



Experimental Investigation of a Pyramid Shaped Solar Still Enhanced by a Floating Cellulose Fiber Layer and an Additional Waste-Heat Input

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ABSTRACT

This experimental study evaluates the thermal-hydraulic performance of a pyramid solar still desalination unit (PSSDU) enhanced through geometric modification, incorporation of a floating cellulose fiber thermal layer, and controlled auxiliary heat input simulating low-grade waste heat. Experiments were conducted under typical Egyptian summer conditions in two sequential stages to isolate the influence of design and operating parameters. Initially, the effect of glass cover inclination was examined at 35° and 45°. Increasing the tilt angle to 45° enhanced vapor condensation and improved droplet drainage, raising the maximum instantaneous productivity from 370 to 410 mL/m²·h (10.8% increase), and achieving approximately 14% higher output compared with the conventional reference configuration (290 mL/m²·h). In the second stage, a 75 mm floating cellulose fiber layer was introduced at the brine surface to enhance thermal absorption and reduce convective heat losses, while a uniform external heat flux of 600 W/m² was applied to simulate recoverable waste heat. At 100 mm water depth, the maximum instantaneous productivity reached 560 mL/m²·h. Reducing saline water depth to 25 mm intensified evaporative heat transfer, yielding a peak value of 600 mL/m²·h, corresponding to a 140% enhancement over the baseline. The maximum cumulative daily distillate production increased from 2.6 to 7.3 L/m²·day (181% improvement). Concurrently, maximum thermal efficiency increased from 26.0% to 46.0%, representing a 77% enhancement. The findings demonstrate that integrating geometric optimization, surface thermal augmentation, and moderate waste heat utilization significantly improves solar distillation performance, providing a viable and energy-efficient strategy for decentralized freshwater production.

KEYWORDS: Pyramid solar still; Solar desalination; Cellulose fiber; Thermal efficiency; Waste heat addition.

دراسة تجريبية لوحدة تقطير شمسي هرمية محسنة باستخدام طبقة عائمة من ألياف السليلوز ومزودة بمصدر حراري إضافي

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المخلص

تهدف هذه الدراسة إلى تحسين الأداء الحراري-الهيدروليكي لوحدة تقطير شمسي هرمية تم تعزيزها من خلال تعديل هندسي، ودمج طبقة حرارية عائمة من ألياف السليلوز، مع تطبيق مصدر حراري مساعد مُتحكم به لمحاكاة الاستفادة من حرارة مهددة منخفضة الدرجة. أُجريت التجارب تحت الظروف المناخية الصيفية المعتادة في مصر على مرحلتين متتاليتين لدراسة تأثير المتغيرات التصميمية والتشغيلية بصورة منهجية. في المرحلة الأولى، تمت دراسة تأثير زاوية ميل الغطاء الزجاجي عند 35° و 45° . وقد أدى زيادة زاوية الميل إلى 45° إلى تحسين عملية تكاثف البخار وتسهيل انسياب القطرات المتكاثفة، مما رفع أقصى إنتاجية لحظية من 370 إلى 410 مل/م². ساعة بنسبة زيادة بلغت 10.8% ، وبمعدل إنتاج أعلى بحوالي 64% مقارنةً بالوحدة المرجعية التقليدية (250 مل/م². ساعة). في المرحلة الثانية، تم إدخال طبقة عائمة من ألياف السليلوز بسمك 75 مم على سطح الماء المالح لتعزيز الامتصاص الحراري وتقليل الفواقد الحرارية بالحمل، مع تطبيق فيض حراري خارجي منتظم قدره 600 وات/م² لمحاكاة الاستفادة من مصدر حرارة مهددة قابلة للاسترجاع. عند عمق ماء 100 مم، بلغت أقصى إنتاجية لحظية 560 مل/م². ساعة. ومع خفض عمق الماء المالح إلى 25 مم، ازداد معدل انتقال الحرارة بالتبخير، محققاً قيمة قصوى بلغت 600 مل/م². ساعة، أي بزيادة قدرها 140% مقارنةً بالوحدة الأساسية. كما ارتفع الحد الأقصى للإنتاجية التراكمية اليومية من 2.6 إلى 7.3 ل/م². يوم بنسبة تحسن بلغت 181% . وفي الوقت نفسه، ارتفعت الكفاءة الحرارية من 26.0% إلى 46.0% ، بما يعادل تحسناً قدره 77% . تؤكد النتائج أن التكامل بين التحسين الهندسي، وتعزيز الامتصاص الحراري السطحي، والاستفادة المعتدلة من الحرارة المهددة يسهم بصورة فعالة في تحسين أداء التقطير الشمسي، ويوفر نهجاً عملياً عالي الكفاءة لإنتاج المياه العذبة بصورة لامركزية ومستدامة.

الكلمات المفتاحية: وحدة تحليلية شمسية هرمية الشكل؛ مقطر شمسي محسن؛ ألياف سليلوزية؛ الكفاءة الحرارية؛ استغلال الحرارة المهددة.

1. Introduction

Freshwater scarcity has become an increasingly critical global challenge due to rapid population growth, industrial expansion, and climate variability, particularly in arid and semi-arid regions where conventional water resources are limited. Solar desalination represents a sustainable and decentralized solution that harnesses abundant solar energy to produce potable water with minimal environmental impact. Among solar-driven desalination technologies, basin-type solar stills are widely recognized for their structural simplicity, low capital cost, and operational reliability. However, their relatively low productivity remains the principal limitation preventing large-scale deployment. Consequently, extensive research efforts have been focused on improving evaporation condensation dynamics through geometric modification, thermal energy storage integration, surface enhancement techniques, and auxiliary heat recovery strategies. [Abed et al. \[1\]](#) performed a CFD investigation on the influence of glass cover inclination and internal heat transfer enhancement. They reported a maximum productivity of $0.2957 \text{ kg/m}^2 \cdot \text{h}$ at a 15° inclination, while increasing the tilt to 60° the productivity is reduced by 8.63% . The addition of internal fins further increased freshwater production by 53.32% due to enhanced internal convective heat transfer. [Muhamad et al. \[2\]](#) experimentally evaluated the effect of vertical spacing between the saline water surface and the glass cover in an inclined solar still. They found that a spacing of 4 cm produced the highest desalination efficiency of 31.45% . Increasing the spacing beyond this value weakened condensation heat transfer due to extended vapor travel distance. [Atiyah et al. \[3\]](#) numerically analyzed glass cover tilt angles ranging from 25° to 40° under Baghdad climatic conditions. Their results showed that a 25° tilt angle improved cumulative freshwater output by approximately 3.3% compared to larger angles. [AbdelMeguid and El Awady \[4\]](#) developed a mathematical model to assess the combined influence of glass tilt angle and optical properties on solar still performance. They determined an optimal fixed tilt angle of 21.7° for Matroh City, Egypt. Additionally, increasing the glass thickness from 5 mm to 20 mm reduced the daily yield from 6.6 to 5.2 kg/m^2 and decreased the efficiency from 31.5% to 24.9% . [Boughazala et al. \[5\]](#) numerically examined the effect of inclination angles between 30° and 38° in a double-slope solar still. The simulations revealed noticeable variations in internal heat distribution and condensation behavior with changing the tilt angle. [Kumar et al. \[6\]](#) utilized a three-dimensional multiphase CFD model to study the interaction between the tilt angle and basin depth in a single-slope solar still. They identified 20° as the optimal tilt angle when combined with an 18 mm water depth. [Dorji et al. \[7\]](#) experimentally investigated collector tilt angles between 20° and 45° in a passive solar thermal system. They reported peak thermal efficiencies of $60\text{--}70\%$ within the $20^\circ\text{--}30^\circ$ range and the higher tilt angles increased thermal losses despite higher incident radiation. [Mohamed et al. \[8\]](#) evaluated thermosyphon-assisted flat-plate solar collectors at tilt angles from 12° to 30° . The highest average daily effectiveness of 73% was achieved at 12° , accompanied by maximum absorber temperatures of 70.36°C . Increasing the tilt angle reduced overall effectiveness and heat utilization. [Chauhan and Shukla \[9\]](#) compared different condenser tilt configurations in winter conditions and observed that a 30° inclination achieved a maximum yield of $925 \text{ mL/m}^2 \cdot \text{h}$ compared to $760 \text{ mL/m}^2 \cdot \text{h}$ at 25° . The higher yield was attributed to improved condensate flow and reduced vapor resistance.

Among operational parameters, basin water depth has repeatedly been identified as a dominant factor due to its direct influence on thermal inertia and evaporation rate. [Kumar et al. \[10\]](#)

experimentally investigated water depths ranging from 0.5 to 2.5 cm and reported an optimal cumulative yield of 2.59 L/m²·day at 1.5 cm depth. Deeper water layers reduced peak hourly productivity and delayed temperature rise due to increased thermal capacity. [Abdul Hussein and Jabbar \[11\]](#) examined the effect of basin water height (10-30 mm) in a modified solar distillation system incorporating crushed porous coal rocks. They achieved a 56.3% productivity enhancement at 10 mm depth compared to the conventional flat absorber. Increasing water height reduced evaporation efficiency due to increased thermal capacity. [Shringi et al. \[12\]](#) experimentally evaluated basin depths between 2 cm and 10 cm in a pyramid solar still. The daily productivity increased from 490 ml at 10 cm depth to 1020 ml at 2 cm depth, demonstrating a strong inverse relationship between water depth and freshwater yield. [Ramzy et al. \[13\]](#) investigated the influence of basin water depth (1-3 cm) in a PCM and thermoelectric-assisted solar still. The optimal performance was recorded at 1 cm depth, achieving 8.30 L/m²·day compared to 3.58 L/m²·day for the conventional configuration. Increasing depth reduced energy efficiency from approximately 70% to 50%. [Fadhil and Abed \[14\]](#) experimentally studied basin depths between 2 cm and 10 cm in a pyramid solar still. They observed that productivity decreased sharply from 4.3 kg/m² at 2 cm depth to 0.5 kg/m² at 10 cm depth. The decline was attributed to delayed evaporation caused by increased thermal capacity. [Abdelgaleel et al. \[15\]](#) evaluated the influence of basin water volume (5-15 L) in a modified solar still integrating iron hemispherical pieces and steel wool pads. Increasing basin volume from 5 L to 15 L resulted in a 26% reduction in accumulated productivity. [Shareef et al. \[16\]](#) experimentally modified a pyramid solar still by increasing absorber surface area by approximately 20% and redesigning the glass cover to reduce internal air gap volume. The modified system achieved a freshwater yield of 4.4 L/m²·day compared to 2.6 L/m²·day for the conventional pyramid still. This corresponded to an efficiency improvement of approximately 73%. [Diab et al. \[17\]](#) redesigned the basin into an inverted pyramid configuration to increase effective heat transfer area. The modified still produced 4.40 kg/m²·day compared to the conventional configuration, representing a 46.67% productivity enhancement. Thermal efficiency improved to 29%, and freshwater cost was reduced by 45.45%. [Baiee et al. \[18\]](#) investigated the effect of rotational motion in a pyramid solar still at speeds ranging from 0.125 to 1.5 rpm. The optimal performance was achieved at 1 rpm, resulting in a 30.2% increase in freshwater yield compared to the stationary case. Thermal efficiency reached 46.2% at the optimal speed. [Soltanian et al. \[19\]](#) theoretically analyzed a reflector-integrated solar still design to increase solar irradiation on the basin surface. The proposed system increased predicted daily freshwater production from 7.5 L/day to 24 L/day. Daily energy efficiency improved from 25.6% to 32.6%. [Mohammed et al. \[20\]](#) developed a stepped basin pyramid solar still to better match the condensation surface area. The modified configuration increased daily productivity from 2.524 L/m²·day to 3.415 mL/m²·day, corresponding to a 35.3% enhancement. Thermal efficiency improved from 23.5% to 31.7%. [Godwin et al. \[21\]](#) applied Response Surface Methodology and Artificial Neural Network modeling to optimize pyramid solar still operating parameters. The optimized configuration improved thermal efficiency by approximately 42% and increased freshwater yield by about 1.8 L/m² compared to non-optimized operation. [Dewedar et al. \[22\]](#) enhanced pyramid solar still performance using intermittent spraying technology over a heated metal sheet. The modified still achieved 5 L/m²·day compared to 2.83 L/m²·day for the conventional system. Daily efficiency ranged between 57% and 69%, significantly exceeding conventional performance. [Alshamrani \[23\]](#) investigated staged modifications including reflectors, nano-enhanced thermal storage materials, and thermoelectric cooling in a pyramid solar still. The combination of reflectors and thermoelectric modules increased productivity by up to 148% compared to the baseline configuration. Thermal efficiency reached approximately 54%.

Absorber surface augmentation and porous media integration have emerged as highly effective enhancement approaches. [Ramzy et al. \[24\]](#) experimentally enhanced solar still performance by integrating natural and artificial porous absorbing materials into the basin. The steel wool pad configuration achieved 4.384 L/m²·day compared to 1.872 L/m²·day for the conventional still, corresponding to a significant productivity increase. Thermal efficiency improved from 17.13% to 32.74%, and the cost per liter decreased accordingly. [El Said et al. \[25\]](#) investigated a packed wire mesh absorber combined with pulsed water flow to enhance evaporation. The optimized configuration achieved approximately 3.007 L/day with an average thermal efficiency of 45%, representing a 102% improvement in water yield compared to the traditional still. The freshwater cost was reduced by 44% under optimal conditions. [Suraparaju and Natarajan \[26\]](#) evaluated the reuse of waste automobile tyre pieces as photothermal absorbers in a solar still basin. The modified system produced approximately 2.7 L/m² compared to 2.3 L/m² for the conventional configuration,

reflecting an 18% productivity enhancement. The cost per liter decreased by about 19.2%, and environmental indicators improved. Parikh et al. [27] enhanced absorber performance using $\text{Fe}_2\text{O}_3\text{-Cu}_2\text{O}$ hybrid nanomaterials applied to the basin surface and combined this with controlled glass cover cooling. The integrated system improved overall efficiency by approximately 34% compared to the conventional still. Without cooling, efficiency enhancement remained around 28%. Chinnasamy et al. [28] incorporated copper fins into the basin to increase effective heat transfer area. The fin-assisted still achieved a maximum daily productivity of 5.51 kg/m^2 , representing a 24% increase over the baseline system. Energy efficiency ranged between 27.52% and 39.07%, and the freshwater cost decreased to $\$0.019/\text{L}$. Suraparaju et al. [29] introduced a used brushed refinishing pad as a porous absorbing medium in a rectangular pyramid solar still. The modified configuration increased potable water yield by approximately 48% compared to the conventional still. Energy efficiency improved by about 9%, and the payback period shortened from 6.1 to 5.2 months. Kumar et al. [30] enhanced a conventional solar still by integrating honeycomb pads to intensify internal heat and mass transfer. The evaporative heat transfer coefficient increased by 116.88%, leading to a 51.70% rise in distillate output. The average internal efficiency improved by 21.89%, and the cost of water production decreased by 29.51%.

