JOURNAL OF APPLIED SCIENCE AND SOCIAL SCIENCE
eISSN 2229-3113 pISSN 2229-3205
Volume 15 Issue 12, December 2025
Impact factor: 2019: 4.679 2020: 5.015 2021: 5.436, 2022: 5.242, 2023: 6.995, 2024 7.75

PERFORMANCE ENHANCEMENT STRATEGIES FOR BASIN-TYPE SOLAR DESALINATION SYSTEMS: A COMPREHENSIVE REVIEW AND NOVEL INTEGRATED DESIGN CONCEPT

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Abstract: Global population growth and freshwater scarcity have intensified the demand for sustainable desalination solutions. Solar stills are environmentally friendly and economical but suffer from low productivity due to significant latent heat losses and limited thermal efficiency. This study reviews key enhancement techniques for basin-type solar stills, including the use of external condensers, solar collectors, nanofluids, and advanced evaporation surfaces. Identified research gaps highlight the need for integrated solutions that improve both evaporation and condensation simultaneously. To address this, a combined basin-type solar desalination system (CBSS) featuring a solar air collector, external condenser, and photovoltaic-powered circulation is proposed. The concept aims to significantly increase freshwater yield and ensure autonomous energy operation for deployment in water-scarce regions.

Keywords: solar desalination, basin-type solar still, external condenser, solar air collector, forced circulation, photovoltaic integration, productivity enhancement.

Introduction. The rapid growth of global industrial development and continuous increase in the world population have led to a significant rise in the demand for fresh water. The escalating scarcity of potable water has become a critical challenge, as the elevated salinity levels and contamination of available water sources contribute to the spread of various diseases. According to reports from the World Health Organization, approximately 30,000 people die every day from waterborne illnesses [1]. UNICEF statistics indicate that nearly one billion people worldwide still lack access to safe drinking water [2]. Therefore, the development and investigation of freshwater production technologies that do not harm the environment are among the most urgent scientific and engineering priorities today. Utilizing solar energy for freshwater production is considered one of the most efficient and sustainable approaches, as solar still systems are environmentally friendly, cost-effective, and simple to operate. Among various solar desalination technologies, the single-slope basin-type solar still is the most widely implemented configuration due to its structural simplicity and practical applicability. Among the key parameters that significantly influence the productivity and efficiency of solar stills are climatic conditions, solar radiation intensity, ambient temperature, the type and thickness of the transparent cover, basin water depth, and wind speed. In most practical cases, even under near-optimal operating conditions, the productivity of conventional basin-type solar stills does not exceed 5 L/m²·day [3]. Such low performance is mainly attributed to the complete loss of latent heat during vapor condensation on the inner surface of the transparent cover, the high energy demand required for water evaporation, and the limited amount of absorbed useful thermal energy.

Literature review. To enhance the performance of conventional solar stills, a number of modified designs incorporating flat-plate solar collectors have been proposed [4]. Shukla and Sorayan [5] developed a single-slope basin still integrated with multiple wicks as an improved evaporation mechanism. Their experimental outcomes were validated through a computer-based model utilizing a modified heat transfer coefficient correlation. Singh et al. [6] investigated two different solar-collector-assisted still configurations. Their results showed that the productivity of a two-stage collector-coupled solar still was approximately 15.19% lower than that of a single-stage collector-integrated system. In both cases, the optimal feed water flow rate was identified as 0.016 m/s, and the system efficiency was maximized when twelve evacuated tubes were employed.

