Optimization of Double Slope Solar Stills Using Taguchi Method: Effects of Solar Intensity and Slope Angle on Performance Parameters

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Abstract: *Employing the Taguchi methodology, a robust statistical technique renowned for optimizing design parameters, this research investigates the enhancement of a double slope solar still. The study centers on analyzing how temperature, water volume fraction, and vapour density are influenced by solar intensity and slope angle, pivotal factors for operational efficiency. The results underscore the critical role of solar intensity in augmenting energy absorption by the absorber surface, thereby elevating water temperature and fostering increased vapour density. Additionally, the optimal slope angle facilitates efficient absorption and transfer of solar energy, exerting significant influence over temperature regulation and the rate of water vaporization within the solar still. These insights underscore the importance of optimizing solar intensity and slope angle to maximize the performance and sustainability of double slope solar stills in generating potable water and renewable energy.*

Keywords: Double slope solar still, Taguchi method, optimization, solar intensity, slope angle, vapour density, water volume fraction, temperature.

I. INTRODUCTION

Solar stills are the most basic instruments to collect potable water using solar power. The solar still has been around for a long time and is a simple way to purify water figure.1. Its lesser production stands out as a big drawback when compared to other desalination procedures. Numerous research has focused on this issue to develop more efficient solar stills. While increasing output, it is critical to keep costs low and design, administration, and process simple. Due to various components, the configuration and complexity of solar stills increases. The various components such as thermal collectors, technology for sun-tracking etc. To reduce investment costs, build the best platform, and increase fresh water production levels, it is essential to increase the efficacy of solar stills. To aid with this, it is helpful to get a robust computational model of solar stills to invest in different factors. Solar stills have been designed using computational fluid dynamics (CFD) [1].

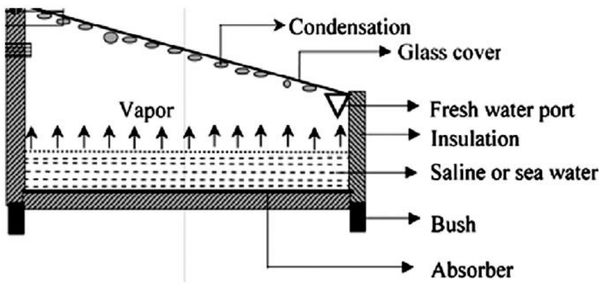

Figure 1. Representation of a single sloping solar still (SSSS).

A. Categories of TES (Thermal Energy Storage)

Thermal energy can be captured as a variable in the material's internal energy, encompassing sensible heat, latent heat, and thermochemical energy, or as a combined effect of these factors figure 2.

(a)

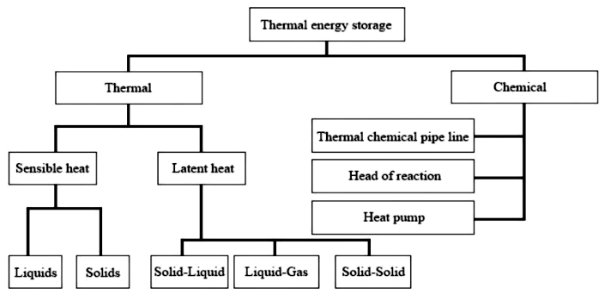

Figure 2. TES system for solar still implementations.

- Sensible Heat Storage: The temperature increases in proportion to the amount of sensible heat deposited in thermal storage from the sun. The Sensible Thermal Storage system keeps an eye on the material's heat capacity and conversion heating rate during the charge/discharge operation.

- Latent Heat Storage: Latent heat storage occurs whenever a collection material varies its state from solid to liquid, liquid to gas, or gas to liquid, or conversely, and heat is trapped or liberated.
- Thermo-chemical Energy Storage: For a reversible series initiated by chemical reactions, energy generated is crucial for decelerating and enhancing molecular bonds in thermos-chemical systems.

B. Working of Single slope solar stills

Solar stills with a single slope can be used to desalinate water. They are most likely one of the most cost-effective freshwater production options. The use of SSSS is still low because the quantity of distilled water produced per unit area is low. A cold surface (glass cover) is strategically positioned to capture and condense the evaporated freshwater. As because of slope in solar still glass, condensed vapours is collected in a distillation vessel through a distillation channel (see figure 3).