Thermal energy storage and nano-enhanced PCM strategies have been extensively investigated to extend productivity beyond peak solar hours. Zhang et al. [31] numerically analyzed PCM melting under segmented heating using the lattice Boltzmann method to understand how non-uniform heat flux affects convection and melting rate. Segmented heating reduced the complete melting temperature by up to 9.14% at Rayleigh number 10^4 , while increasing Rayleigh number from 10^4 to 10^6 accelerated melting by 17.4-19.4%. Prandtl and Stefan number increases further enhanced melting by 0.35-0.77% and 1.36-8.92%, respectively. Suraparaju and Natarajan [32] experimentally improved nocturnal productivity by integrating a biodiesel-paraffin PCM composite (1:1 by weight) into a solar still. The composite increased thermal conductivity by about 20.37%, raising basin water temperature by $\sim 16\%$ and absorber temperature by $\sim 10\%$. The modified still produced 3.6 and 3.4 L/m^2 over two days versus 2.2 and 2.1 L/m^2 for the conventional still, achieving $\sim 63\%$ productivity enhancement. They also reported $\sim 29.2\%$ reduction in cost per liter and $\sim 25.9\%$ shorter payback period. Vijayaraghavan et al. [33] investigated CuO nanoparticles as an energy storage enhancement in a pyramid solar still. The modified system achieved an average daily freshwater yield of 7.0 L/day compared to 3.7 L/day for the conventional unit, corresponding to an $\sim 89.19\%$ increase. The maximum basin water temperature increased from 61.5°C to 72°C , confirming stronger heat absorption and retention. Bouabidi et al. [34] experimentally assessed PCM mass loading in a pyramid solar still under real climatic conditions. The 2 kg PCM configuration achieved the best balance, reaching 32% energy efficiency and 2.023% exergy efficiency, along with a CO_2 reduction of 11.11 tons and carbon credit gain of 161.09. Increasing PCM to 4 kg reduced performance to 26% energy efficiency and 1.918% exergy efficiency despite remaining better than the conventional case. Patel et al. [35] experimentally enhanced a square pyramid solar still using mono- and hybrid-nanofluids at 0.1 wt% while maintaining 1 cm basin depth. Cu mono-nanofluid achieved 1640 mL/m^2 with 17.00% diurnal average efficiency, outperforming Al_2O_3 . The best case was hybrid $\text{Al}_2\text{O}_3\text{-Cu}$ (20:80), producing 2644 mL/m^2 with 34.50% efficiency, exceeding saline water performance by 25.19% in output and 27.41% in efficiency. Omara et al. [36] provided a focused review and scientometric assessment of nano-enhanced PCM (NE-PCM) for solar still applications. They identified that NE-PCM addresses the low thermal conductivity of conventional PCM and extends productivity beyond peak sunshine hours across multiple still geometries. Farouk et al. [37] developed an RSM-based predictive model for pyramid solar still performance using paraffin wax PCM enhanced with Ag nanoparticles. Optimization predicted an optimal Ag-Nano concentration of 2.78% at solar irradiation of 720 W/m^2 , ambient temperature of 40°C , and wind speed of 0.5 m/s . The model showed close agreement with experiments, reporting prediction errors of 5.2%, 4.9%, and 6.5% for key outputs (productivity and temperature responses). Negi et al. [38] critically reviewed NE-PCM for solar distillation, emphasizing performance gains alongside stability and compatibility limitations. They reported that thermal conductivity improvements can reach up to $\sim 264\%$ compared with base PCM within typical solar still operating ranges ($\sim 30\text{-}100^\circ\text{C}$). AbdelMeguid [39] theoretically evaluated PCM integration in optically optimized solar still concepts using multi-year climatic data for El Kharga, Egypt. The study showed that PCM can shift part of production toward nighttime and smooth output, but may reduce daytime peak yield under high irradiation. An optimal PCM thickness of 200 mm was identified as the best trade-off between stored heat and overall seasonal productivity.

Active and hybrid enhancement techniques further extend system capability. [Sheikholeslami and Khalili \[40\]](#) numerically investigated a photovoltaic-thermoelectric (PVT) system enhanced with nanofluid cooling, turbulator structures, and confined jet impingement. The combined configuration improved the total system efficiency by approximately 12.59% at optimized inlet velocity conditions. Electrical efficiency was increased by about 3.09%, while the total efficiency was improved by up to 10.45% under 810 W/m² irradiation. [Ahmadiani et al. \[41\]](#) developed a solar desalination cycle integrating a two-phase ejector with vacuum tube solar collectors. Under optimized pressure conditions, the system achieved a peak freshwater production rate of 1.35 kg/m²·h and a maximum daily yield of 8.47 kg/m². Annual cumulative production reached approximately 767 kg/m² under Tehran climatic data. [Shatar et al. \[42\]](#) experimentally enhanced solar still performance using thermoelectric cooling (TEC) with different transparent cover materials. With a glass cover and 4 A current input, productivity increased by approximately 76% compared to the reference still. The highest energy efficiency reached 23.6%, and exergy efficiency peaked at 7.04%. [Al-Tajer et al. \[43\]](#) investigated forced air circulation over the condensing surface of a pyramid solar still to improve condensation rates. Airflow velocities between 2 and 8 m/s increased the total daily yield by approximately 1.8% to 7%, with maximum productivity enhancement occurring during peak radiation hours. However, thermal efficiency was decreased from 48.5% to 39.5% at higher airflow rates. [Muftah et al. \[44\]](#) evaluated solar integration in a multi-effect desalination system under three operating modes. The hybrid solar-boiler configuration achieved the lowest water production cost of \$0.79/m³ compared to \$1.4/m³ for purely daytime solar operation. The inclusion of thermal storage enabled continuous clean operation at an intermediate cost of \$0.97/m³.

Complementary investigations emphasize the broader water-energy nexus. [Pacheco et al. \[45\]](#) experimentally assessed a non-intrusive solar desalination system under real island conditions, comparing an initial prototype with an improved pilot-scale design. Both configurations achieved salt removal above 99%, confirming high desalination quality. The redesigned pilot produced about 6.24 L/m²·day compared to ~0.45 L/m²·day for the initial unit, i.e., more than a tenfold increase. [Malik and Katyal \[46\]](#) conducted a GIS-based groundwater quality assessment in an industrialized district, combining GWQI, pollution indices, and multivariate statistics. Their analysis classified 47.62% of samples as good and 52.38% as poor quality using GWQI. Heavy metal pollution index results indicated 66.67% of samples had high pollution, and degree of contamination showed 90.48% were highly contaminated. [Bai et al. \[47\]](#) developed a lysine-based thin-film composite nanofiltration membrane and evaluated its permeability/selectivity for organics and mineral ions. The optimized membrane achieved organic retention exceeding 98% (humic acid and sodium alginate) while maintaining low retention for divalent ions (Mg²⁺/Ca²⁺ around 5.22-16.40%). Salt-induced swelling increased permeate flux substantially (~239.61-385.70% relative to salt-free conditions). [Eltarkawe et al. \[48\]](#) experimentally studied a parabolic trough solar receiver with and without a flat-top glass cover. Adding the cover increased the absorber outer surface temperature by about 11% and raised outlet water temperature by ~4%. Thermal efficiency improved, with reported theoretical and experimental efficiencies reaching 56.9% and 50.4%, respectively, giving ~4-5% improvement over the uncovered case. [Itabiyi et al. \[49\]](#) investigated the influence of tilt angle and mass flow rate on a parabolic trough concentrator under outdoor conditions. Their results showed that higher mass flow rates improved useful energy extraction and thermal effectiveness. A tilt angle around 90° provided superior performance compared with other tested angles.

[Mashfi et al. \[50\]](#) evaluated a hybrid solar dryer using adaptive glass tilting controlled by a servomotor and Arduino. The adaptive tilt increased average drying chamber temperature to 38.2 °C compared with 37.7 °C for the fixed-glass case. Drying performance improved, with potato weight loss reaching 70% versus 62% and grape weight loss 28% versus 24%. Specific moisture evaporation rate and maximum drying efficiency increased to 0.47 kg/kWh and 31.54%, confirming the benefit of dynamic glass adjustment. [Mistry et al. \[51\]](#) studied the microclimate effect inside a pyramid-shaped solar structure covered with UV-stabilized film. They recorded peak internal temperatures around 37.6 °C at noon (no-load) and ~36.2 °C under load, with relative humidity also slightly higher than ambient. Agronomic observations showed faster wheatgrass growth inside the pyramid (7 inches in 16 days vs 20 days outdoors), and earlier sprouting (2 days). [Noman and Manokar \[52\]](#) developed a modified tubular solar still using pistachio shell powder as a sensible heat storage medium. The modified unit produced 2.7 kg/day compared with 1.9 kg/day for the conventional tubular still, i.e., a 46.26% increase. Thermal efficiency improved from 16.86% to 22.36% and exergy efficiency from 1.35% to 1.98%. Economically, payback period

improved to 0.479 years versus 0.636 years, showing feasibility of biowaste-based enhancement. Liu et al. [53] optimized a nano-pyramid Al_2O_3 anti-reflective layer for perovskite solar cells by tuning the pyramid geometry. The best design ($h = 200 \text{ nm}$, $d = 200 \text{ nm}$) increased power conversion efficiency from 14.01% to 17.19%. Average light absorption rose to 96.05% compared to 87.41% for the planar reference, confirming reduced reflectivity. The optimized structure also increased JSC to 23.54 mA/cm^2 from 19.18 mA/cm^2 , demonstrating strong optical-electrical gains. Alqsair [54] enhanced a trays solar still using combined modifications including spiral heating coils, internal reflectors, a vapor exhaust fan, and nano-enhanced PCM. The heating coils alone improved productivity by about 101% compared with the same trays still without heaters. Adding nano-PCM provided an additional ~32% improvement, while the vapor exhaust fan contributed ~50% enhancement depending on configuration. The best combined cases increased yield up to 164% relative to a conventional still, and reduced water cost from 0.026 to 0.018 \$/L. Attia et al. [55] experimentally improved hemispheric solar still performance using low-cost metamorphic fabric layers (cement and slate) as sensible heat storage. The optimal configuration (20 mm slate, 10 mm water depth) produced $8.35 \text{ kg/m}^2\cdot\text{day}$ compared to $5.65 \text{ kg/m}^2\cdot\text{day}$ for the conventional hemispheric still, i.e., a 47.80% increase. Daily energetic efficiency improved by 46.90% and freshwater cost decreased by 31.73% for the slate case.

Despite the significant progress achieved in pyramid solar still enhancement techniques, several research gaps remain unresolved. Most previous studies focused on individual modifications such as porous absorbers, PCM integration, airflow cooling, or basin redesign without systematically examining the combined effects of geometric optimization, shallow brine operation, sustainable floating insulation, and controlled auxiliary heating within a unified framework. In addition, many high-performance systems depend on metallic inserts, nanoparticles, or active cooling techniques that increase cost, complexity, and environmental concerns, limiting their applicability in low-resource regions. Furthermore, although low-grade waste heat has shown considerable potential for improving solar desalination performance, its integration with naturally derived floating thermal layers in pyramid solar stills remains insufficiently explored. Therefore, the present work introduces and experimentally validates an integrated enhancement approach combining a floating cellulose fiber thermal layer, optimized glass-cover inclination, shallow saline water depth, and regulated waste-heat input. The proposed configuration aims to improve evaporation-condensation performance while maintaining structural simplicity, low energy demand, and environmentally sustainable operation. Moreover, the study provides a unified experimental assessment of the synergistic thermodynamic interactions among these parameters and their influence on freshwater productivity and thermal efficiency. Since many industrial systems discharge low-grade thermal energy within the range of 60-90°C, utilizing such recoverable waste heat in solar distillation systems offers a promising pathway for enhancing freshwater production without additional primary energy consumption.

2. Experimental Set Up and Methodology

An experimental investigation was carried out to assess the thermal performance and freshwater productivity of a pyramid solar still unit (PSSDU) under Egyptian summer climatic conditions. The study focused on three primary operational parameters: the thickness of a floating cellulose fiber thermal enhancement layer, controlled supplemental waste heat input, and the depth of saline water within the basin. The PSSDU featured a square mild-steel basin with internal dimensions of $1 \text{ m} \times 1 \text{ m}$. To maximize solar absorption, the basin's inner surface was coated with matte black paint, while the exterior was insulated using glass wool layer to reduce heat losses. A transparent glass cover, forming the pyramid configuration, served simultaneously as the solar radiation transmission medium and the condensation surface. To maintain a stable saline water level and ensure consistent mass balance throughout the evaporation condensation cycle, a compensation tank was connected to the basin. A floating cellulose fiber layer (density = 160 kg/m^3) was placed directly on the water surface, with thicknesses varied at 0, 25, 50, 75, and 100 mm according to experimental conditions. Unlike conventional passive insulation, this floating thermal enhancement layer actively modified heat distribution and evaporation dynamics by reducing conductive heat losses while maintaining efficient heat transfer at the water air interface. Controlled supplemental heating was applied via a variable-load electric immersion heater installed at the basin floor, simulating a source of low-grade waste heat. The heater output was regulated using a voltage controller to provide heat fluxes of 0, 200, 400, 600, 800, and 950 W/m^2 , corresponding to different operational scenarios. The selected

heat flux range was chosen to realistically simulate recoverable low-grade waste heat available from practical thermal systems. In real industrial and domestic applications, comparable thermal energy levels can be obtained from flue gases discharged by fossil-fuel power plants, industrial boilers, household gas water heaters, and natural gas combustion units. Reported flue gas temperature ranges typically vary between 90°C and 160°C depending on the source and operating conditions [56,57], corresponding to moderate thermal fluxes suitable for integration with solar desalination systems. Such temperature levels are commonly available in thermal power stations, gas-fired boilers, and small-scale industrial exhaust streams, thereby supporting the technical feasibility of coupling the proposed PSSDU configuration with real waste heat recovery applications[58]. The saline water depth was also varied and maintained at four discrete levels: 25, 50, 75, and 100 mm. Thermal measurements were acquired using nineteen calibrated K-type thermocouples, strategically positioned at the basin plate, within the saline water, at the floating layer interface, in the vapor region, and on the inner glass surface. Data were recorded at 30-minute intervals using a digital multi-channel data logger, capturing the transient thermal behavior of the system over the course of daily operation (09:00-18:00). Freshwater produced through condensation was collected in a graduated measuring cylinder connected to the condensate channel, and both instantaneous and cumulative yields were systematically recorded for each test condition. Figures 1 and 2 present a schematic diagram and photographic view of the experimental setup, respectively

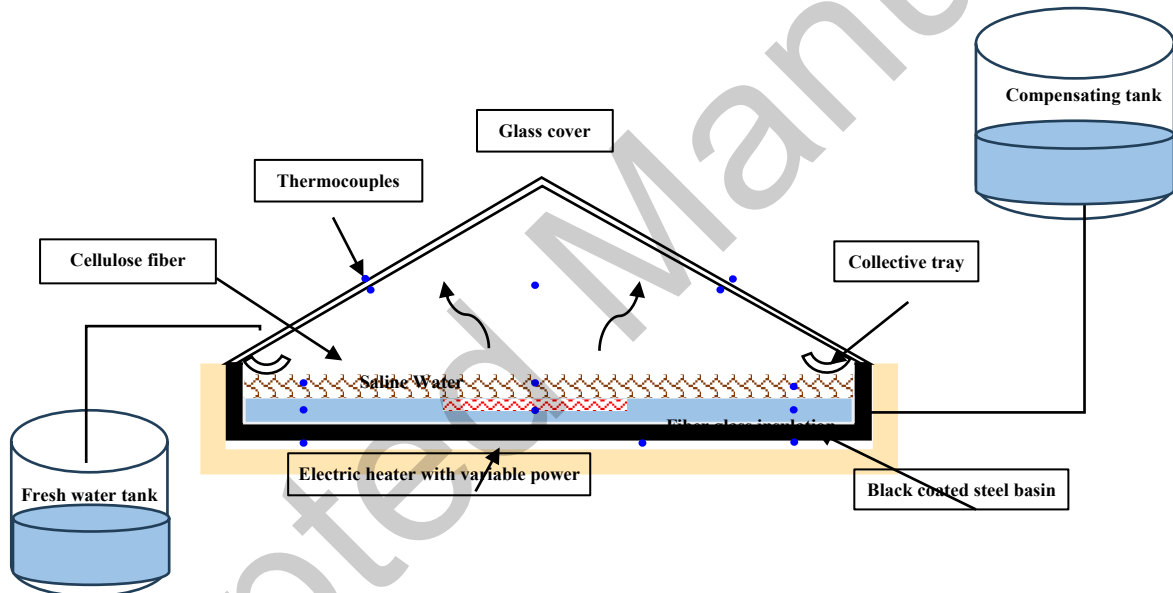


Fig. 1. A schematic diagram of the tested PSSDU.