Water vapor generated from the saline feed water separates and moves upward, then condenses and flows down along the inner surface of the transparent cover due to free convection heat transfer occurring between the evaporation and condensation zones. The freshwater productivity of a solar still can be enhanced by employing an external condenser, which effectively reduces the temperature of the condensation surface. The simultaneous application of nanotechnology and external condensation techniques has been shown to significantly improve the output performance of solar still systems. Eltawil and Omara [7] investigated the influence of integrating a solar collector and an external condenser into a solar still. Their results demonstrated that the daily freshwater yield increased by 51% and 82%, respectively, depending on the mode of operation. In a subsequent study, Hassan et al. [8] proposed a modified solar still and compared its performance to that of a conventional system. Their results showed that freshwater productivity increased by 67% when using a parabolic-trough collector, and by 7.3% when employing a fine-spray external condenser. It is well established that the temperature difference between the transparent cover and the saline water layer is a dominant factor governing evaporation rate inside the distillation chamber. Therefore, numerous studies have focused on increasing water temperature while decreasing the cover temperature, utilizing technologies such as solar collectors and PV/T panels. Shoeibi et al. [9] conducted research aimed at maximizing this temperature gradient. To achieve optimal performance, the authors simultaneously cooled the outer surface of the transparent cover and elevated the temperature of the saline water. Their results revealed improvements in productivity, energy efficiency, and exergy efficiency of 79.4%, 11.2%, and 45.7%, respectively. In a further investigation, Shoeibi et al. [10] explored performance enhancement of single-slope solar stills using a novel design incorporating vacuum-tube and heat-pipe solar collectors along with an external condenser. The modified configuration demonstrated a freshwater yield 2.13 times greater than that of a conventional solar still.

Dunkle [11] introduced empirical correlations for convective and evaporative heat transfer coefficients, as well as governing heat and mass transfer equations, for single-basin solar stills.

When the ambient air temperature and basin water temperature are known, the temperature of the transparent cover can be determined using an overall heat balance equation. Kumar and Tiwari [12] formulated a theoretical model to determine the convective mass transfer coefficient for different ranges of the Grashof number during the solar desalination process. Linear regression analysis was applied to experimental data to obtain the empirical constants c and n, enabling accurate prediction of still characteristics across varying Grashof number ranges. Sakthivel et al. [13] proposed a modified mathematical model and conducted experimental research to enhance the productivity of a conventional single-slope basin still. In their design, a strip of wool fabric was vertically positioned at the center of the basin, while another wool layer was attached along the rear interior wall of the evaporation chamber to improve wetted surface area and evaporation rate. Srivastava and Agrawal [14] investigated both theoretically and experimentally the performance of a basin-type solar still enhanced with floating, low-thermal-inertia porous materials on the water surface. Their results revealed a 68% increase in freshwater productivity compared to a traditional still. El-Sebaii et al. [15] developed a single-slope, single-basin solar still equipped with a suspended baffle-type absorber and established a mathematical model to simulate its behavior. The suspended absorber divides the basin water into upper and lower sections, improving heat absorption and evaporation. The modified system achieved a daily productivity enhancement of approximately 18.5–20% relative to a conventional still.

Setoodeh et al. [16] developed a three-dimensional, two-phase CFD model to simulate the evaporation and condensation phenomena inside a single-slope, single-basin solar still. The numerical findings demonstrated strong agreement with experimental results, validating the proposed modeling approach. Tiwari et al. [17] performed a detailed modeling analysis of an active solar desalination system integrated with various solar collector configurations, including a flat-plate collector, evacuated tube collector, condenser, and a heat-pipe-assisted evacuated tube collector. Their results indicated that the system equipped with a heat-pipe evacuated tube collector offered the highest productivity and thermal efficiency, reaching 4.24 kg/(m^2·day) and 18.26%, respectively.

Results. A comprehensive review of the aforementioned studies clearly reveals several research gaps. Despite numerous attempts to improve the performance of basin-type solar stills, strategies such as incorporating a solar air collector (SAC) to enhance heat transfer within the evaporation chamber, integrating an external condenser to accelerate condensation, implementing forced circulation within the desalination loop, and utilizing photovoltaic modules to supply auxiliary power remain insufficiently explored. Considering these gaps, a novel conceptual configuration of a combined basin-type solar still system powered by an external condenser, solar air collector, and photovoltaic module (PV) has been developed (Fig. 1).