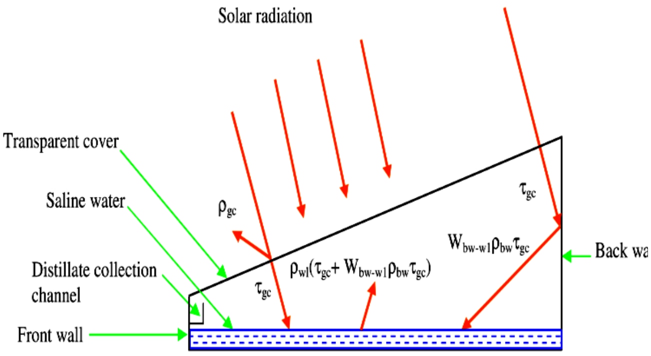

Figure 3. Schematic representation of single slope solar still

C. Working of double slope solar stills

Prior literature has highlighted different methods of modelling of SSSS, especially for double-slope solar stills (DSSS), have concentrated on their solar still configuration, either including or excluding boosting elements. In SSSS the input energy is solar radiation and it falls on glass with single slope (see Figure 4.). Consequently, the effect of topography of solar still on solar energy amount as a input is missing in past studies. Because solar stills use solar power as their primary source of energy, increasing the amount of energy used can result in significant enhancement in complete performance.

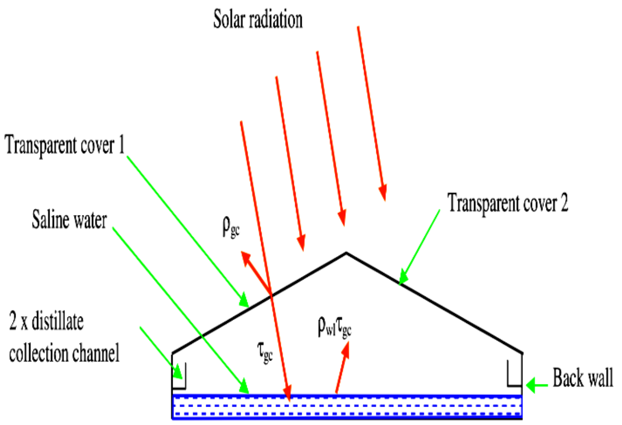

Figure 4. Schematic representation of double slope solar still.

D. Energy analysis of the solar still with PCM

The objective of energy assessment is to create formulae for investigating the temperature of different solar still elements including the absorber plate, saline water, condenser glass cover and Phase change material layer (figure 5). The condenser glass cover passes through a portion where solar radiation falls on it. Meanwhile, the remaining solar energy is reflected back into the atmosphere. Some of the solar energy reaches the portion of saline water present in basin and others are absorbed by glass cover.

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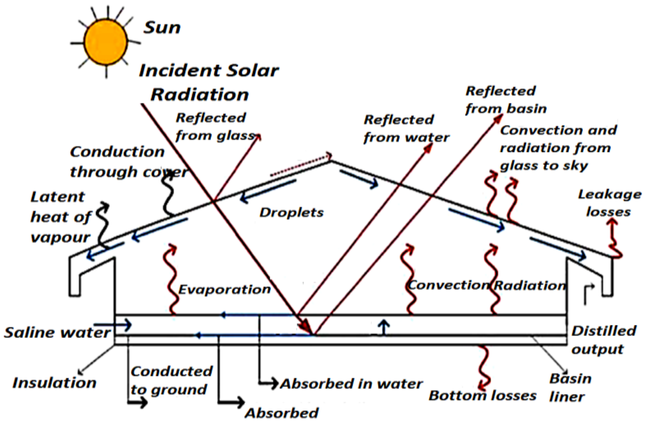

Figure 5. Energy balance for solar still

II. LITERATURE REVIEW

Lucas Lima Rodrigues et al. (2020) introduces a Generalized Predictive Control (GPC) approach tailored for Doubly Fed Induction Generation (DFIG) systems within wind energy applications. The controller utilizes a state-space formulation as the prediction model and incorporates vector control techniques to regulate stator active and reactive power. To address voltage limitations and prevent voltage values from surpassing rated levels, constraints are introduced. Additionally, a parameter selection methodology for GPC is proposed, based on the analogous closed-loop transfer function. The predictive controller, complete with constraints, is then implemented on a Digital Signal Processor (DSP) in a practical test environment, and the results from experiments provide empirical validation of the proposed methodology.