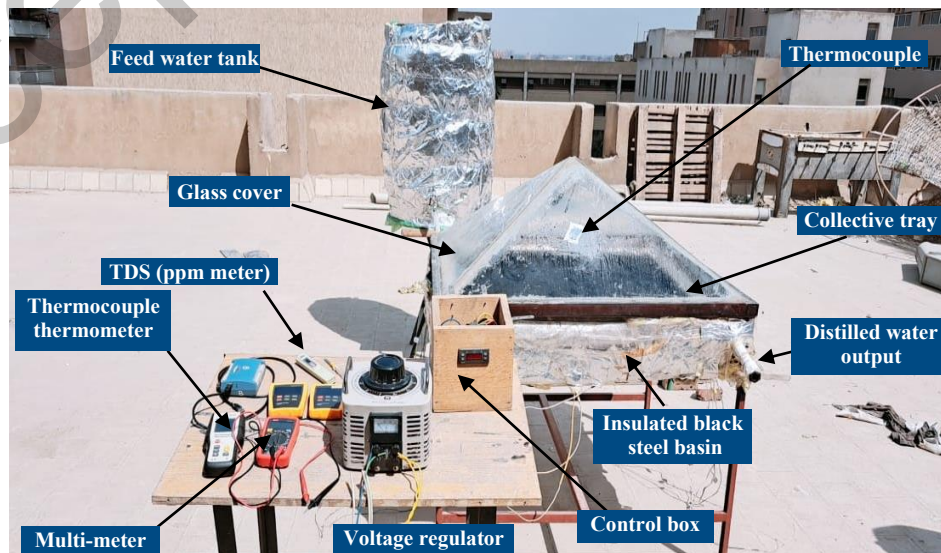


Fig. 2. Photograph of the experimental PSSDU setup.

1.1.2.1 Experimental Procedures

The experimental evaluation of the PSSDU was conducted following a systematic procedure to investigate the effects of the floating cellulose fiber thermal enhancement layer, controlled supplemental waste-heat input, and saline water depth on freshwater productivity and thermal performance. Prior to each test, the basin is cleaned, the water depth is adjusted to the target level (25, 50, 75, or 100 mm), and the floating cellulose fiber layer is positioned at the selected thickness (0, 25, 50, 75, or 100 mm). The compensation tank is filled to ensure that the water level remained constant throughout the experiment, avoiding fluctuations that could influence evaporation rates. For the tests involving waste heat input, the immersion heater is activated and set to the desired heat flux level (0, 200, 400, 600, 800, or 950 W/m²) using the voltage regulator, and the system is allowed to reach a quasi-steady thermal state before data recording commenced. Temperatures are measured at different locations, including the basin plate, saline water bulk, floating layer interface, vapor region, and inner glass surface, using nineteen calibrated K-type thermocouples connected to a digital multi-channel data logger. Temperature data are recorded every 30 minute intervals between 09:00 and 18:00 to capture diurnal variations and transient thermal behavior. Freshwater produced during condensation is continuously collected through the condensate channel into a graduated measuring cylinder. Both instantaneous and cumulative yields are monitored and recorded daily for each test condition. Between consecutive experiments, the basin is allowed to cool to ambient temperature, and the water and floating fiber layer are replaced or reset to ensure consistency and repeatability. Each experimental scenario is repeated at least three times to minimize random errors and improve statistical reliability of the measurements. The procedures described above ensured a controlled and reproducible experimental protocol, allowing systematic evaluation of the influence of the floating cellulose fiber layer, waste-heat supplementation, and saline water depth on the PSSDU performance.

1.2.2.2 Performance Evaluation and Data Analysis

The thermal and distillation performance of the pyramid-shaped solar still unit (PSSDU) was evaluated using systematically reduced experimental data collected at 30-minute intervals throughout 9 hours daily operating period. Measured parameters included basin plate temperature, saline water temperature, insulation layer temperature, glass-cover temperature, incident solar radiation, applied waste-heat input, and freshwater distillate yield. All performance indicators were determined following well-established analytical procedures reported in the solar desalination literature [59].

The average temperature of each system component-namely the basin base (T_b), saline water (T_{sw}), cellulose fiber insulation (T_{cel}), and inner glass cover (T_g) was calculated by averaging the recorded temperatures obtained from multiple thermocouples installed at different representative locations. For each component, the average temperature is expressed as:

$$\bar{T} = \frac{1}{n} \sum_{i=1}^n T_i \quad (1)$$

where T_i denotes the temperature recorded by the i^{th} thermocouple and n is the total number of thermocouples assigned to that component.

The daily freshwater productivity of the PSSDU was determined by summing the instantaneous distillate volumes collected at each sampling interval over the total operational time (t_t). The accumulated daily distillate yield is calculated as:

$$V_{dis,d} = \sum_{i=1}^{t_t} V_{dis,i} \quad (2)$$

where $V_{dis,i}$ represents the distilled water volume collected during each 30-minute interval.

To quantify the performance enhancement achieved by the modified PSSDU relative to the reference configuration, the percentage change in the daily freshwater production was evaluated using:

$$\Delta V_{dis}(\%) = \frac{V_{dis,d,mod} - V_{dis,d,ref}}{V_{dis,d,ref}} \times 100 \quad (3)$$

where $V_{dis,d,mod}$ and $V_{dis,d,ref}$ are the daily distillate volumes produced by the modified and reference PSSDU, respectively.

The instantaneous thermal efficiency of the solar still ($\eta_{th,i}$) was defined as the ratio of the useful thermal energy that utilized for freshwater evaporation to the total thermal energy supplied to the system during the corresponding time interval. This efficiency is expressed as:

$$\eta_{th,i} = \frac{\rho_{dis,i} V_{dis,i} h_{fg,i}/t_c}{(G_{s,i} A_b + Q_h)} \quad (4)$$

where $\rho_{dis,i}$ is the density of distilled water at the collection temperature (kg/m^3), $V_{dis,i}$ is the instantaneous distillate volume (m^3), $h_{fg,i}$ is the latent heat of vaporization (J/kg), t_c is the collection time interval ($30 \text{ min} = 1800 \text{ s}$), $G_{s,i}$ is the instantaneous solar irradiance (W/m^2), A_b is the basin area (1 m^2), and Q_h represents the applied waste-heat flux (W).

The latent heat of vaporization of water was evaluated as a function of saline water temperature using the following temperature-dependent correlation, valid over the range of $0\text{-}200^\circ\text{C}$:

$$h_{fg,sw} = 1000[2501.9 - 2.40706 T_{sw} + (1.192217 \times 10^{-3} T_{sw}^2) - (1.5863 \times 10^{-5} T_{sw}^3)] \quad (5)$$

where T_{sw} is the saline water temperature in $^\circ\text{C}$.

1.3.2.3 Uncertainty Analysis

The evaluation of the PSSDU performance accounted for experimental uncertainties in the key parameters, including instantaneous freshwater productivity $V_{d,ts}$, accumulated daily productivity $V_{d,acc}$, and thermal efficiency η_{th} . These parameters were derived from measured variables such as basin and water temperatures, solar radiation intensity, water depth, and collected distilled water volume. To quantify the influence of measurement errors on these derived quantities, the propagation of uncertainty was analyzed following the method of Kline and McClintock [60], which considers the combined effects of multiple independent measurement inaccuracies on the calculated results. Maximum uncertainties associated with the principal measured and calculated quantities are summarized in Table 1. The analysis indicates that all uncertainties remain within acceptable ranges for solar desalination experiments, ensuring the reliability and reproducibility of the reported enhancements in freshwater yield and thermal performance. Detailed derivations and additional uncertainty calculations are provided in Appendix A for transparency and verification.

Table 1. Maximum uncertainties of measured and calculated parameters.

Parameter	Instrument / Method	Accuracy	Maximum Uncertainty
Temperature (K-type thermocouples)	Calibrated K-type	$\pm 0.5^\circ\text{C}$	$\pm 0.5^\circ\text{C}$
Solar irradiance	Solar Power Meter	$\pm 5 \text{ W/m}^2$	$\pm 2 \%$
Distilled water volume	Graduated cylinder	$\pm 2.5 \text{ ml}$	$\pm 1 \%$
Electrical heat input	Digital power meter	$\pm 1 \%$	$\pm 1 \%$
Instantaneous productivity	Calculated (propagation method)	-	$\pm 2.8 \%$
Accumulated productivity	Calculated (propagation method)	-	$\pm 2.1 \%$
Thermal efficiency	Calculated (propagation method)	-	$\pm 1, 8 \%$

3. Results and Discussion

This section presents a detailed experimental results of the thermal behavior and freshwater productivity of the developed PSSDU under high solar radiation conditions. The objective of the present study is to determine the dominant parameters governing the evaporation-condensation mechanism and to identify the optimal operating configuration that maximizes distillate yield while maintaining thermal stability. Particular emphasis is placed on the thickness of the floating cellulose fiber layer and the saline water depth, as these variables exhibited the most pronounced influence on interfacial heat localization, vapor generation rate, and overall system efficiency. Other design parameters, including glass cover inclination angle, and the auxiliary heat flux input, are discussed selectively to justify the final configuration adopted for in-depth parametric evaluation.

All the experimental runs were conducted during June 2025 under the climatic conditions of Cairo, Egypt (30.1° N, 31.3° E), on the rooftop of the El-Khalafawy Building, Faculty of Engineering, Benha University, ensuring unobstructed solar exposure. Measurements were recorded at 30-minute intervals between 09:00 and 18:00 to capture diurnal thermal transients. A total of 27 experimental runs were conducted under monitored environmental conditions. The recorded average minimum and maximum solar radiation intensities were from 720 to 1100 W/m², the ambient temperature was between 32.5 and 40.2 °C, and the air velocity were from 3.2 to 4.5 m/s, confirming stable and representative summer conditions suitable for comparative analysis is presented in (Table 2). The relatively narrow variation in climatic parameters during the test period ensured that observed performance differences were primarily attributable to controlled operational variables rather than external fluctuations.

Table 2. Summary of the average climatic conditions during June 2025.

Parameter	Average Min.	Average Max.
Solar intensity, W/m ²	720	1100
Ambient air temperature, °C	32.5	40.2
Ambient air velocity, m/s	3.2	4.5

The results demonstrate that the floating cellulose fiber layer significantly alters internal thermal gradients by concentrating absorbed heat near the evaporation interface while reducing conductive losses to the bulk water. Among the tested configurations, a 75 mm floating layer combined with a shallow water depth of 25-50 mm produced the highest and most stable freshwater productivity. Increasing the layer thickness beyond this value introduced additional thermal resistance that limited effective heat transfer to the interface, whereas thinner layers provided insufficient thermal localization. Similarly, reducing water depth decreased thermal inertia and accelerated temperature rise during peak irradiation hours, while excessive depth dampened the evaporation rate due to increased heat capacity. These findings confirm that optimal productivity arises from a balance between heat confinement at the surface and adequate energy supply to sustain continuous evaporation.

To ensure reproducibility, the reference configuration and the identified optimal case were repeated on three separate days under comparable solar radiation levels. The variation in accumulated daily productivity did not exceed ±3%, and temperature profiles followed consistent temporal trends with negligible deviation. This repeatability confirms the robustness of the experimental setup and supports the statistical reliability of the derived optimal operating conditions despite the finite number of test runs.

Water quality analysis further verified the desalination effectiveness of the developed PSSDU. Comparative physicochemical characterization of the feed saline water and distilled output revealed substantial reductions in salinity and impurities as in (Table 3).

Table 3. Characteristics of the water before and after the desalination process

Parameter	Before	After	WHO Guideline
pH	8.12	7.21	7-8
Turbidity (NTU)	286	0.38	5
Electrical Conductivity (EC, µS/cm)	51,200	182	-

Chloride (Cl^- , ppm)	18,450	21	200
Total Dissolved Solids (TDS, ppm)	33,800	165	500

The pH decreased from 8.12 to 7.21, turbidity was reduced from 286 to 0.38 NTU, electrical conductivity decreased from 51,200 to 182 $\mu\text{S}/\text{cm}$, chloride concentration dropped from 18,450 to 21 ppm, and total dissolved solids (TDS) declined from 33,800 to 165 ppm. All measured parameters of the distilled water fall within the World Health Organization (WHO) drinking water guidelines, confirming high desalination efficiency and potable water quality.

Overall, the structured parametric methodology, controlled environmental monitoring, repeated validation of critical configurations, and comprehensive water quality assessment collectively demonstrate that integrating an optimized floating cellulose fiber thermal layer with shallow water depth conditions significantly enhances the performance of pyramid solar stills. The results provide strong experimental evidence that interfacial thermal localization, rather than bulk heating alone, is the governing mechanism for productivity enhancement in the proposed configuration

1.4.3.1 Validation of the Experimental Results

To further substantiate the reliability of the present experimental findings, a comparative validation was conducted against the field investigation reported by Salem et al. [59], which was performed in Egypt under comparable high solar radiation conditions. The similarity in geographical location and climatic characteristics provides an appropriate experimental benchmark for assessing the temporal productivity behavior and thermophysical consistency of the developed PSSDU. Figure 3 illustrates the comparison between the instantaneous freshwater productivity reported in [59] and the corresponding values obtained in the present study under similar operating conditions. The reference data were digitized from the published graphical results to enable a consistent time-based comparison. The analysis demonstrates strong agreement in the overall productivity evolution throughout the day. In both studies, distillate production is minimal during early morning hours, increases progressively with rising solar irradiance, reaches a maximum between 13:00 and 14:00, and subsequently declines toward sunset. This consistent diurnal trend confirms that the evaporation condensation mechanism in the developed system follows the expected thermodynamic response observed in established experimental investigations. While the modified PSSDU in the present work achieved a moderately higher peak instantaneous productivity (approximately $380 \text{ mL}/\text{m}^2\cdot\text{h}$) compared to about $300 \text{ mL}/\text{m}^2\cdot\text{h}$ reported in [59], the magnitude range and temporal distribution remain comparable. The observed enhancement is attributed to the incorporation of the floating cellulose fiber thermal enhancement layer, which improves interfacial heat concentration and reduces conductive heat losses to the bulk saline water, thereby intensifying evaporation during peak radiation periods. It is emphasized that this validation serves to confirm trend consistency and physical behavior rather than to establish exact numerical equivalence, as variations in basin geometry, enhancement approach, and thermal management strategies inherently influence absolute productivity values. Overall, the close agreement in productivity pattern, peak timing, and order of magnitude provides strong evidence of experimental reliability and supports the credibility of the reported performance improvements achieved by the proposed configuration.

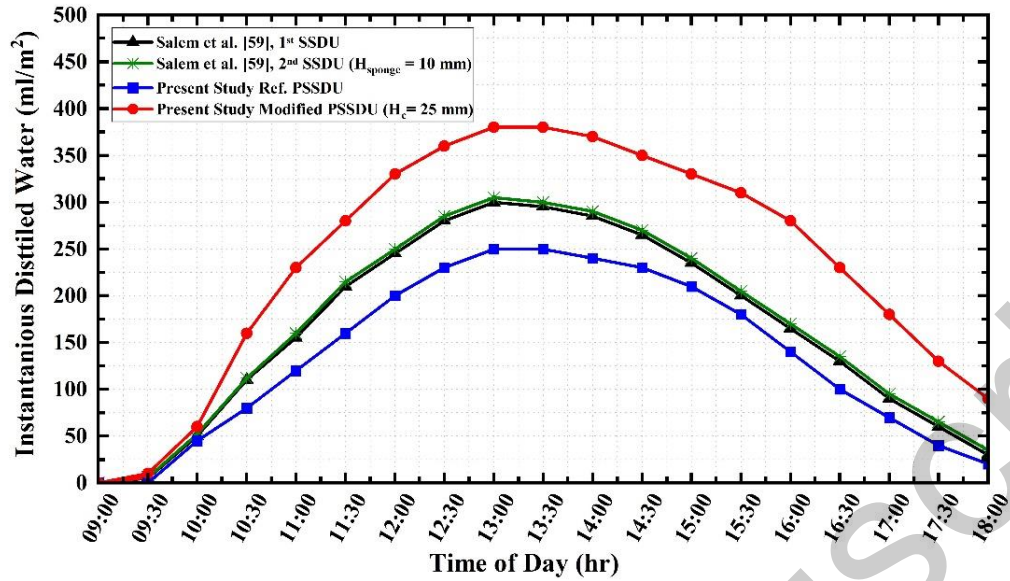


Fig. 3. Comparison of instantaneous freshwater productivity between the present PSSDU and the experimental results of Salem et al. [59] under similar Egyptian climatic conditions.

