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Research Article

Experimental Investigation of Single Slope Solar Still by Varying Water Depth and with External Reflector

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Abstract

Solar distillation converts salt water into drinkable water, requiring minimal maintenance and energy-saving. However, the desalination process has drawbacks because the system's slow evaporation and condensation rate leads to low freshwater output. Consequently, this method is not widely utilized due to its limited productivity. To address this issue, the study's primary aim was to enhance the productivity of the single-slope solar still. This was achieved by altering the water depth from 3 cm to 6 cm and incorporating an external reflector. The experiments were conducted in Coimbatore, Tamil Nadu, India (11.0168° N, 76.9558° E), with a condensing cover inclined at 11 degrees. The research occurred on varying days between October and November 2023, with water depths ranging from 3 to 6 cm. A comprehensive analysis investigated the influence of different factors on daily production, such as ambient temperature, solar intensity, and inner and outer glass temperatures. The experimental results indicate that the solar still with a single basin, operating at a water depth of 3 cm, achieved the highest water productivity (2.68 L/day) and displayed the best efficiency (30.52%) compared to 4, 5, and 6cm depths. Furthermore, incorporating an external reflector into the solar system still demonstrated a notable elevation in temperature, resulting in a significant boost in water productivity of 3.085 liters per day. This improvement also led to an increase in efficiency of 35.1 %.

1. Introduction

Recently, the decrease in groundwater resources has been associated with the effects of global warming. In ancient times, individuals employed various methods to purify and separate water to render it safe for drinking. Other desalination technologies have been extensively tested to address the limited fresh water supply issue and to produce safe drinking water. The traditional water purification system necessitates electricity, human resources, and extensive maintenance, all employing energy-intensive methods [1]. Considerable research has been dedicated to renewable energy projects in recent years. Solar energy is a readily accessible and highly esteemed choice among renewable energy sources. The solar desalination system, commonly called a solar still, is acknowledged as an efficient method for purifying brackish water in coastal and desert areas. Its simplicity and compatibility make it an ideal technology for arid and semi-arid regions. Many authors have conducted extensive research to enhance the performance of solar stills. Scientists employ various methods to improve the effectiveness of these solar stills.

Madiouli et al. [2] carried out tests to measure the efficiency of solar stills utilizing various energy storage materials. The researchers found that the output generated in the still was 16.1%. The accomplishment was facilitated using a heat-storing substance as a spherical ball containing salt. Sathyamurthy et al. [3] The study's findings revealed that a comprehensive analysis was conducted on the outcomes derived from a solar still that was enhanced with a heat storage layer composed of sand. It was observed that the inclusion of sand into the basin during the evening resulted in a notable 12% augmentation in production. Ravichandran et al. [4] conducted experiments to enhance the efficiency of the solar still, which focused on integrating various energy storage materials. These experiments involved adjusting the proportions of the mixture at four specific mass quantities: 150 g, 250 g, 350 g, and 450 g. The results indicated a substantial improvement of 39.7 percent in the effectiveness of the 300 g mixed layer.

Singh et al. [5] carried out an experiment utilizing servo-therm oil and a layer of sand as a medium for heat transmission. The sand was positioned beneath the basin, serving as the foundation for the still. The results revealed a slight improvement in the efficiency during the night. Nougriaya et al. [6] and Kabeel et al. [7] investigated the relationship between the water level in the basin and the production range. A comparison of distillate production of different substances was carried out. This was achieved by incorporating cost-effective and easily accessible sensible heat storage materials into the still basin. The study's results revealed a clear correlation between decreasing water depth in the basin and increased productivity. Mugisidi et al. [8] experiments were carried out to assess the impact of different storage materials and distillation methods on yields. The materials under scrutiny were dye, black rubber, and ink. The results demonstrated that the distillation yield of black rubber increased by 38%, while black ink and dye experienced increases of 29% and 25%, respectively. Arjunan et al. [9] and Elashmawy and Ahmed [10] investigated strategies to improve solar stills' efficiency. Beyond the capabilities of conventional solar stills, a noteworthy 17% increase in production was obtained by adding black granite gravels to the still basin. The same crew produced another alteration in which they used jute cloth to store energy in a solar still that was regenerative. Abed and Hachim [11] investigated the impact of varying charcoal particle sizes (fine, coarse, and medium) on the outcomes of a modified still. The research showed that bigger charcoal particles increased production by 15% compared to other particle sizes. Different sponge pieces were analyzed to determine their impact on the distillation yield. They utilized black coals and yellow sponges as their preferred materials for the investigation. The capillary behavior of the sponge cubes improves the evaporation rate.

According to the experimental data, the modified double-slope solar still experienced a significant 18% growth in distillation output [12]. Shivhare et al. [13] and Kanka et al. [14] examined the influence of various enhancement elements on the efficiency of a solar desalination system. Moreover, an evaluation was conducted to assess the thermal performance of the still. Lalitha Narayana and Ramachandra Raju [15] examined the impact of flat plate collectors on the efficiency of the still. Kabeel et al. [16] analyzed the short-term dynamics of solar still incorporating a tubular solar collector. Analytical solutions were obtained to comprehend the system's behavior, enabling a comprehensive understanding of its transient characteristics.