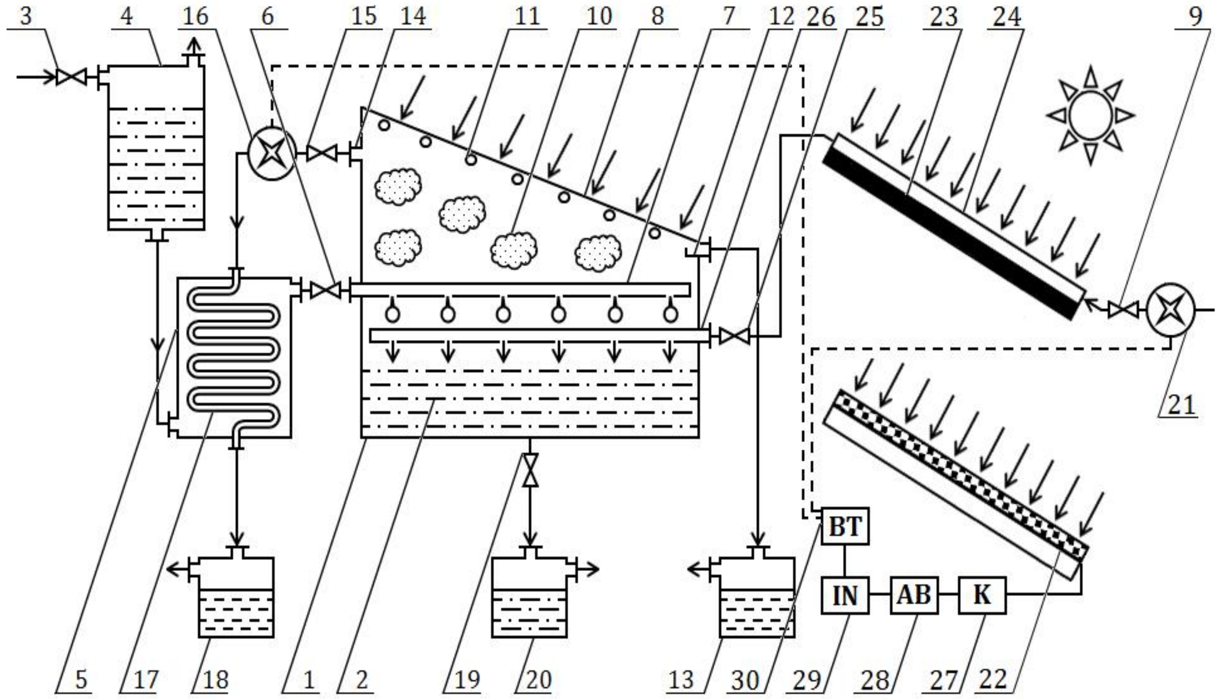

Fig. 1. Schematic diagram of the integrated basin-type solar desalination system:

1-basin-type solar still; 2-saline water; 3, 6, 9, 15, 19, 25-valves; 4-saline water storage tank; 5-vapor-water heat exchanger (external condenser); 7, 26-hot air and saline water distribution pipes; 8-transparent cover; 10-water vapor; 11-condensate droplets; 12-collection channel; 13, 18-freshwater collection tank; 14-inlet/outlet pipe; 16, 21-fans; 17-serpentine coil; 20-brine reject tank; 22-photovoltaic (PV) module; 23-thermal insulation; 24-solar air collector; 27-controller; 28-battery storage; 29-inverter; 30-control system