Prasad, et al. (2020) explores the speed control of a three-phase induction motor through the application of the Switching-Table-Based Direct Torque Control (ST-DTC) technique. The study involves MATLAB/SIMULINK simulations and assesses the motor's performance under load torque variations. Parameters such as electromagnetic torque response, speed tracking capabilities, and stator flux trajectories are analyzed across different speed and torque settings. The simulation outcomes demonstrate enhanced dynamic performance of the induction motor when employing the proposed ST-DTC method compared to a conventional fixed PI controller. Furthermore, ST-DTC exhibits superior speed control across a wide range of operational scenarios.

Li, Shuhui & Haskew et al. (2012) The doubly-fed induction generator (DFIG) wind turbine, a prominent variable speed wind turbine in the modern wind power industry, has primarily relied on a decade-old technology in commercial applications. However, this paper highlights limitations in conventional vector control methods. It introduces a novel direct-current vector control approach for DFIG wind turbines, leading to the development of an integrated control strategy encompassing wind energy extraction, reactive power management, and grid voltage support. A transient simulation system employing Sim Power System is constructed to validate this innovative control methodology. Comparative assessments are made between the conventional and proposed control techniques for DFIG wind turbines, considering both steady-state and gusty wind conditions. The study demonstrates that the DFIG system, operating under the DC vector control configuration, exhibits superior performance across various parameters.

Abdelhak Dida et al. (2020) focuses on the comprehensive analysis, modeling, and control of a doubly-fed induction generator employed in variable-speed wind turbine systems. It establishes the wind turbine's startup procedure, including grid synchronization. The research introduces novel sensorless control schemes, one for standalone operation and grid synchronization known as "direct voltage control," and another for grid-connected mode known as "direct power control." To enhance system robustness in the face of machine parameter variations, a fuzzy logic controller is incorporated. The study encompasses various operational scenarios, such as wind turbine acceleration, braking, limited power and speed operation, power maximization, and standalone operation with variable load supply. The complete startup procedure is meticulously simulated using Matlab/Sim Power Systems, and the results across various transient conditions underscore the efficacy of the proposed control strategy.

Alshbib, M. M., et al. (2022) introduces an enhanced and robust approach to direct torque and rotor flux control (DTRFC) for an induction motor (IM) to eliminate uncontrollable angles (UCAs) across the entire speed spectrum. The method ensures that each voltage vector (VV) generates the desired torque and flux effects without any counteractive influence. Initially, the DTRFC algorithm's behavior was assessed at low and high speeds to identify UCAs, revealing issues at medium and high speeds. Consequently, a specialized strategy with 18 sub-sectors (SSs) was proposed for medium and high speeds, while retaining the basic 6-sector strategy for low speeds. The transition speed between these strategies was determined to guarantee the absence of UCAs throughout all speed ranges. Simulation results were obtained using the MATLAB/Simulink environment, and the effectiveness of the approach was validated through experiments using a dSPACE-based induction motor DTRFC drive system.

III. OBJECTIVE

There are following objectives of the present work;

- To optimise the design of double slope solar still by varying geometrical parameter Taguchi method.
- To study the effect of slope and solar intensity on temperature, vapour density, volume fractions.

IV. METHODOLOGY

Q_PCM is the energy stored by PCM during the day; it has been assumed that the system is well insulated.

When the temperature of PCM is not equal to mean temperature;

$$Q_{PCM} = \left[\frac{M_e}{A_p}\frac{dT_{pcm}}{dt}\right] = \left[\frac{T_l - T_{pcm}}{R_t}\right] - Q_{loss} \qquad eq(1)$$

When the temperature of PCM is equal to mean temperature;

$$Q_{PCM} = \frac{m_{pcm}.L_{pcm}}{A_p.\Delta t} = \left[\frac{T_l - T_{pcm}}{R_t}\right] - Q_{loss} \qquad eq(2)$$

M_e= Equivalent heat capacity of PCM

A_p = Area of basin water (m2)

T_pcm = Temperature of PCM

T_l = Temperature of liquid

R_t = Total thermal resistance of PCM (m2K/W)

Q_loss = heat loss

L_pcm = Latent heat of PCM (J/kg)

A. Computational Fluid Dynamics Analysis of Solar Still

Computational fluid dynamics involves the analysis of fluid flow and heat transfer systems through computer-based simulations. This powerful technique finds applications across diverse industrial and non-industrial domains. The present study utilizes a phase-shifting substance for CFD assessments in solar stills, employing ANSYS Fluent for the simulations. The mathematical model includes expressions for conservation of momentum and energy.