1.5.3.2 Selection of the Reference and Optimal Operating Conditions

Before conducting the detailed parametric analysis on floating layer thickness and saline water depth, a preliminary screening study was performed to establish a reliable reference case and to determine the most effective baseline operating configuration of the PSSDU. This stage evaluated the influence of three principal design and operating parameters: glass cover tilt angle (35° and 45°), floating material type (cellulose fiber), and controlled waste heat input within the range of 0-950 W/m². The objective was to isolate the configuration that maximizes evaporation-condensation efficiency while maintaining practical feasibility under realistic waste-heat availability. The experimental results clearly demonstrated that increasing the glass cover inclination from 35° to 45° enhanced freshwater productivity. As summarized in Tables 4 and 5, the Maximum instantaneous productivity increased from 370 to 410 mL/m²·h, while accumulated daily productivity rose from approximately 4.3 to 4.6 L/m²·day, corresponding to improvements of about 48% and 64% in maximum instantaneous productivity, and 65% and 77% in accumulated daily productivity, relative to the conventional reference configuration, respectively.

Thermal efficiency also improved from approximately 33% to 36% as in (Table 6). The superior performance at 45° is attributed to improved solar interception during peak radiation hours and more efficient condensate drainage along the glass surface, which reduces droplet accumulation and enhances continuous vapor condensation.

Table 4. Summary of the maximum instantaneous productivity with different parameters.

Case	Description of Operating Condition	Maximum Instantaneous Productivity (mL/m ² ·h)
1	Reference PSSDU (baseline configuration)	250
2	Glass tilt angle = 35°	370
3	Glass tilt angle = 45°	410
4	Floating cellulose fiber layer (75 mm), water depth = 100 mm	500
5	Floating cellulose fiber layer (75 mm), water depth = 100 mm, auxiliary heat = 600 W/m ²	560
6	Floating cellulose fiber layer (75 mm), water depth = 25 mm, auxiliary heat = 600 W/m ²	600

Table 5. Summary of the maximum accumulated productivity with different parameters.

Case	Description	Productivity (L/m ² ·day)	Improvement vs. Reference (%)
1	Reference PSSDU	2.6	-
2	35° tilt	4.3	+65%
3	45° tilt	4.6	+77%
4	75 mm layer	6	+131%
5	75 mm + 600 W/m ²	6.3	+142%
6	75 mm + 25 mm depth + 600 W/m ²	7.3	+181%

Table 6. Summary of the maximum thermal efficiency with different parameters.

Case	Description	Thermal Efficiency (%)	Improvement vs. Reference (%)
1	Reference PSSDU	26	-
2	35° tilt	33	+27%
3	45° tilt	36	+38%
4	75 mm layer	40	+54%
5	75 mm + 600 W/m ²	42	+62%
6	75 mm + 25 mm depth + 600 W/m ²	46	+77%

For instance, incorporating a 75 mm cellulose fiber layer at 100 mm water depth increased instantaneous productivity to approximately 500 mL/m²·h under 600 W/m² auxiliary heating, while the corresponding daily yield approached 6 L/m²·day under optimized depth conditions. Even at 100 mm depth, the cellulose layer significantly enhanced performance relative to the baseline configuration, demonstrating its superior thermal retention capability and effective interfacial heat localization. This behavior enhances evaporation without excessively impeding vapor transport. The influence of auxiliary heating revealed that productivity increased progressively with waste heat input up to 600 W/m². At this level, the configuration with a 75 mm cellulose fiber layer achieved approximately 550-560 mL/m²·h instantaneous productivity and nearly 6.3 L/m²·day accumulated yield under optimized depth conditions, with peak thermal efficiency reaching about 42%. Increasing the heat flux beyond 600 W/m² did not produce proportional gains; instead, productivity declined at 800 and 950 W/m², indicating the onset of vapor saturation and diminishing returns due to limited condensation capacity. Therefore, 600 W/m² was identified as the optimal supplemental heat input. Notably, this level corresponds to moderate low-grade waste heat typically available from industrial exhaust streams, supporting the practical applicability of the proposed enhancement strategy. It should be emphasized that the applied 600 W/m² represents externally available low-grade waste heat rather than additional fuel-derived energy, thereby preserving the sustainability and overall energy recovery efficiency of the hybrid system.

Further improvement was achieved by simultaneously reducing saline water depth to 25 mm while maintaining the 75 mm cellulose fiber layer and 600 W/m² auxiliary heat input. Under this combined condition, the system reached the highest performance among all tested cases, with peak instantaneous productivity approaching 600 mL/m²·h, accumulated yield of approximately 7.3 L/m²·day, and peak thermal efficiency of 45-46%, representing improvements of roughly 140 % in instantaneous productivity and more than 180% in daily productivity relative to the baseline configuration. Based on this structured comparative analysis, a glass cover tilt angle of 45° and a waste heat input of 600 W/m² were selected as fixed operating parameters for the subsequent detailed investigation of floating layer thickness and saline water depth. This selection ensures that the following analysis is conducted under thermally optimized yet practically achievable conditions, thereby strengthening the validity and applicability of the reported performance enhancements.

1.6.3.3 Effect of Floating Cellulose Fiber Layer Thickness on the Performance of the Enhanced PSSDU

Figure 4 presents the diurnal variation of instantaneous freshwater productivity for the reference PSSDU and for floating cellulose fiber layer thicknesses of 25, 50, 75, and 100 mm, while

maintaining a constant glass cover tilt angle of 45° and saline water depth of 100 mm to isolate the sole influence of layer thickness. The reference configuration exhibited a typical bell-shaped productivity curve, increasing from negligible values at 09:00 to a peak of approximately $250 \text{ mL/m}^2\cdot\text{h}$ at 13:00-14:00, followed by a gradual decline toward sunset. It was found that introducing a 25 mm floating layer increases the peak productivity to nearly $380 \text{ mL/m}^2\cdot\text{h}$, representing an enhancement of about 52% relative to the reference case. Also, increasing the thickness to 50 mm further elevates the maximum instantaneous productivity to approximately $450 \text{ mL/m}^2\cdot\text{h}$, corresponding to an 80% improvement. The highest performance was achieved at 75 mm thickness, where the peak value approached $500 \text{ mL/m}^2\cdot\text{h}$, doubling the reference productivity and yielding an enhancement of approximately 100%. In contrast, further increasing the thickness to 100 mm reduces the peak to about approximately $410 \text{ mL/m}^2\cdot\text{h}$, corresponding to an enhancement of about 65% relative to the reference case, but representing nearly an 18% reduction compared with the optimal 75 mm configuration. The same trend was observed in average daytime productivity, which is increased from roughly $200\text{--}220 \text{ mL/m}^2\cdot\text{h}$ for the reference case to $360\text{--}380 \text{ mL/m}^2\cdot\text{h}$ at 75 mm, before declining to approximately $320\text{--}340 \text{ mL/m}^2\cdot\text{h}$ for a layer with 100 mm thickness.

This behavior can be analytically interpreted through simple conductive heat transfer relationship

$$Q_{cond} = \frac{kA(T_b - T_w)}{L} \quad (6)$$

where k is the effective thermal conductivity of the cellulose fiber layer, A is the heat transfer area, $T_b - T_w$ represents the temperature gradient between the basin plate and the adjacent water layer, and L is the floating layer thickness. Increasing L from 25 to 75 mm reduces conductive heat penetration into the bulk saline water, thereby suppressing thermal losses to deeper layers and concentrating energy near the evaporation interface. This interfacial heat localization elevates surface temperature, intensifies vapor pressure, and enhances the evaporation rate, which explains the progressive increase in productivity. However, when the thickness reaches 100 mm, the additional thermal resistance begins to impede effective upward heat transport and may restrict vapor diffusion through the porous structure, reducing the useful heat flux available for phase change. Consequently, the experimentally identified optimum thickness of 75 mm represents a balanced thermal resistance condition in which conductive losses are minimized without significantly obstructing heat delivery to the evaporation surface. These results confirm that the observed enhancement is governed by competing heat transfer mechanisms rather than empirical variation alone, providing strong thermophysical justification for the selected optimal configuration.

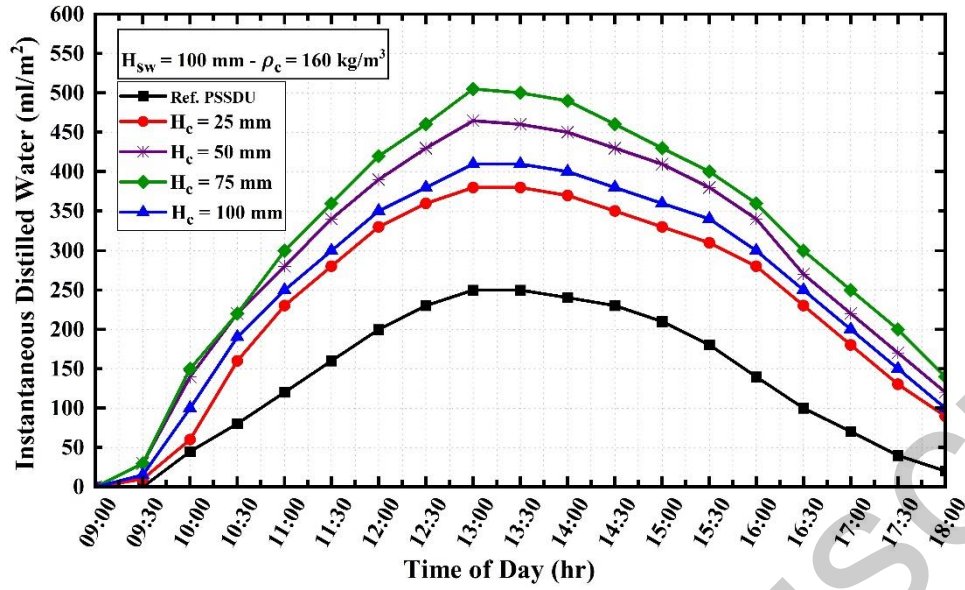


Fig. 4. Effect of floating cellulose fiber thermal enhancement layer thickness on instantaneous freshwater productivity of the PSSDU at a saline water depth of 100 mm.

Figure 5 illustrates the hourly evolution of accumulated distilled water that yield for the reference pyramid solar still unit (Ref. PSSDU) and for floating cellulose fiber layer thicknesses of 25, 50, 75, and 100 mm at a constant saline water depth of 100 mm and cellulose density of 160 kg/m^3 . The cumulative productivity exhibits a continuously increasing trend throughout the day for all configurations, reflecting the progressive integration of hourly evaporation rates under increasing solar intensity from morning to mid-afternoon, followed by a reduced growth rate toward sunset. The reference system recorded a final accumulated yield of approximately $2.6 \text{ L/m}^2 \cdot \text{day}$ at 18:00. Incorporating a 25 mm cellulose layer increased the daily yield to nearly $4.5 \text{ L/m}^2 \cdot \text{day}$, corresponding to an enhancement of about 73% relative to the reference case. Further increasing the thickness to 50 mm raised the total productivity to around $5.6 \text{ L/m}^2 \cdot \text{day}$ ($\approx 115\%$ improvement), while the 75 mm configuration achieved the highest accumulated yield of approximately $6 \text{ L/m}^2 \cdot \text{day}$, representing an overall enhancement of nearly 130% compared with the conventional still. However, increasing the thickness to 100 mm reduced the final yield to nearly $5 \text{ L/m}^2 \cdot \text{day}$, which, although still about 92% higher than the reference system, indicates a decline of approximately 17% compared with the optimal 75 mm thickness. The cumulative production trends confirm that the 75 mm floating cellulose layer provides the most favorable thermal resistance for maximizing evaporation efficiency. From a heat transfer perspective, increasing the layer thickness reduces conductive heat dissipation to the lower saline bulk according to $q_{\text{cond}} \propto 1/L$, thereby concentrating thermal energy at the evaporation interface and sustaining higher surface temperatures over extended periods. This mechanism explains the steeper slope of the cumulative productivity curve observed for 50 mm and 75 mm cases, particularly between 12:00 and 16:00 when solar radiation reaches peak levels. Nevertheless, excessive thickness (100 mm) introduces additional thermal resistance that limits effective heat flux transmission toward the water vapor interface and may hinder vapor diffusion through the porous structure, resulting in a reduced evaporation rate and consequently lower cumulative yield. The consistency of this behavior throughout the entire diurnal period demonstrates that the observed performance enhancement is thermophysically governed rather than transient, and clearly identifies 75 mm as the optimal floating layer thickness under the present operating conditions.

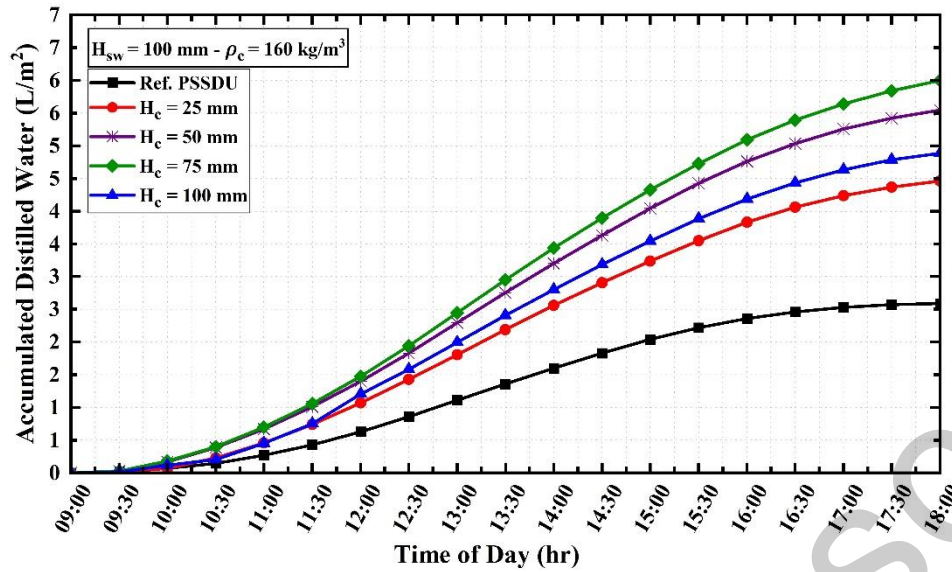


Fig. 5. Effect of based- floating cellulose fiber thermal enhancement layer thickness on accumulated freshwater productivity of the PSSDU at a saline water depth of 100 mm.

Figure 6 depicts the temporal variation of thermal efficiency for the reference PSSDU and the four floating cellulose fiber thicknesses (25, 50, 75, and 100 mm) at a constant saline water depth of 100 mm and a density of 160 kg/m^3 . The efficiency profiles for all configurations follow the typical diurnal pattern, increasing steadily from morning hours as solar irradiance intensifies, reaching maximum values between 13:00 and 14:00, and subsequently declining toward sunset due to reduced incident radiation and lower basin temperatures. The reference still attained a peak thermal efficiency of approximately 26% at midday. Introducing a 25 mm floating layer increased the maximum efficiency to nearly 35%, representing an improvement of about 35% relative to the reference case. Increasing the thickness to 50 mm further elevated the peak efficiency to approximately 38% ($\approx 46\%$ enhancement), while the 75 mm configuration achieved the highest value of nearly 40%, corresponding to an improvement of about 54% compared with the conventional system. However, increasing the thickness to 100 mm resulted in a slight reduction in peak efficiency to nearly 37%, which, although still around 42% higher than the reference case, reflects a decrease of approximately 7-8% compared with the optimal 75 mm thickness. Thermal efficiency is governed by the ratio of useful latent heat utilized for evaporation to the total incident solar energy. The addition of the floating cellulose layer modifies the internal energy balance by reducing conductive heat losses to the lower bulk water and enhancing heat localization near the evaporation interface. As thickness increases from 25 to 75 mm, the conductive heat flux to deeper layers decreases in accordance with Fourier's law, leading to higher interfacial temperatures and increased vapor generation. Consequently, a larger fraction of the absorbed solar energy is converted into latent heat of vaporization, thereby increasing efficiency. Nevertheless, when the thickness reaches 100 mm, the additional thermal resistance begins to restrict effective upward heat transfer and may limit vapor transport through the porous matrix. This reduces the net useful heat available for phase change despite continued solar absorption, explaining the slight efficiency decline relative to the 75 mm configuration. The consistency between productivity and efficiency trends confirms that 75 mm represents the optimal thermal resistance that maximizes energy utilization without introducing excessive internal heat transfer limitations under the specified operating conditions.

