriate.

8. Artificial Intelligence and Digital Optimization

Solar stills involve dozens of variables, including water depth, salinity, cover angle, solar intensity, wind speed, ambient temperature, condenser temperature, PCM quantity, and nanofluid concentration. Classical one-factor-at-a-time experimental methods cannot fully reveal the interactions among these parameters. Therefore, Taguchi methods, response surface methodology,

Grey Relational Analysis, metaheuristic algorithms, and machine-learning techniques are being used increasingly [15].

A 2024 study combined Taguchi experimental design, multi-criteria decision-making, and the Artificial Bee Colony algorithm for a pyramid solar still, demonstrating simultaneous optimization of several operating parameters [15]. In the future, if such methods are integrated with real-time sensor data, a solar still could automatically select its operating mode according to weather forecasts.

The digital twin concept is also promising. By integrating a physical model, real-time sensors, and machine learning, it is possible to predict future system productivity, the thermal state of the PCM, and maintenance needs. This approach may reduce one of the major gaps between laboratory prototypes and commercial devices: reliable control under different climatic and operating conditions.

9. Major Research Gaps

1) Standardized experimental protocols are lacking. Direct comparison among results is difficult because solar intensity, water depth, climate, salinity, and measurement periods vary across studies.

2) The transfer of laboratory results to long-term real-world operation has not been studied sufficiently. Salt scaling, cover fouling, corrosion, and material degradation often remain outside the scope of short-term experiments.

3) The 4E analysis should be expanded. In addition to energy and economic indicators, life-cycle performance, environmental risk, and water-quality indicators should be assessed jointly.

4) Safety issues related to nanoparticles and PCMs remain unresolved. Productivity gains should be reported together with evidence of the chemical safety of the distillate.

5) The optimal point between system complexity and efficiency in hybrid systems has not been established. Each additional component may increase productivity, but it also raises capital and maintenance costs.

6) Long-term experimental data for Central Asia, including Uzbekistan, remain insufficient. Under conditions of arid climate, high summer solar radiation, and water scarcity, optimization of locally appropriate design parameters should be treated as a distinct research direction.

10. Prospective Development Concept

Based on the synthesis of the literature, future solar stills should preferably be built around a modular and adaptive architecture rather than a single technology. In such a system, a solar collector or PV/T unit serves as the primary energy source, PCM functions as a short-term thermal accumulator, and an efficient condenser acts as the mass-transfer node. Sensors measure solar radiation, water and cover temperatures, water level, and distillate flow, while a control algorithm automatically optimizes the operating mode.

A second important direction is modular scaling. A small 1–5 m² unit can serve household or laboratory needs, while identical modules can be connected in parallel to meet the needs of a village or small community. This approach enables gradual scaling of capital investment and simplifies maintenance.

A third direction is localization. Producing the absorber, housing, thermal storage element, and condenser from locally available materials can reduce dependence on imported components.

At the same time, as emphasized in the WHO 2024 guidelines for small water supplies, safety, monitoring, and sanitary management in small systems are as important as technical efficiency [16].

11. Conclusion

Solar water stills remain a technically attractive solution for small-scale and decentralized freshwater production in water-scarce regions. Their main advantages are the direct use of solar energy, structural simplicity, and low dependence on the electrical grid. However, the low productivity of conventional solar stills and the variability of solar radiation limit large-scale deployment.

Recent scientific findings indicate that these limitations can be substantially reduced through PCM, nano-PCM, nanofluids, PV/T systems, evacuated-tube collectors, active condenser cooling, and hybrid desalination configurations. At the same time, for Q1-level research, the criterion of "how much productivity increased" alone is insufficient. The exergy efficiency of the system, unit water cost, life-cycle emissions, material safety, maintenance requirements, and long-term reliability should be assessed together.

The PV/T–PCM–solar still–smart control hybrid architecture can be identified as one of the most promising future concepts. By jointly generating electrical and thermal energy, storing heat, and applying real-time control, such a system can improve the utilization of solar energy. However, before commercialization, standardized long-term experiments, life-cycle assessment, and field testing in different climate zones are required.

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