The modeling of Dual Voltage Source Inverter system is done which is capable of feeding the load with either solar or wind resources depending on the availability thus making the system more reliable

Therefore, three main components are employed to address and solve Computational Fluid Dynamics problems.

1) Pre-processor,
2) Solver and
3) Post-processor.

B. CAD modelling of single slope solar still

Using ANSYS design modular, a three-dimensional CAD model showcasing a single slope solar still has been carefully crafted. The dimensions of the base measure 1.1 m x 1.1 m, while the front wall stands at 0.25 m in height and the back wall at 0.9 m. Refer to figure 6. for a visual representation of the three-dimensional CAD model of the solar still.

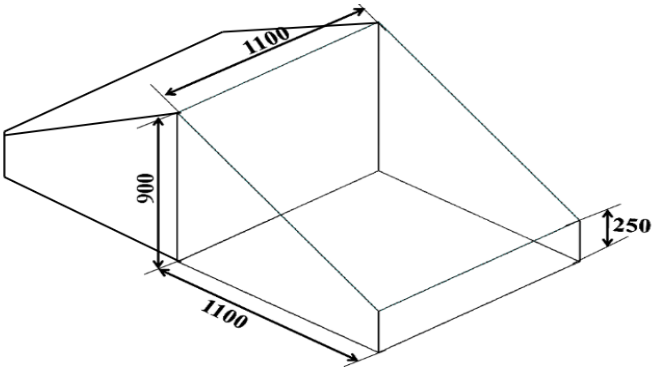

Figure 6. CAD model of double slope solar still

C. Meshing

Once the CAD geometry of the single slope solar still was completed, it was imported into ANSYS workbench for further analysis. The next step in this process was meshing, an essential component of finite element analysis. During this step, the CAD geometry was broken down into numerous small pieces, known as the mesh. The mesh created for the single slope solar still in this project can be seen in Figure 7, showcasing the intricate breakdown of the geometry for analysis. Total number of nodes: 137082 and total numbers of Elements are 128832 having hexahedral type of element.

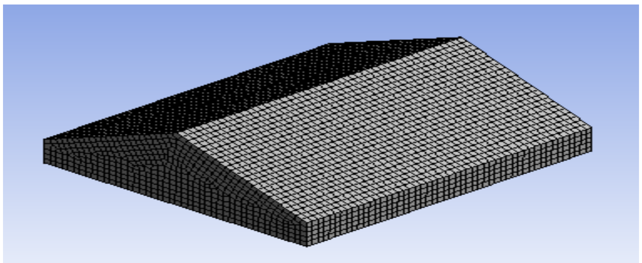

Figure 7. Meshing of double slope solar still

D. CAD modelling of double slope solar still

We utilized ANSYS design modular to construct a detailed three-dimensional CAD model of a double slope solar still, measuring 2.2 m x 1.1 m at the base. The front wall stands at a height of 0.25 m, while the back wall measures 0.9 m. Have a look for a visual representation of the solar still's three-dimensional CAD model.

The imposition of boundary conditions in the study involved a combination of deductions from physical phenomena and simulations carried out in the ANSYS CFD software. The categorization of boundary conditions for different sections of the solar still, along with their respective types, is presented in Table 1.

Table 1.Boundary Conditions

Boundary Name	Type	Thermal conditions	Body type
Absorber plate	Wall	Adiabatic wall (Heat flux = 0)	Opaque
Front wall	Wall	Adiabatic wall (Heat flux = 0)	Opaque
Back wall	Wall	Adiabatic wall (Heat flux = 0)	Opaque
Glass	Wall	Constant Heat flux (1000 W/m2)	Semi-transparent

Side wall (left)	Wall	Adiabatic wall (Heat flux = 0)	Opaque
Side wall (right)	Wall	Adiabatic wall (Heat flux = 0)	Opaque

To facilitate their selection in the CFD simulation work, real or physical boundary conditions were normalized and idealized. As an illustration, the side walls of the solar still, treated as adequately insulated, were assumed to possess a heat flux of zero. Further details regarding the input parameters for the CFD analysis are outlined in Table 2.