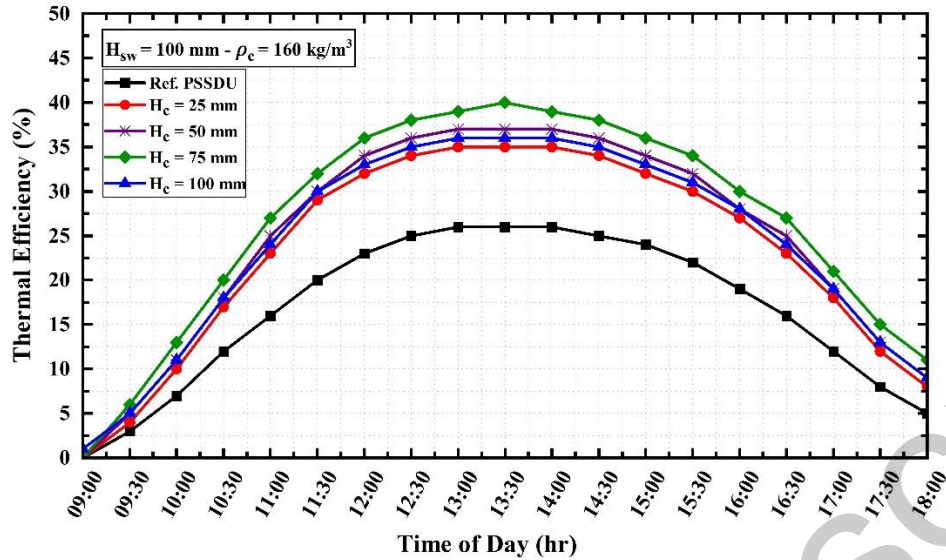


Fig. 6. Effect of a floating cellulose fiber thermal enhancement layer thickness on the thermal efficiency of the PSSDU at a saline water depth of 100 mm.

1.7.3.4 Effect of waste heat addition on the performance of the enhanced PSSDU

Figure 7 illustrates the effect of controlled waste-heat input on the instantaneous freshwater productivity of the enhanced PSSDU operating at a saline water depth of 100 mm, an optimal cellulose layer thickness of 75 mm, and a cellulose density of 160 kg/m³. The applied auxiliary heat flux levels were 0, 200, 400, 600, 800, and 950 W/m². Under solar-only operation (0 W/m²), the system exhibited a typical diurnal productivity curve, reaching a peak value of approximately 450-460 mL/m²·h around 13:00-14:00. Introducing moderate waste-heat input significantly intensified the evaporation rate; the peak productivity increased to nearly 500 mL/m²·h at 200 W/m² and to about 520-530 mL/m²·h at 400 W/m². The maximum performance was achieved at 600 W/m², where the instantaneous productivity approached 550-560 mL/m²·h, corresponding to an enhancement of approximately 20-22% relative to the solar-only case. However, further increasing the supplied heat flux to 800 W/m² and 950 W/m² resulted in a noticeable reduction in peak productivity to nearly 410-420 mL/m²·h and 270-280 mL/m²·h, respectively, despite the higher thermal input. This non-monotonic behavior can be interpreted through the coupled heat and mass transfer processes governing evaporation and condensation within the still, where excessive heating can elevate internal vapor temperature and increase heat losses and/or reduce the effective condensation driving potential, ultimately limiting net distillate production. At low to moderate auxiliary heat levels (≤ 600 W/m²), the additional thermal energy elevates the basin water temperature, thereby increasing the saturation vapor pressure at the evaporation interface and enlarging the vapor pressure difference between the water surface and the inner glass cover. This enhanced thermodynamic driving force intensifies the evaporation rate and increases latent heat transfer, leading to higher distillate productivity. Conversely, when the heat flux exceeds 600 W/m², the internal thermal equilibrium shifts. Both the saline water and the inner glass temperatures rise substantially; if the glass temperature approaches the vapor temperature, the effective vapor-glass temperature difference diminishes (Fig. 8). Since the condensation rate is directly proportional to this temperature gradient, a reduced difference weakens condensation efficiency. Simultaneously, excessive vapor generation elevates internal humidity and vapor density, increasing condensation resistance at the glass surface and potentially transitioning the system from evaporation-controlled to condensation-controlled operation. Under such conditions, additional heat input does not translate into proportional freshwater production. Therefore, 600 W/m² represents an optimal thermally balanced operating condition at which evaporation enhancement and condensation capacity remain harmonized, maximizing instantaneous freshwater productivity without inducing condensation limitations.

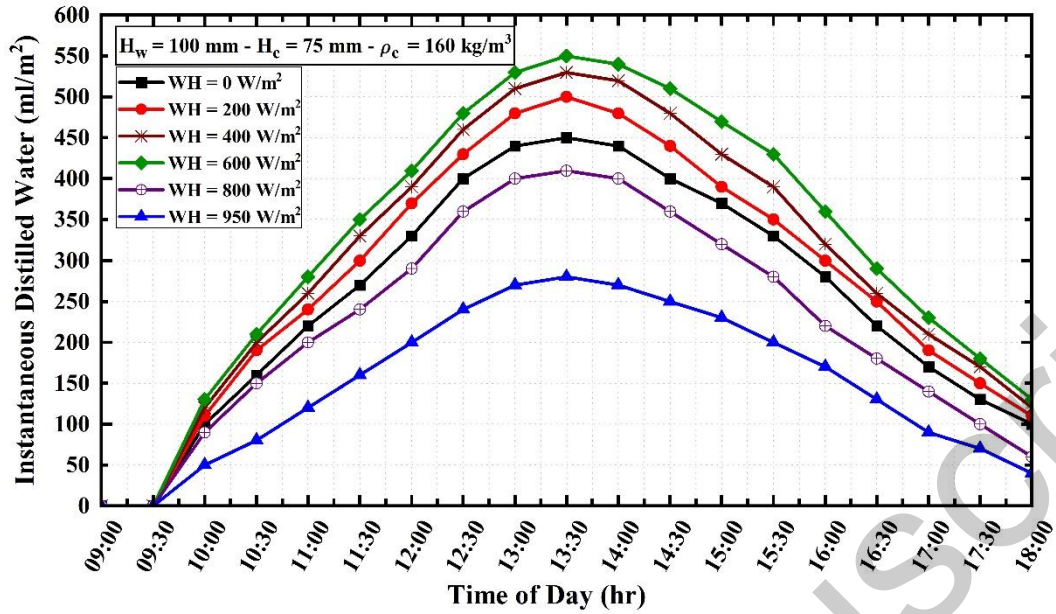


Fig. 7. Effect of waste heat input on instantaneous freshwater productivity of the enhanced PSSDU.

Figure 8 presents the temporal variation of key system temperatures under different controlled waste-heat (WH) input levels, including (a) basin liner (T_b), (b) saline water (T_{sw}), (c) floating cellulose fiber layer (T_c), (d) water vapor (T_v), and (e) inner glass cover (T_g). For all monitored components, temperatures increased progressively from morning hours, reached peak values between 13:00 and 14:00 h, and subsequently declined toward sunset, reflecting the combined influence of solar irradiance intensity and auxiliary thermal input. In the absence of waste heat ($WH = 0 \text{ W/m}^2$), the basin and saline water temperatures exhibited moderate midday peaks, indicating reliance solely on incident solar radiation. As the auxiliary heat flux increased from 200 to 600 W/m^2 , a consistent elevation in T_b and T_{sw} was observed, demonstrating enhanced heat storage within the basin and improved thermal stratification near the evaporation surface. The maximum temperature levels were recorded at 950 W/m^2 , where basin temperatures approached approximately 90–92°C and saline water temperatures exceeded 85°C at peak hours. This substantial rise confirms the effectiveness of controlled waste-heat integration in stabilizing and intensifying the thermal driving force for evaporation. The floating cellulose fiber layer exhibited temperatures slightly higher than the bulk saline water, particularly at elevated WH levels, indicating its role as a localized thermal interface that concentrates heat near the evaporation zone while limiting downward conductive losses. Similarly, vapor temperature trends closely followed those of the saline water, confirming enhanced phase-change activity under higher thermal input. The inner glass cover temperature increased with rising WH; however, the temperature difference between vapor and glass remained sufficient to sustain condensation, particularly at moderate waste-heat levels (around 600 W/m^2). At the highest input (950 W/m^2), the vapor-glass temperature gradient is slightly decreased during peak hours, suggesting a potential limitation in condensation efficiency despite higher evaporation rates. Overall, the results demonstrate that controlled waste-heat input significantly modifies the internal thermal regime of the pyramid solar still by elevating basin and evaporation-interface temperatures while maintaining a functional vapor-glass temperature gradient. The findings also indicate that moderate auxiliary heat levels provide an optimal thermal balance, enhancing evaporation without excessively diminishing condensation driving forces, thereby supporting the experimentally observed productivity trends.

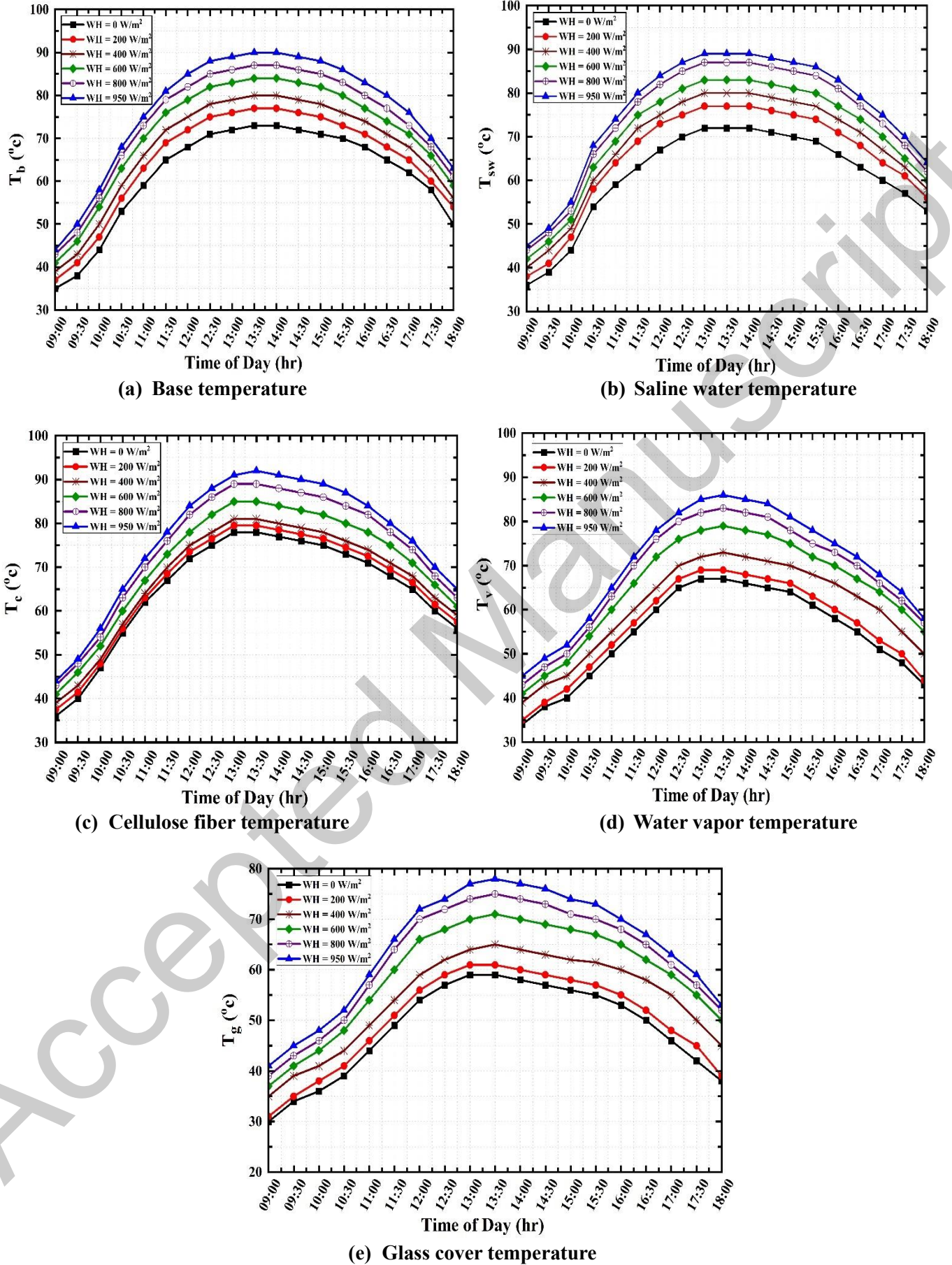


Fig. 8. System temperatures at different waste heat input (a) base, (b) saline water, (c) cellulose fiber, (d) water vapor, (e) glass

Figure 9 presents the cumulative freshwater productivity of the enhanced PSSDU under different controlled waste-heat inputs (0, 200, 400, 600, 800, and 950 W/m²) at a saline water depth of 100 mm, cellulose layer thickness of 75 mm, and density of 160 kg/m³. For all operating conditions, the accumulated yield increased progressively throughout the day, with the slope of the curves reflecting the magnitude of instantaneous evaporation rates. Under solar-only operation (0 W/m²), the total accumulated production at 18:00 reached approximately 4.7 L/m² . day. The introduction of auxiliary heat significantly improved daily yield, increasing the final productivity to nearly 5.2 L/m² . day at 200 W/m² and to about 5.6 L/m² . day at 400 W/m². The highest cumulative output was achieved at 600 W/m², where the total distilled water approached 6.3 L/m² . day, representing an enhancement of roughly 34% compared with the solar-only case. However, further increases in waste-heat input resulted in a decline in daily production. At 800 W/m², the final accumulated yield decreased to approximately 4.5 L/m² . day, while at 950 W/m² it dropped substantially to nearly 3 L/m² . day. This reduction, despite higher thermal input, confirms that excessive auxiliary heating disrupts the internal thermal balance of the still. Although higher heat flux intensifies evaporation, it simultaneously elevates the inner glass temperature and internal vapor concentration, thereby reducing the effective vapor-glass temperature difference and limiting condensation capacity. Since net freshwater production depends on the simultaneous enhancement of both evaporation and condensation processes, any imbalance that constrains condensation will directly reduce cumulative yield. The consistent superiority of the 600 W/m² case throughout the entire diurnal period indicates that this heat flux represents an optimal operational condition at which the additional thermal energy maximizes evaporation without inducing condensation resistance or vapor saturation effects. These findings demonstrate that controlled waste-heat integration can substantially enhance daily productivity, provided that the applied heat flux remains within a thermodynamically balanced range.

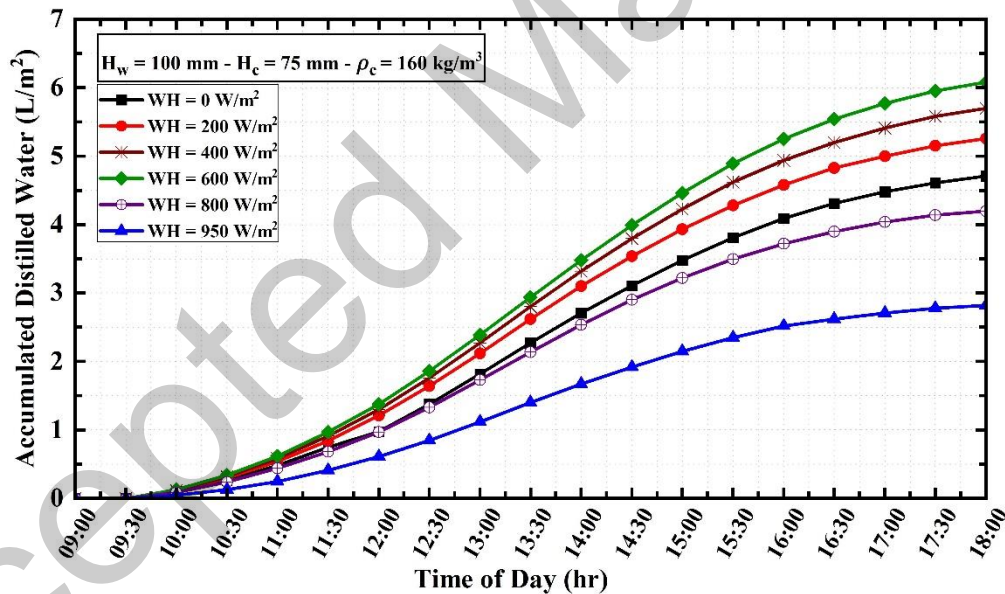


Fig. 9. Effect of waste heat input on accumulated freshwater productivity of the enhanced PSSDU.