The operation of the combined basin-type solar desalination system (CBSS) proceeds as follows: initially, the required water level of the saline feed water (2) inside the evaporation chamber of the basin solar still (1) is ensured by supplying saline water from the feed water tank (4) through the external condenser (5), valve (6) (kept fully open), and the saline water distribution pipe (7), while valve (3) remains open. When the water level in the evaporation chamber reaches approximately 3 cm, valve (6) is closed, and once the feed water tank (4) is filled to the necessary level, valve (3) is also closed. When solar radiation penetrates through the transparent cover (8), the temperature of the saline water (2) inside the evaporation chamber gradually rises. Once the feed water attains sufficient thermal energy for phase change, evaporation occurs, generating water vapor (10). The vapor then diffuses upward and condenses as droplets (11) on the inner surface of the transparent cover (8). The condensate flows downward due to gravitational force and is collected through the channel (12) into the freshwater collection tank (13). To enhance freshwater yield and intensify condensation within the evaporation chamber, excessive vapor is extracted via forced circulation. For this purpose, a fan (16) is connected to the vapor outlet pipe (14) through valve (15) (kept open during operation). The fan draws the vapor (10) through the outlet pipe (14) and directs it toward the serpentine coil (17) located inside the external condenser (5). There, the vapor releases its latent heat to the cooling saline water supplied from the feedwater tank (4), resulting in condensation. The produced condensate is accumulated in a separate freshwater collection tank (18). After the necessary amount of vapor extraction is completed, the fan (16) is switched off and valve (15) is closed. As evaporation causes a reduction in the feed water mass inside the basin, the level is continuously restored using saline water from the feed water tank (4) through the external condenser (5), valve (6) (adjusted to maintain appropriate flow), and distribution pipe (7). To further improve the evaporation intensity, an auxiliary hot air supply system is incorporated. Ambient air is drawn by a fan (21), and its flow is regulated through valve (9) before entering the insulated solar air collector with turbulators (24). Through solar radiation absorption inside the SAC (24), the air temperature rises to approximately 60–70°C. The heated air is then directed via valve (25) and distribution pipe (26) toward the surface of the saline water (2), promoting rapid evaporation. As a result, both the evaporation rate and the overall freshwater yield from the basin solar still (1) are significantly increased. Upon completion of the desalination process, the remaining brine is discharged from the evaporation chamber via valve (19) into the brine reject tank (20). The air circulation fans (16, 21) of the CBSS receive electrical power from the control system (30), which consists of the photovoltaic module (22), charge controller (27), battery storage (28), and inverter (29).

Discussion. The literature review highlights that although conventional basin-type solar stills remain attractive due to their operational simplicity and low environmental impact, their productivity is significantly limited by inherent thermal inefficiencies. The primary weakness is the loss of latent heat during condensation inside the chamber, which restricts the amount of usable thermal energy for the evaporation process. Modern research has therefore focused on applying various enhancement techniques such as external condensers, solar collectors, nanofluids, and improved evaporation surfaces. Studies incorporating external condensers have demonstrated substantial improvements in distillate yield by facilitating heat recovery and reducing condensation temperature. Meanwhile, the integration of solar collectors—particularly vacuum tube and heat-pipe systems-has effectively enhanced the thermal input to the saline water, accelerating evaporation. Nanofluid-based designs provide further improvements due to higher thermal conductivity, though practical scalability and long-term fluid stability remain challenges. Despite notable advancements, several technical gaps are still evident. Many modified systems rely on either enhanced evaporation or improved condensation individually, whereas simultaneous optimization of both mechanisms is required to achieve maximum productivity. Additionally, the reliance on external electrical power sources for forced circulation systems raises concerns regarding sustainability in isolated regions where solar stills are most needed. The proposed combined basin-type solar desalination system (CBSS) addresses these limitations by utilizing a solar air collector to elevate evaporation rates, an external condenser to improve condensation efficiency, and a photovoltaic system to supply autonomous electrical power for auxiliary components. This integrated configuration has the potential to deliver significantly higher freshwater productivity and improved thermal management relative to traditional designs.

Conclusion. Based on the comprehensive analysis of existing solar desalination technologies, the following conclusions are drawn: Conventional single-slope basin-type solar stills exhibit low productivity due to significant thermal energy losses and slow evaporation–condensation dynamics. Enhancements such as external condensers, solar-assisted heating, and nanofluids have demonstrated notable performance improvements, although limitations in system complexity, cost, and energy dependence remain. There is a clear need for integrated solutions that simultaneously optimize evaporation, condensation, and energy autonomy. The proposed CBSS configuration—combining a solar air collector, an external condenser, and photovoltaic-powered forced circulation-offers a promising pathway to significantly increase freshwater output while maintaining environmental sustainability. Future work should include experimental validation and computational performance modeling to quantify improvements under varying climatic conditions and operational parameters. In summary, the integrated approach to heat and mass transfer enhancement in solar stills represents an effective and practical solution for addressing global freshwater shortages, especially in remote or arid regions with abundant solar resources.

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