Table 2. CFD analysis Input parameters.

Setup		**Descriptions**
General	General	Absolute velocity formulation, pressure based steady state analysis. Gravity = -9.81 m/s2 in y-direction
Model	Multiphase	Volume of fluid, Implicit formulation, Sharp Interface modelling Number of Eulerian phase = 3
	Energy	On
	Viscous	K-epsilon, Standard model with Standard wall function
	Radiation	Rosseland Radiation Model, Solar Ray Tracing method with Direct solar irradiation = 1000 W/m2, Longitude 77.4oE, Latitude 23.2599oN, Time zone GMT+5:30 hour
Materials	Fluid	Air, Water-liquid, Water-vapour
	Solid	Glass, Steel, Wood, Paraffin C18
Phase	Primary	Air, Mass transfer mechanism : evaporation-condensation
	Secondary-1	Water-liquid, Mass transfer mechanism : evaporation-condensation
	Secondary-2	Water vapor, Mass transfer mechanism : evaporation-condensation
Solution	Pressure-Velocity coupling, Scheme- SIMPLE. Spatial Discretization: Momentum- Second order Upwind, Volume fraction- Compressive,	

	Turbulent KE & Dissipation rate- Second order Upwind, Energy- Second order Upwind

From the below contour table 3.shows results comparison with previous study it has been observed that Volume fraction of water showing 3.69% variation while the temperature difference of 6.1 degree showing 1.99% variation and the vapour density showing 5.94% variation. All above compared results show very good agreement between base paper and present work, hence the further analysis with same boundary with modified design have to be done.

Table 3 Results comparison with previous study

S. No	Parameters	C. Gnanavel et al (2020)	Present work	% Difference
1	Water Volume Fraction on Glass	0.1056	0.1095	3.69%
2	Temperature (K)	305.1	311.2	1.99%
3	Vapour density (g/ml)	0.8104	0.8585	5.94 %

V. SIMULATION AND RESULT ANALYSIS

Table 4. Presents the results of the simulation runs conducted for the double slope solar still. Each run varied in slope angle and solar intensity, yielding different outcomes for water volume fraction, vapour density, and temperature. Key observations include higher solar intensities generally correlating with increased water volume fraction and vapour density, while slope angles showed varying effects on these parameters. For instance, higher slopes tended to slightly elevate temperature readings. These findings underscore the complex interplay between slope angle, solar intensity, and the thermal performance of the solar still, crucial for optimizing its efficiency in water vaporization and energy conversion.

Table 4. Shows the results of simulation run.

Run	Slope	Solar intensity	Water volume fraction	Vapour density	Temperature
1	25o	1000	0.1045	0.7645	312.42
2	30o	1500	0.1262	0.8585	316.71
3	35o	2000	0.1549	0.8862	318.56
4	25o	1500	0.1333	0.8045	317.54
5	30o	2000	0.1451	0.8771	318.66
6	35o	1000	0.1662	0.9342	319.32
7	25o	2000	0.1332	0.8239	317.59
8	30o	1000	0.1424	0.8328	315.43
9	35o	1500	0.1541	0.8439	314.11

When the slope of a solar still increases, it can affect the collection and condensation of water vapor. A steeper slope might enhance the runoff of condensed water from the surface, leading to an initial increase in vapor density. This could be due to improved drainage, preventing the re-evaporation of condensed water.

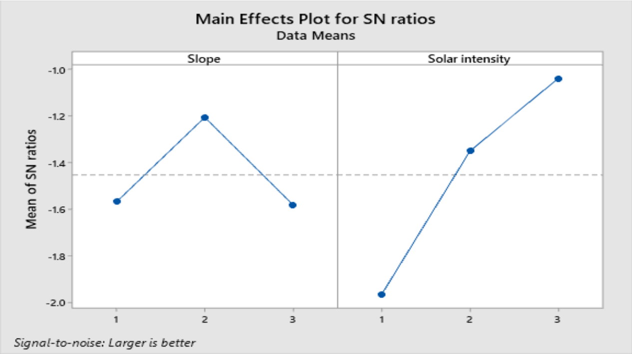

Figure 8.Variation of slope and solar intensity on vapour density

However, when the slope is doubled, it seems to have an adverse effect on vapor density. A very steep slope might cause water to flow too quickly, reducing the contact time between the condensing surface and the air. This reduced contact time can result in lower vapor density, as less water vapor has the opportunity to condense. Further based on fig. 8, the optimum parameter is A2B3.