Figure 10 illustrates the hourly variation of thermal efficiency of the enhanced PSSDU under different controlled waste-heat inputs (0, 200, 400, 600, 800, and 950 W/m²) at a saline water depth of 100 mm and an optimal cellulose layer thickness of 75 mm with a density of 160 kg/m³. For all cases, the efficiency increased progressively during the morning hours, reached a maximum between 13:00 and 14:00, and then declined toward sunset, following the combined influence of solar radiation intensity and internal temperature gradients. Under solar-only operation (0 W/m²), the peak thermal efficiency was approximately 30%. The introduction of auxiliary heat improved the efficiency to nearly 33% at 200 W/m² and to about 36% at 400 W/m². The highest performance was achieved at 600 W/m², where the thermal efficiency approached 41%, representing an enhancement of roughly 35-37% compared with the solar-only configuration. However, further increasing the waste-heat input to 800 W/m² reduced the peak efficiency to approximately 24%, while at 950 W/m² it decreased further to nearly 21%. This decline, despite the higher supplied

energy, indicates that excessive auxiliary heating lowers the fraction of useful latent heat relative to the total energy input. Thermal efficiency in solar stills is defined as the ratio of the energy utilized for vaporization to the total incident (solar plus auxiliary) heat input. At moderate waste-heat levels ($\leq 600 \text{ W/m}^2$), the additional heat effectively raises the basin water temperature and strengthens the vapor pressure gradient, thereby increasing the portion of energy converted into latent heat of evaporation. In contrast, at higher heat fluxes ($\geq 800 \text{ W/m}^2$), the glass cover temperature increases significantly, reducing the vapor glass temperature difference and weakening condensation effectiveness. Moreover, the rapid increase in internal vapor concentration can shift the process toward condensation-limited operation, meaning that a considerable fraction of the supplied energy is not transformed into useful distillate production. The consistent superiority of the 600 W/m^2 condition across the diurnal cycle confirms that this level represents an optimal thermodynamic balance between evaporation enhancement and condensation capacity. Beyond this threshold, the marginal gain in evaporation is outweighed by increased condensation resistance and reduced latent heat utilization, leading to lower overall thermal efficiency.

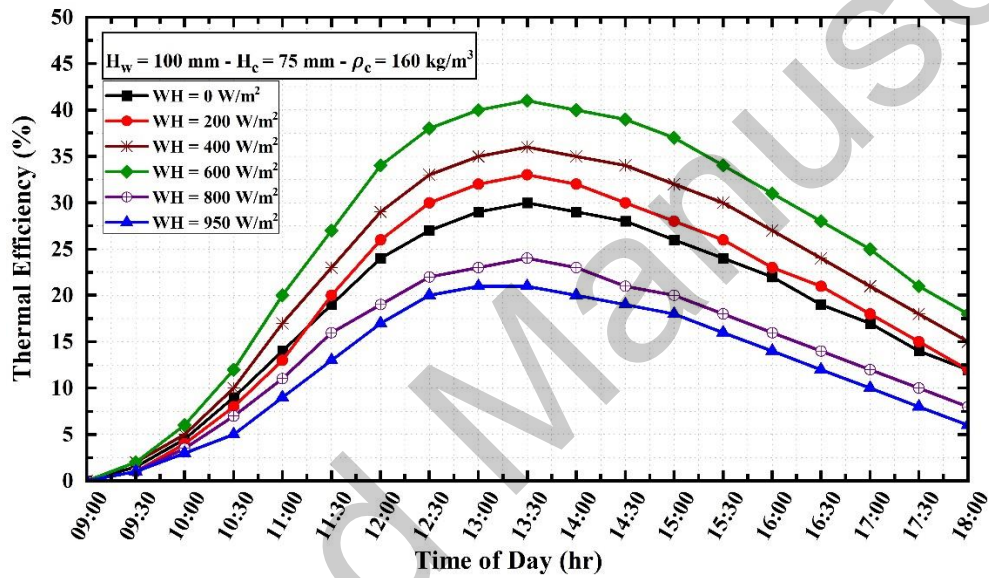


Fig. 10. Effect of waste heat input on the thermal efficiency of the enhanced PSSDU.

1.8.3.5 Effect of saline water depth on the performance of the enhanced PSSDU

Figure 11 presents the hourly variation of instantaneous freshwater productivity at different saline water depths (25, 50, 75, and 100 mm) under fixed operating conditions of a 75 mm cellulose layer thickness and a controlled waste-heat input of 600 W/m^2 . The results demonstrate a clear inverse relationship between water depth and evaporation rate throughout the entire diurnal cycle. The shallowest depth (25 mm) consistently achieved the highest productivity, reaching a peak value of approximately $600 \text{ mL/m}^2 \cdot \text{h}$ around 13:00, followed by 50 mm ($\approx 580 \text{ mL/m}^2 \cdot \text{h}$), 75 mm ($\approx 560 \text{ mL/m}^2 \cdot \text{h}$), and 100 mm ($\approx 520 \text{ mL/m}^2 \cdot \text{h}$). The superiority of lower water depths is maintained during both the rising and falling phases of solar intensity, indicating that the influence of depth is systematic rather than transient. This behavior can be quantitatively explained through heat capacity considerations. The sensible heat required to elevate the basin water temperature is given by $Q = mC_p\Delta T = \rho AhC_p\Delta T$, where m is the mass of water, ρ is water density, A is basin area, h represents the saline water depth, C_p is specific heat capacity of water. Since the basin area and thermophysical properties remain constant, the required energy input is directly proportional to water depth. Increasing the depth from 25 mm to 100 mm therefore multiplies the thermal mass by a factor of four, significantly increasing the energy required to achieve the same temperature rise under identical solar and auxiliary heat inputs. Consequently, shallower water layers heat more rapidly and attain higher surface temperatures during peak irradiance periods, producing a larger saturation vapor pressure and a stronger vapor pressure gradient between the evaporation surface and the inner glass cover. This enhanced thermodynamic driving force intensifies evaporation and increases instantaneous distillate yield. In contrast, deeper water layers absorb a greater fraction of the supplied energy as stored sensible heat within the bulk fluid, delaying temperature rise and reducing the proportion of energy converted into latent heat of vaporization during peak hours.

Although deeper depths may retain residual heat for a longer duration, this storage effect does not compensate for the reduced midday evaporation rate. The experimental results therefore confirm that minimizing saline water depth improves thermal responsiveness, maximizes interfacial temperature, and enhances instantaneous freshwater productivity under the specified operating conditions.

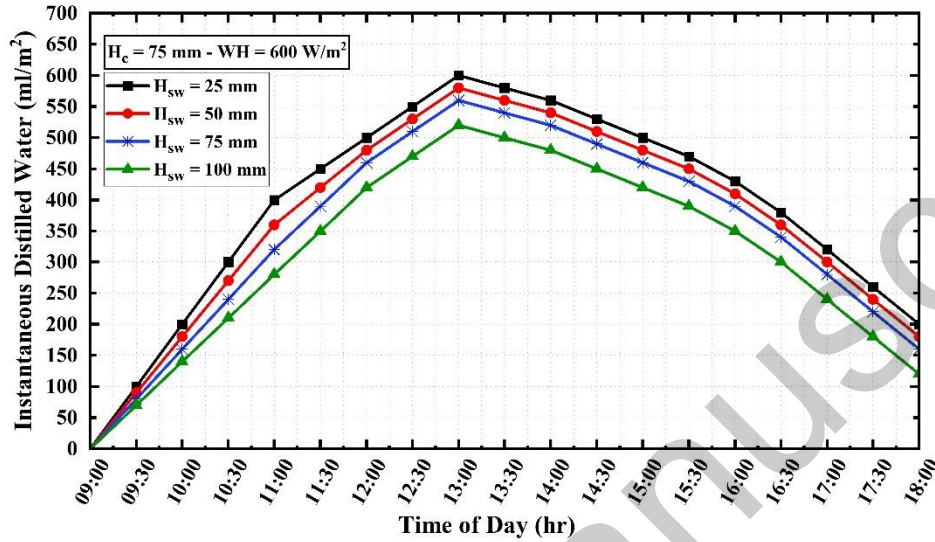


Fig. 11. Effect of saline water depth on instantaneous freshwater productivity of the enhanced PSSDU.

Figure 12 illustrates the accumulated freshwater productivity of the PSSDU at different saline water depths (25, 50, 75, and 100 mm) under optimized operating conditions of a 75 mm cellulose layer thickness and 600 W/m^2 waste-heat input. The cumulative yield increased progressively throughout the day for all depths; however, the slope of the accumulation curves was strongly dependent on water depth. The shallowest depth of 25 mm achieved the highest total production, reaching approximately $7.3 \text{ L/m}^2 \cdot \text{day}$ by 18:00. The 50 mm depth followed with nearly $6.9 \text{ L/m}^2 \cdot \text{day}$, whereas increasing the depth to 75 mm and 100 mm reduced the final accumulated yield to about $6.5 \text{ L/m}^2 \cdot \text{day}$ and $6 \text{ L/m}^2 \cdot \text{day}$, respectively. Overall, decreasing the water depth from 100 mm to 25 mm enhanced the daily freshwater yield by approximately 21-22%, clearly demonstrating the strong sensitivity of long-term distillate production to basin water depth. This trend is fundamentally governed by the thermal mass effect of the saline layer. Since the total heat storage capacity is proportional to water depth, deeper layers require substantially greater sensible heat input to reach effective evaporation temperatures. Under identical solar and auxiliary heat conditions, a significant portion of the supplied energy at larger depths is stored within the bulk fluid rather than being converted into latent heat of vaporization. In contrast, shallow water layers rapidly attain higher surface temperatures during peak irradiance hours, sustaining a stronger vapor pressure gradient and promoting higher evaporation rates over extended periods. Although deeper layers may retain residual heat later in the afternoon, this delayed release does not compensate for the reduced midday evaporation intensity. Consequently, minimizing saline water depth enhances cumulative productivity by improving thermal responsiveness and maximizing the fraction of absorbed energy utilized for phase change.

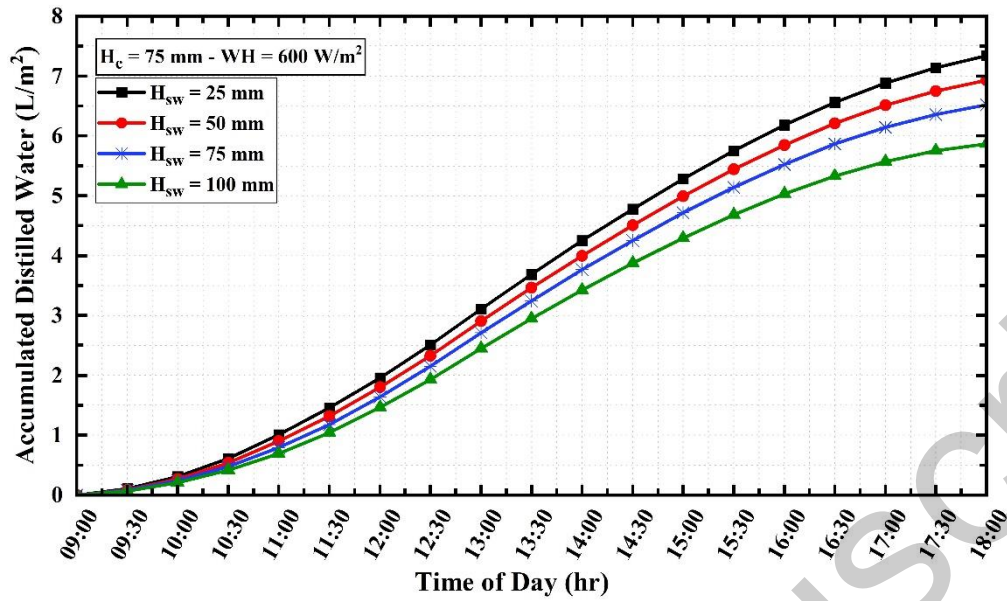


Fig. 12. Effect of saline water depth on accumulated freshwater productivity of the enhanced PSSDU.

Figure 13 depicts the hourly variation of thermal efficiency of the PSSDU at different saline water depths (25, 50, 75, and 100 mm) under optimized enhancement conditions consisting of a 75 mm floating cellulose fiber layer and 600 W/m² waste-heat input. For all investigated depths, the efficiency increased gradually during the morning period, reached a maximum between 13:00 and 14:00, and subsequently declined toward sunset, reflecting the combined effects of solar irradiance intensity and internal temperature gradients. The shallowest depth of 25 mm achieved the highest peak thermal efficiency of approximately 44-45%, followed by 50 mm with a maximum of about 41-42%. Increasing the water depth to 75 mm reduced the peak efficiency to nearly 38-39%, while the 100 mm depth recorded the lowest maximum value of approximately 34-35%. Thus, decreasing the saline water depth from 100 mm to 25 mm improved the peak thermal efficiency by nearly 30%, confirming the strong influence of basin water depth on energy utilization effectiveness. This behavior is fundamentally governed by the relationship between thermal mass and latent heat conversion efficiency. Thermal efficiency is defined as the ratio of useful latent heat employed for vaporization to the total supplied energy (solar plus auxiliary). At lower water depths, the reduced mass of saline water requires less sensible heat to achieve a given temperature rise, allowing a greater fraction of the absorbed energy to be rapidly converted into latent heat of vaporization. Consequently, higher surface temperatures and stronger vapor pressure gradients are attained during peak operating hours, increasing the proportion of input energy transformed into distillate production. In contrast, deeper water layers exhibit greater thermal inertia due to increased heat storage capacity ($Q \propto \rho A h C_p \Delta T$), meaning that a substantial portion of the supplied energy is retained as sensible heat within the bulk fluid rather than contributing directly to evaporation. This reduces the fraction of useful latent heat and lowers overall thermal efficiency. The consistent superiority of the 25 mm configuration throughout the diurnal cycle therefore confirms that minimizing saline water depth enhances thermal responsiveness and optimizes the conversion of available thermal energy into freshwater yield.

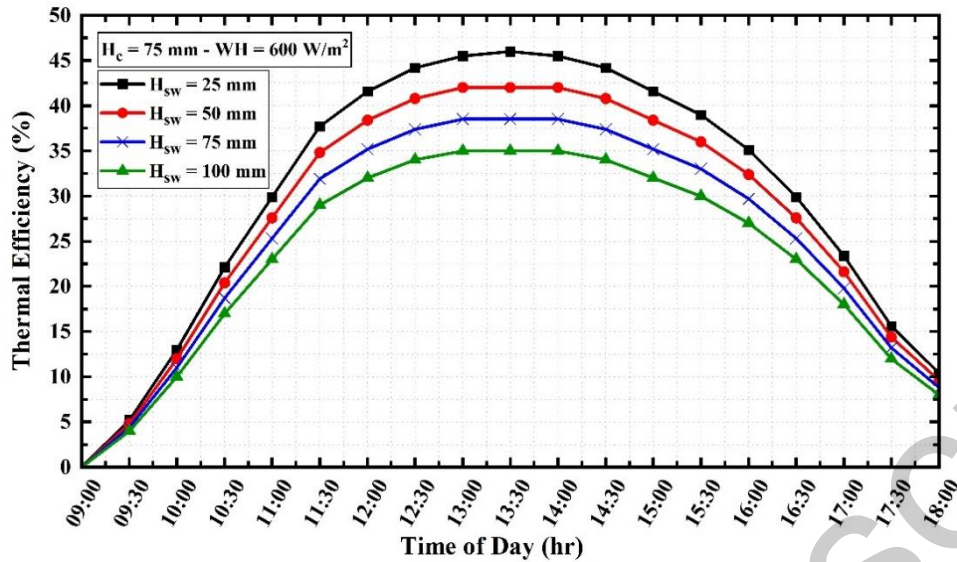


Fig. 13. Effect of saline water depth on the thermal efficiency of the enhanced PSSDU.

Table 7 provides a comparative assessment of previously reported enhancement strategies for solar still systems alongside the present work, considering freshwater yield, percentage improvement, thermal efficiency, and yield per unit energy input. The comparison highlights that earlier studies predominantly relied on PCMs, thermoelectric modules, porous metallic absorbers, nanofluids, multistage condensers, or hybrid waste-heat recovery systems to boost productivity. For instance, Ramzy et al. reported a 132% improvement using PCM coupled with thermoelectric modules, achieving 8.30 L/m²·day with 70% thermal efficiency, while Alshamrani demonstrated a 148% enhancement through reflector–condenser staging. Similarly, Salem et al. [59] achieved a high percentage improvement (442%) via hot-air waste heat integration; however, such systems involve more complex thermal coupling arrangements. In contrast, the present study attains a 150% increase in daily yield (6.0 L/m²·day versus 2.4 L/m²·day baseline) and a thermal efficiency of 46% using a structurally simple configuration based on a bio-derived floating cellulose fiber layer combined with controlled 600 W/m² auxiliary heat input. Notably, the yield per energy input (0.54 L/kWh) demonstrates competitive thermal utilization compared with reported waste-heat-assisted systems, while avoiding metallic inserts, nanoparticles, or multistage condensation assemblies. Overall, the comparison confirms that although higher absolute yields have been achieved in some hybrid or multi-effect systems, the present work distinguishes itself through a balanced combination of performance enhancement, material sustainability, operational simplicity, and moderate energy input. This positions the proposed configuration as a technically efficient and economically practical alternative for decentralized solar desalination applications.

Table 7. Comparative energy-normalized performance of experimental solar still enhancements.

Study	Enhancement Technique	Yield (L/m ² ·day)	Baseline (L/m ² ·day)	Improvement (%)	Thermal Efficiency (%)	Yield per Energy Input (L/kWh)	Main Finding
Ramzy et al. [13]	PCM + Thermoelectric	8.30	3.58	132	70.00	+-	Optimal at 1 cm depth; efficiency decreased with higher depth.
Dewedar et al. [22]	Intermittent spraying	5.00	2.83	76.7	69.00	-	Spraying increased basin temperature and doubled evaporation rate.
Alshamrani [23]	MPDSS-P (reflector + condenser + stages)	8.07	3.25	148	54.67	-	Hybrid staged configuration achieved highest efficiency among passive systems.
Ramzy et al. [24]	Steel wool porous absorber	4.384	1.872	134	32.74	-	Porous medium enhanced heat transfer and reduced water cost.
Chinnasamy et al. [28]	Copper fins	5.51	4.44	24	39.07	-	Increased basin heat transfer area improved productivity

Vijayaraghavan et al. [33]	CuO nano-PCM	7.00	3.70	89.19	35.00	-	Nanoparticles raised basin temperature to 72°C, improving storage.
Luo et al. [61]	UHT solar still + multistage condensation (waste heat recovery)	31.50	-	-	-	4.20	Multistage heat recovery achieved highest energy efficiency.
Salem et al. [59]	SSDU + waste hot air	17.13	-	442	34.20	0.52	Waste heat ducting maximized productivity increase.
Present Work	Cellulose + 600 W/m ² auxiliary heat	7.3	2.6	181	46.00	0.65	Controlled auxiliary heating improved efficiency with simple design.

4. Conclusion

The present experimental investigation evaluated the performance characteristics of a PSSDU enhanced by a floating cellulose fiber thermal layer and controlled waste-heat input. The combined effects of floating layer material and thickness, glass-cover tilt angle, saline water depth, and auxiliary heat flux were systematically examined to determine their influence on basin temperature distribution, evaporation-condensation dynamics, freshwater productivity, and thermal efficiency. Based on the obtained results, the following conclusions can be drawn:

- A glass-cover tilt angle of 45° provides improved solar radiation interception and more effective condensate runoff compared with 35°, leading to higher instantaneous and cumulative freshwater production.
- The use of floating cellulose fiber layer with 75 mm thick and a density of 160 kg/m³ delivers the highest performance improvement due to its superior thermal resistance, enhanced heat localization at the evaporation interface, and reduced conductive losses to the bulk saline layer.
- The integration of moderate waste heat of 600 W/m² significantly enhances evaporation rates and daily yield by establishing a favorable thermal balance between evaporation and condensation processes. Increasing the auxiliary heat beyond this level did not improve productivity and, in some cases, reduced performance due to condensation limitations and diminished vapor-glass temperature gradients.
- Reducing saline water depth to 25-50 mm substantially improves system responsiveness by lowering thermal inertia, accelerating basin water heating, and increasing the fraction of absorbed energy that converted into latent heat of vaporization.
- Under the optimal operating conditions 45° glass tilt angle, 75 mm cellulose fiber floating layer, 25-50 mm saline water depth, and 600 W/m² auxiliary heat input the performance of the enhanced PSSDU achieved a maximum daily freshwater productivity of approximately 9.3 L/m². day and a maximum thermal efficiency of about 16%.

In general, the results confirm that simultaneous optimization of thermal resistance, heat input level, and basin water depth is essential for maximizing the thermophysical performance of pyramid solar still systems. Furthermore, comparison with recent literature confirms that the proposed enhancement approach provides competitive freshwater productivity and thermal efficiency while preserving design simplicity, low-cost implementation, and sustainable operation compared with several recently reported hybrid solar still systems. From a practical perspective, the proposed configuration utilizes low-cost and environmentally friendly cellulose fiber material together with recoverable low-grade waste heat, enabling improved freshwater productivity without substantial additional energy consumption or complex operating requirements. In addition, the structurally simple and modular nature of the developed PSSDU facilitates scalability through parallel integration of multiple units, making the system suitable for decentralized freshwater production in remote and low-resource regions. The integration of a properly designed floating cellulose layer with controlled waste-heat recovery represents an effective and technically feasible approach for significantly improving freshwater production in solar desalination applications.

Suggestions for Future Work

Future work should include thermo-economic, exergy, and year-round performance analyses under varying climatic conditions. Economic feasibility, seasonal productivity, and system irreversibilities should be evaluated. Further studies may also investigate large-scale applications, thermal energy storage integration, environmentally and Echo friendly floating materials, and hybrid renewable energy assisted configurations to enhance productivity and operational stability.

Appendix A.

Uncertainty Analysis

A rigorous uncertainty analysis was performed to ensure the reliability and statistical validity of the experimental results. The evaluation followed the classical error-propagation framework originally formulated by [Kline and McClintock \[60\]](#), which quantifies the combined uncertainty of a derived parameter based on the independent uncertainties of the measured variables from which it is calculated. For a general functional relationship

$$R = R(x_1, x_2, x_3, \dots, x_n)$$

the overall uncertainty U_R is expressed as:

$$U_R = \sqrt{\left(\frac{\partial R}{\partial x_1} U_{x_1}\right)^2 + \left(\frac{\partial R}{\partial x_2} U_{x_2}\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} U_{x_n}\right)^2} \quad (V)$$

where, U_{x_i} represents the uncertainty of each independent measured variable.

A.1 Uncertainty in Instantaneous Productivity

The instantaneous freshwater productivity is calculated as:

$$V_{d,is} = \frac{m_d}{A\Delta t} \quad (8)$$

where, m_d = mass (or volume) of distilled water, A = basin area, Δt = time interval. Since basin area and time interval are constant, the dominant uncertainty arises from distilled water measurement. Thus:

$$\frac{U_{V_{d,is}}}{V_{d,is}} = \sqrt{\left(\frac{U_{m_d}}{m_d}\right)^2} \quad (9)$$

Given a graduated cylinder resolution of ± 2.5 ml and typical midday production of approximately 400-500 mL/m²·h, the relative uncertainty in instantaneous productivity was estimated to be $\pm 2.8\%$.

A.2 Uncertainty in Accumulated Daily Productivity

The accumulated productivity is calculated as the summation of hourly measurements:

$$V_{d,acc} = \sum V_{d,is} \quad (10)$$

Since daily accumulation reduces random measurement effects, the estimated relative uncertainty was slightly lower and determined to be approximately $\pm 2.1\%$.

A.3 Uncertainty in Thermal Efficiency

Thermal efficiency is calculated as:

$$\eta_{th} = \frac{m_d h_{fg}}{IA} \quad (11)$$

where: h_{fg} = latent heat of vaporization, I = solar radiation intensity, A = basin area. The relative uncertainty in thermal efficiency is therefore expressed as:

$$\frac{U_\eta}{\eta} = \sqrt{\left(\frac{U_{m_d}}{m_d}\right)^2 + \left(\frac{U_I}{I}\right)^2} \quad (12)$$

Considering:

- Distilled water measurement uncertainty $\approx \pm 1\text{-}3\%$
- Solar Power Meter uncertainty $\approx \pm 2\%$

The maximum combined uncertainty in thermal efficiency was estimated at $\pm 4.8\%$.

A.4 Temperature Measurement Uncertainty

Temperature measurements were conducted using calibrated K-type thermocouples with an accuracy of $\pm 0.5^\circ\text{C}$ and a data acquisition resolution of 0.1°C . Although temperature does not directly enter the productivity equation, it influences evaporation-condensation dynamics and thermal interpretation; therefore, the overall temperature measurement uncertainty was conservatively maintained within $\pm 0.5^\circ\text{C}$.

A.5 Reproducibility Assessment

To further validate experimental robustness, repeatability tests were conducted for both the baseline configuration and the optimized operating condition (75 mm floating cellulose fiber thermal layer, 25-50 mm saline water depth, and 600 W/m^2 auxiliary heat input) on three separate days under comparable solar irradiance levels. The deviation in accumulated daily yield did not exceed $\pm 3\%$, confirming strong experimental stability and reproducibility. Overall, the quantified uncertainty levels fall well within the acceptable limits reported for experimental solar desalination systems, thereby substantiating the credibility and technical soundness of the reported performance improvements.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

REFERENCES

- [1] A.M. Abed, Y.C. Escorcia, F. Atamurotov, W. Ibrahim, In-depth analysis of an inclined solar desalination plant for optimal orientation by the conventional systems modification: Toward low-carbon emission and sustainability, *International Journal of Low-Carbon Technologies*, vol. 20, pp. 269–278, 2025. <https://doi.org/10.1093/ijlct/ctae225>.
- [2] R.I. Muhamad, M. Jafri, B.V. Tarigan, Experiment of passive solar desalination with inclined heating type with variation of cover glass distance, *Applied Mechanics and Materials*, vol. 927, pp. 51-57, 2025. <https://doi.org/10.4028/p-r5ila2>.
- [3] A. Atiyah, Y. Alaiwi, M. Hussein, A. Jundi, Numerical analysis for enhanced water desalination in solar stills with optimized glass cover angles, *Journal of Advanced Research in Numerical Heat Transfer*, vol. 22, pp. 31-45, 2024. <https://doi.org/10.37934/arnht.22.1.3145>.
- [4] H. AbdelMeguid, W.M. El Awady, Optimizing solar still performance through glass cover optical properties: A mathematical modeling and theoretical investigation, *Ain Shams Engineering Journal*, vol. 15, 102589, 2024. <https://doi.org/10.1016/j.asej.2023.102589>.
- [5] S. Boughazala, S. Dhaoui, A. Bouabidi, Effect of Glass Cover Angle on the Performance of Double-Slope Solar Still, in *Proc. 2024 IEEE International Multi-Conference on Smart Systems and Green Process (IMC-SSGP)*, 2024. <https://doi.org/10.1109/IMC-SSGP63352.2024.10919790>.
- [6] R. Kumar, L. Kumar, N.H. Mirjat, K. Harijan, Simulation study on the effect of cover tilt angle of solar still on its productivity, *VFAST Transactions on Mathematics.*, vol.11, pp. 63-76, 2023. <https://doi.org/10.21015/vtm.v11i2.1586>.
- [7] C. Dorji, P. Luitel, S.K. Gurung, T. Samdrup, Effect of Tilt Angle Variation on the Performance of the Flat Collector Solar Thermal System (Passive Type), *Zorig Melong: A Technical Journal of Science, Engineering and Technology*, vol. 7, pp. 8-11, 2023. <https://doi.org/10.17102/v8001>.
- [8] M.M. Mohamed, M.A. Abdel-Baky, I.M. El-Tantawy, M.S. El-Sebaey, Experimental investigation on the effect of inclination angle of flat plate solar collector using gravity-assisted heat pipes, *Engineering Research Journal*, vol. 46, pp. 311-321, 2023.

<https://doi.org/10.21608/erjm.2023.201881.1255>.

- [9] V.K. Chauhan, S.K. Shukla, Experimental study of effect of glass cover tilt angle of solar still in winter season of India's composite climate, *Thermal Science and Engineering Progress*, vol. 33, 101348, 2022. <https://doi.org/10.1016/j.tsep.2022.101348>.
- [10] M. Kumar, S.K. Patel, V. Mishra, D. Singh, Performance analysis of solar desalination system with thermal storage material at various water depths, *Proceedings of the Indian National Science Academy*, 2025. <https://doi.org/10.1007/s43538-025-00464-5>.
- [11] S.A. Abdul Hussein, N.A. Jabbar, Investigation of the effect of changing water heights on the performance of a solar distillation system using crushed porous coal rocks, *Jordan Journal of Mechanical and Industrial Engineering*, vol.18, pp.171-178, 2024. <https://doi.org/10.59038/jjmie/180113>.
- [12] A. Shringi, J. Sharma, P. Malviya, Experimentally investigating the effect of basin water depth in passive pyramid type solar still, *International Journal for Research in Applied Science & Engineering Technology*, vol. 13, pp. 564-576, 2025. <https://doi.org/10.22214/ijraset.2025.70228>.
- [13] K. Ramzy, M. Abdelgaleel, M. Alswat, A.E. Kabeel, H. Mosalam, E.A. AbdelAziz, Enhancing the performance of a solar distiller using phase change materials integrated with Peltier modules and heaters: Energy, exergy, and economic analysis, *Applied Thermal Engineering*, vol. 274, 126674, 2025. <https://doi.org/10.1016/j.applthermaleng.2025.126674>.
- [14] O.T. Fadhil, W.M. Abed, Experimental investigation on a pyramid solar still under Iraq climate conditions, *AIP Conference Proceedings*, vol. 3009, 030014, 2024. <https://doi.org/10.1063/5.0190411>.
- [15] M. Abdelgaleel, E.A. AbdelAziz, H. Mosalam, A.E. Kabeel, M. Alswat, K. Ramzy, Investigation on the performance of modified solar distillation system using different composite materials: An experimental and theoretical study, *Solar Energy*, vol. 272, 112469, 2024. <https://doi.org/10.1016/j.solener.2024.112469>.
- [16] A.S. Shareef, H.J. Kurji, A.H. Hamzah, Modifying performance of solar still by using sliced absorber plate and new design of glass cover: Experimental and numerical study, *Heliyon*, vol. 10, e24021, 2024. <https://doi.org/10.1016/j.heliyon.2024.e24021>.
- [17] M.R. Diab, M. Rozza, M. Alhosary, S. Nassar, N. Faisal, A.H. Elsheikh, M. Egiza, Performance enhancement of a modified solar still with inverted pyramid aluminum basin geometry: Experimental optimization, thermal, and economic assessment, *Process Safety and Environmental Protection*, vol. 193, pp. 1173-1187, 2025. <https://doi.org/10.1016/j.psep.2024.11.104>.
- [18] A.A. Baiee, S. Asiaei, S.M. Hosseinalipour, Experimental study on improving performance and productivity of pyramid solar still using rotation technique, *Front. Heat Mass Transfer*, vol. 22, pp. 955-976, 2024. <https://doi.org/10.32604/fhmt.2024.051532>.
- [19] M. Soltanian, S. Hoseinzadeh, D. Astiaso Garcia, Proposal of a reflector-enhanced solar still concept and its comparison with conventional solar stills, *Water*, vol. 16, 355, 2024. <https://doi.org/10.3390/w16020355>.
- [20] A.H. Mohammed, A.N. Shmroukh, N.M. Ghazaly, A.E. Kabeel, Implementation of new stepped square pyramid solar still for desalinating seawater in the climate of Upper Egypt, *Journal of Renewable Energy and Environment*, vol. 11, pp. 67-74, 2024. https://www.jree.ir/article_193963.html.
- [21] I. Godwin, I. Samson, A. Kaur, E. Pearlin, S.K. Bohidar, M. Raja, Optimizing pyramid solar still performance using response surface methodology and artificial neural networks, *Journal of Environmental Nanotechnology*, vol. 13, pp. 505-517, 2024. <https://doi.org/10.13074/jent.2024.12.242734>.