A. Optimisation of Water Volume Fraction

From figure 9, it is observed that as the slope of a solar still increases, it can enhance the runoff of condensed water from the condensing surface. A steeper slope might improve drainage, preventing the re-evaporation of condensed water and allowing it to flow more efficiently into the collection area. This could lead to an initial increase in the water volume fraction.

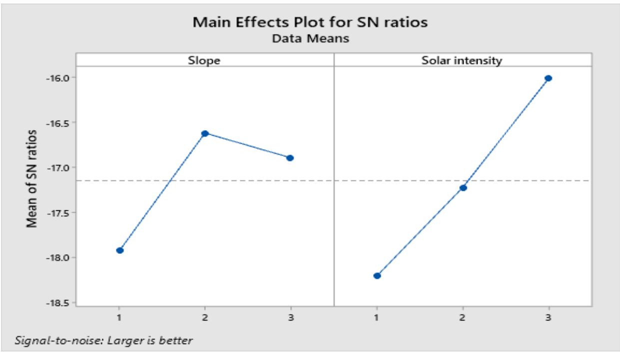

Figure 9. Variation of slope and solar intensity on water volume fraction

When the slope is doubled, it might cause water to flow too quickly, reducing the contact time between the condensing surface and the air. This rapid flow could result in less efficient condensation, and water may not have enough time to fully collect. As a result, the water volume fraction could decrease with a double increase in slope.

B. Optimisation of Temperature

Based on Figure 10, when the slope of a solar still increases, it can enhance the absorption of solar radiation by the collector surface. A steeper slope might improve the exposure of the collector to sunlight, leading to increased absorption of solar energy. This can result in higher temperatures within the solar still. There is an optimal slope that maximizes the absorption of solar radiation. Initially, as the slope increases, the solar still may capture more sunlight and experience a rise in temperature.

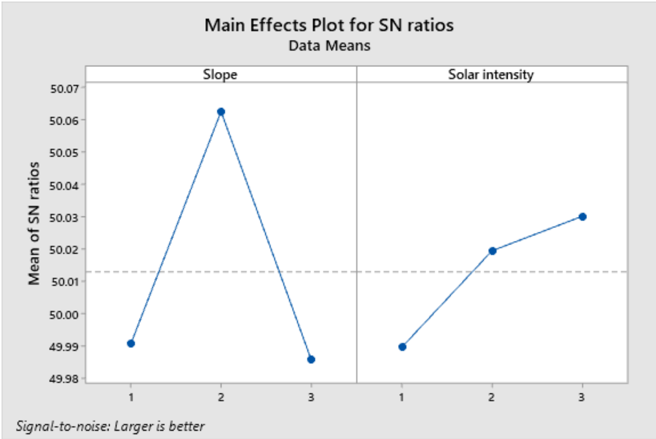

Figure 10. Variation of slope and solar intensity on temperature

However, beyond a certain point, increasing the slope further may not lead to a proportional increase in solar absorption. In fact, it might even lead to reduced efficiency due to factors such as shading and heat loss.

V. CONCLUSION

Finally, by concentrating on important variables like temperature, water volume fraction, and vapour density, the study optimized a double slope pv still employing the technique known as Taguchi. The results show that sunlight intensity is the main factor affecting these variables; higher photovoltaic cells intensity increases the absorber surface's ability to absorb energy, which in turn raises the temperature of the water and produces more vapour. The still's slope angle is also important because it influences the effectiveness of solar energy absorption and the transmission of heat to the water, which in turn affects the system's temperature and the amount of evaporation. To maximize the effectiveness of photoelectric stills in turning energy from the sun into useable water resources, ideal arrangements of solar intensity and slope angle are essential. These findings highlight the possibility of such systems for producing water sustainably in areas with abundant solar radiation, supporting larger initiatives in the areas of water sustainability and the application of energy from renewable sources. Subsequent investigations may go deeper into extra design variables or substitute materials to improve the efficiency and suitability of solar stills in various ecological scenarios.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

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