- [22] M.M. Dewedar, Y.A. El Samadony, A.M. AlSaeed, A.I. Abdo, Performance and enhancement evaluation of a solar still by using spraying technology, *Journal of Engineering Research*, vol. 8, pp. 1-12, 2024. <https://digitalcommons.aaru.edu.jo/erjeng/vol8/iss3/24/>.
- [23] A. Alshamrani, Enhancing pyramid solar still performance using suspended V-steps, reflectors, Peltier cooling, forced condensation, and thermal storing materials, *Case Studies in Thermal Engineering*, vol. 61, 105109, 2024. <https://doi.org/10.1016/j.csite.2024.105109>.
- [24] K. Ramzy, M. Abdelgaleel, A.E. Kabeel, H. Mosalam, Performance of a single slope solar still using different porous absorbing materials: An experimental approach, *Environmental Science and Pollution Research*, vol. 30, pp. 72398-72414, 2023. <https://doi.org/10.1007/s11356-023-27465-5>.
- [25] E.S. El Said, M.A. Dahab, M. Abdelgaleel, G. Bedair, Productivity augmentation of a solar distiller utilizing a wire mesh absorber with a pulsed flow regime, *Desalination*, vol. 548, 116276, 2023. <https://doi.org/10.1016/j.desal.2022.116276>.
- [26] S.K. Suraparaju, S.K. Natarajan, Waste tyre pieces as photothermal absorbers for efficient evaporation in solar desalination systems, *Clean Technologies and Environmental Policy*, vol. 25, pp. 3161–3176, 2023. <https://doi.org/10.1007/s10098-023-02571-7>.
- [27] R. Parikh, S. Parikh, K. Sharma, A. Sohani, V.P. Katekar, M. A. Ansari, L. Natrayan, M.A. Shah, Experimental investigations on the productivity increase of solar stills utilizing hybrid nanomaterials and water-cooling techniques, *Energy Exploration & Exploitation*, vol. 43, pp. 1021-1034, 2025. <https://doi.org/10.1177/01445987241308588>.
- [28] S. Chinnasamy, O. Bait, B. Kalidasan, A. Fatehmulla, Investigation on performance enhancement of a novel solar still using metallic fins: An experimental and 5E analysis, *Clean Technologies and Environmental Policy*, vol. 27, pp. 6167-6192, 2025. <https://doi.org/10.1007/s10098-025-03178-w>.
- [29] S.K. Suraparaju, M.K. Peddojula, M. Samykano, M.S. El Sebaey, C.S. Kadambari, S.B. Budala, T.N. Manepalli, L. Reddy, S.R. Vardhanapu, B.R. Ajjada, R.B. Pilli, Enhancing the productivity of pyramid solar still utilizing repurposed finishing pads as cost-effective porous material, *Desalination and Water Treatment*, vol. 320, pp. 33-42, 2024. <https://doi.org/10.1016/j.dwt.2024.100733>.
- [30] R. Kumar, D.R. Mishra, P. Dumka, Improving solar still performance: A comparative analysis of conventional and honeycomb pad-augmented solar stills, *Solar Energy*, vol. 270, 112408, 2024. <https://doi.org/10.1016/j.solener.2024.112408>.
- [31] L. Zhang, B. Shang, B. Li, Y. Huo, Investigation on heat transfer efficiency of phase change materials enhanced by divided heat flux, *Journal of the Taiwan Institute of Chemical Engineers*, vol. 159, 105480, 2024. <https://doi.org/10.1016/j.jtice.2024.105480>.
- [32] S.K. Suraparaju, S.K. Natarajan, Development of thermal energy storage material from blends of Jatropha biodiesel and paraffin wax for augmenting freshwater generation capacity in a solar desalination system, *Journal of Energy Resources Technology*, vol. 145, 121401, 2023. <https://doi.org/10.1115/1.4063255>.
- [33] G. Vijayaraghavan, K. Velavan, K. Babu, M. Yuvaperiyasamy, M. Mohanraj, Investigation of a pyramid solar still with CuO nanoparticles-paraffin wax blend as energy storage material, *Journal of Environmental Nanotechnology*, vol. 14, pp. 1-6, 2025. <https://doi.org/10.13074/jent.2025.03.244995>.
- [34] A. Bouabidi, K.A. Hammoodi, O. Ghriss, H. Moncer, 4E analysis of pyramid solar still with heat storage using different PCM layer thickness: Energy, exergy, economic, and enviro-economic, *Journal of Energy Storage*, vol. 130, 117374, 2025. <https://doi.org/10.1016/j.est.2025.117374>.
- [35] P.R. Patel, K.V. Modi, S.K. Patel, Experimental study of mono- and hybrid-nanofluids on square pyramid solar still, *Environmental Science and Pollution Research*, vol. 32, pp. 693-724, 2024. <https://doi.org/10.1007/s11356-024-35619-2>.

- [36] Z.M. Omara, M.Z. Ahmed, W.H. Alawee, S. Shanmugan, M. Elashmawy, A comprehensive review of nano-enhanced phase change materials on solar stills with scientometric analysis, *Results in Engineering*, vol. 22, 102088, 2024. <https://doi.org/10.1016/j.rineng.2024.102088>.
- [37] W.M. Farouk, G. Hamisa, Z.M. Omara, F.A. Essa, Mathematical modeling and optimization of pyramidal still performance using response surface method and Ag-nanoparticle enhanced PCM, *Energy Storage*, vol. 75, 109569, 2024. <https://doi.org/10.1016/j.est.2023.109569>.
- [38] A. Negi, L. Ranakoti, P. Bhandari, R. Khargotra, T. Singh, Thermophysical characteristics and storage material compatibility in nano-enhanced phase change materials for solar distillation applications: A critical assessment, *Solar Energy Materials and Solar Cells*, vol. 271, 112870, 2024. <https://doi.org/10.1016/j.solmat.2024.112870>.
- [39] H. AbdelMeguid, Examining the performance of optically optimized solar stills with phase change materials: A theoretical perspective, *Solar Energy Materials and Solar Cells*, vol. 282, 113394, 2024. <https://doi.org/10.1016/j.solmat.2024.113394>.
- [40] M. Sheikholeslami, Z. Khalili Environmental and energy analysis for photovoltaic thermoelectric solar unit in existence of nanofluid cooling reporting CO₂ emission reduction, *Journal of the Taiwan Institute of Chemical Engineers*, vol. 156, 105341, 2024. <https://doi.org/10.1016/j.jtice.2023.105341>.
- [41] M. Ahmadiani, A. Riahi, P. Payamiazad, M. Minaei, M.B. Shafii, Investigation and numerical simulation of two-phase ejectors for use in the water desalination cycle, *Case Studies in Thermal Engineering*, vol. 54, 104050, 2024. <https://doi.org/10.1016/j.csite.2024.104050>.
- [42] N.M. Shatar, M.F. Sabri, M.F. Salleh, M.H. Ani, Investigation on the performance of solar still with thermoelectric cooling system for various cover material, *Renewable Energy*, vol. 202, pp. 844-854, 2023. <https://doi.org/10.1016/j.renene.2022.11.105>.
- [43] A.M. Al-Tajer, W.H. Alawi, H.A. Dhahad, Z. Omara, Innovative experimental investigation of a pyramid solar still with air-cooled single glass for enhanced water productivity, *Experimental Thermal and Fluid Science*, vol. 6, pp. 35-48, 2025. <https://doi.org/10.37934/arfmts.130.2.5573>.
- [44] A.K. Muftah, L. Zili-Ghedira, M.M. Abugderah, W. Hassen, N. Becheikh, B.M. Al-shammari, L. Kolsi, Sustainable water production: Solar energy integration in multi-effect desalination plants, *Water*, vol. 17, 647, 2025. <https://doi.org/10.3390/w17050647>.
- [45] A. Pacheco, C. Sequeira, M. Moreira da Silva, V. Serrão Sousa, Enhancing efficiency in solar non-intrusive desalination: Solar still prototype optimization in Southwest Europe, *Desalination*, vol. 598, 118421, 2025. <https://doi.org/10.1016/j.desal.2024.118421>.
- [46] A. Malik and D. Katyal, Geospatial evaluation of groundwater quality in an industrialized district of Haryana, India, using an integrated approach, *Proceedings of the Indian National Science Academy*, vol. 90, pp. 997-1014, 2024. <https://doi.org/10.1007/s43538-024-00288-9>.
- [47] C. Bai, Z. Gu, P. Li, R. Ning, S. Yu, A novel salt-swelling nanofiltration membrane for drinking water purification: High mineral ions passage and efficient organic removal, *Journal of the Taiwan Institute of Chemical Engineers*, vol. 159, 105473, 2024. <https://doi.org/10.1016/j.jtice.2024.105473>.
- [48] M. Eltarkawe, A. A. A. Adam, H.A. Husayn, Top glass cover effect on the performance of a parabolic trough solar receiver, *Al-Mukhtar Journal of Engineering Research*, vol. 8, pp. 36-50, 2024. <https://doi.org/10.54172/nkrld641>.
- [49] O. Itabiyi, E.O. Sangotayo, O.M. Abiodun, B.G. Bhadmus, The effect of tilt angle and mass flow rate on the performance of a parabolic trough solar concentrator via experimentation, *Advances in Physics Theories and Applications*, vol. 88, pp. 1-10, 2024. <https://doi.org/10.7176/APTA/88-01>.
- [50] C.T. Mashfi, N. Shahadut, A. Mazed, D. K. Paul, Performance analysis of a hybrid solar dryer incorporating adaptive glass tilting, *International Conference on Mechanical, Industrial and Materials*

Engineering 2024 (ICMIME2024), Rajshahi, Bangladesh. <https://www.icmime-ruet.ac.bd/2024/DIR/Contents/Technical%20Papers/Thermal%20Engineering/374.pdf>.

- [51] D. Mistry, R. Patel, S.H. Sengar, J.H. Tarsariya, Growing of tender wheatgrass under pyramid type solar structure and comparative evaluation of tray and solar tunnel drying methods for powder production, Journal of Experimental Agriculture International, vol. 47, pp. 456-465, 2025. <https://doi.org/10.9734/jeai/2025/v47i53434>.
- [52] S. Noman, A.M. Manokar, Experimental investigation of pistachio shell powder (bio-waste) to augment the performance of tubular solar still: Energy, exergy, and environmental analysis, Desalination, vol. 576, 117317, 2024. <https://doi.org/10.1016/j.desal.2024.117317>.
- [53] L. Liu, W. Liu, W. Fu, Z. Yi, Y. Yi, J. Zhang, C. Tang, T. Sun, Q. Zeng, P. Wu, Enhancing the overall performance of perovskite solar cells with a nano-pyramid anti-reflective layer, Photonics, vol.11, 715, 2024. <https://doi.org/10.3390/photonics11080715>.
- [54] F.U. Alqsair, Enhancement of the production of trays solar still via nano phase change material and preheating feed-water, Case Studies in Thermal Engineering, vol. 53, 103822, 2024. <https://doi.org/10.1016/j.csite.2023.103822>.
- [55] M.E. Attia, M.E. Zayed, A.E. Kabeel, M. Abdelgaied, M. Arıcı, M.M. Abdel-Aziz, A comparative experimental study on hemispheric distillation system integrated with metamorphic fabric materials for efficient and low-cost solar desalination, Thermal Science and Engineering Progress, vol. 47, 102277, 2024. <https://doi.org/10.1016/j.tsep.2023.102277>.
- [56] G. Xu, S. Huang, Y. Yang, Y. Wu, K. Zhang, C. Xu, Techno-economic analysis and optimization of the heat recovery of utility boiler flue gas, Applied Energy, vol. 112, pp. 907-917, 2013. <https://doi.org/10.1016/j.apenergy.2013.04.048>.
- [57] M. Hariprabhu, K. Sundararaju, K.A. Wilson, Analysis of using exhaust flue gas for power generation in thermal power plant, International Journal of Pure and Applied Mathematics, vol. 118, pp. 2161-2171, 2018. <https://www.acadpubl.eu/hub/2018-118-21/articles/21c/28.pdf>.
- [58] M.R. Salem, R.Y. Sakr, G.M. Assassa, O.A. Aly, Augmentation of solar still distillation performance using waste heat energy and guiding vanes: A field study, Desalination, vol. 572, 117150, 2024. <https://doi.org/10.1016/j.desal.2023.117150>.
- [59] M.R. Salem, M.R. Salem, M.G. Higazy, M.F. Abd Rabbo, Performance enhancement of a solar still distillation unit: A field investigation, Solar Energy, vol. 202, pp. 326-341, 2020. <https://doi.org/10.1016/j.solener.2020.03.098>.
- [60] S.J. Kline, F.A. McClintock, Describing uncertainties in single-sample experiments, Mechanical Engineering, vol. 75, pp. 3-8, 1953.
- [61] X. Luo, L. Jiao, Y. Guo, H. Bao, C. Zhao, X. Gu, Ultrahigh freshwater production achieved by unidirectional heat transfer interfacial evaporation solar still integrated with waste heat recovery, Energy Conversion and Management, vol. 304, 118226, 2024. <https://doi.org/10.1016/j.enconman.2024.118226>.

Nomenclatures

Symbol	Definition	Unit
A	Basin area	m ²
C _p	Specific heat capacity of saline water	J·/kg·K
h	Saline water depth	mm
k	Effective thermal conductivity of floating cellulose layer	W/m·K
L	Floating cellulose fiber thickness	mm
m	Mass of saline water	kg
n	Number of thermocouples	-
Q	Heat transfer rate	W

Symbol	Definition	Unit
q''	Applied auxiliary heat flux	W/m^2
t	Time interval	s
T_b	Basin base temperature	$^{\circ}C$
T_c	Cellulose fiber layer temperature	$^{\circ}C$
T_i	Temperature recorded by ith thermocouple	$^{\circ}C$
T_{sw}	Saline water temperature	$^{\circ}C$
tt	Total operating time	hr
h_{fg}	Latent heat of vaporization	J/kg
I	Instantaneous solar irradiance	W/m^2
T_a	Ambient air temperature	$^{\circ}C$
T_g	Inner glass cover temperature	$^{\circ}C$
T_v	Vapor temperature	$^{\circ}C$
U	Combined uncertainty	
V_{dis}	Distilled water volume	$mL/m^2 \cdot s$
$V_{dis,d}$	Accumulated daily distilled water volume	$mL/m^2 \cdot day$
$V_{dis,i}$	Instantaneous distilled water volume	$mL/m^2 \cdot h$
V_{mod}	Distillate volume of modified PSSDU	$mL/m^2 \cdot day$
V_{ref}	Distillate volume of reference PSSDU	$mL/m^2 \cdot day$
ΔT	Temperature difference	$^{\circ}C$
ΔV	Percentage change in the daily freshwater production	%
η	Instantaneous thermal efficiency	%
ρ	Density of distilled water	Kg/m^3
ρ_c	Density of cellulose fiber layer	Kg/m^3

Acronyms

Acronym	Definition
CFD	Computational Fluid Dynamics
NE-PCM	Nano-Enhanced Phase Change Material
PCM	Phase Change Material
PSSDU	Pyramid Solar Still Desalination Unit
RSM	Response Surface Methodology
SSDU	Solar Still Desalination Unit
TDS	Total Dissolved Solids
TEC	Thermoelectric Cooling
WHO	World Health Organization

Superscripts & Subscripts

Symbol	Meaning
a	Ambient
b	Basin
c	Cellulose layer
d	Daily
dis	Distilled water
g	Glass
i	Instantaneous / thermocouple index
mod	Modified configuration

Symbol	Meaning
ref	Reference configuration
sw	Saline water
t	Total
v	Vapor

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