Benhammou and Sahli [17], Khan et al. [18], and Alptekin and Ezan [19] employed a combination of latent heat and sensible heat storage materials to attain enhanced results. Servantine oil was chosen as the heat transmission fluid to maximize the efficiency of daytime output. The heat transfer fluid provides thermal energy to the basin water through a heat exchanger mechanism through the parabolic trough collector. By adding phase change materials in the evening, production continuously increased. Additionally, a performance evaluation of the still was carried out using various reasonable heat storage materials. It was more effective since Grapheme showed the highest heat conductivity among the investigated materials. The effect of a sand bed constructed in a solar still, layer by layer, was investigated in research. El-Sebaii et al. [20] conducted a study where energy absorber materials were employed in different forms. Implementing a fin-shaped absorber resulted in an augmentation of the solar still's production. Compared to the alternative absorber type, this configuration yielded an additional 5.21 L/day distillate.

The device's performance was assessed by modifying the masses of pumice stone in the solar still basin while maintaining a constant water volume. This alteration led to a noticeable decline in the overall production. However, there was a significant increase in productivity during nighttime, which can be attributed to the higher energy storage density. Panchal [21] utilizing blue metal stones and cakes of cow dung as heat-storage materials proved judicious in constructing the solar still. Compared to alternative methods, including cow dung and blue metal stone in the conventional solar still yields a substantial increase in output, with a 35 percent and 20 percent improvement, respectively. Rejebet al. [22] reviewed the results from a solar panel, and the variables that affected its efficiency were dissected. El-Sebaii et al. [23] used a mathematical model to predict its transient behavior in solar still construction. This model considered two scenarios: one with sensible heat storage materials and one without. Experimental findings indicated that integrating a sand storage medium resulted in a significant 23.8 percent increase in daily productivity.

Many studies have been conducted to improve the efficiency of solar stills during both daytime and nighttime. A detailed analysis of the literature has revealed that several researchers have utilized different energy storage materials to increase the temperature of the basin water. Further research is still required to enhance the productivity of single-basin solar stills through internal and external modifications. To improve the efficiency of single-basin solar still, this study explores the impact of different water levels and the addition of an external reflector. The investigation comprises two key components: the initial phase involves determining the optimal water depth by adjusting it between 3 and 6 cm. In contrast, the subsequent phase focuses on evaluating the productivity and efficiency of the single-basin solar still, with and without an external reflector. The experimental methodology employed in this research is visually represented in Figure 1.

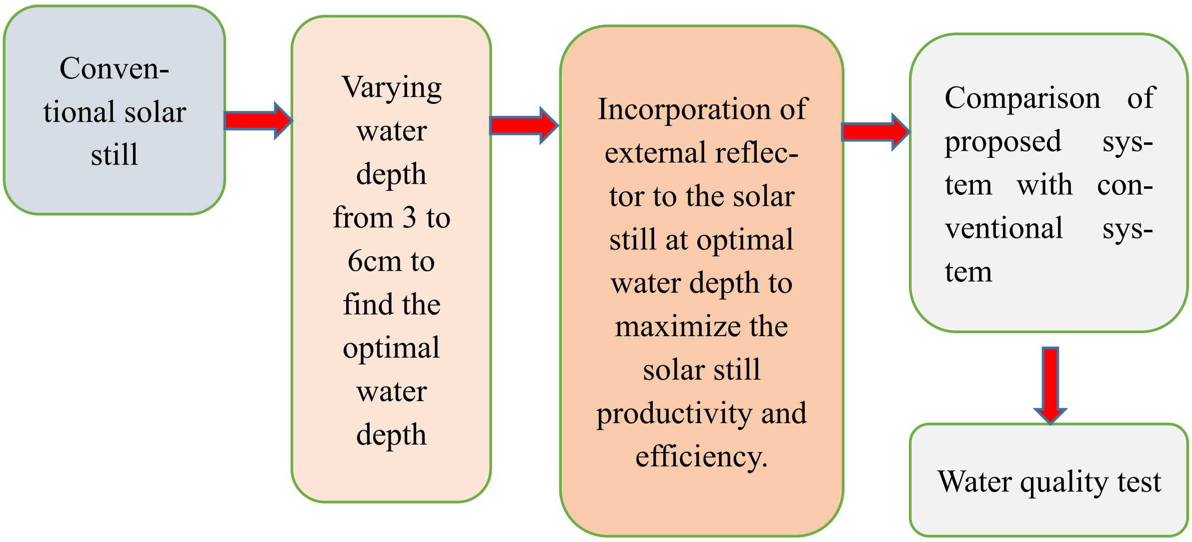

Figure 1. Methodology of the work

2. Experimental Setup and Procedure

Figure 2 illustrates the schematic diagram of a single-slope solar still. The solar still was assembled utilizing an angled glass cover and galvanized iron sheet. The base of the still was measured to be 85 cm × 70 cm in size. One effective way to manage the increased sun radiation is by utilizing a single exterior mirror. The solar still system incorporates five thermocouples to monitor multiple temperatures effectively. These temperatures encompass the water temperature, vapor temperature, temperature of the glass surfaces (both inside and outside), and the surrounding air temperature. A visual representation of the suggested solar still's 3D diagram is depicted in Figure 3. In the construction process of the single-slope solar still, plywood sheets of 20 mm thickness were employed. Reflectors were installed on the inner walls of the solar still to amplify the solar radiation. Ravindra et al. [24] have found that incorporating an external reflector can significantly enhance the device's efficiency by redirecting sunlight toward the basin. The basin is constructed from galvanized iron and has measurements of 85 cm × 70 cm × 10 cm. The entire basin was coated with black paint to enhance radiation absorption. To reduce heat losses, a recent study applied a 50 mm layer of thermocol to insulate the interior surfaces of the solar still device [25]. The transparent coverings were made with window glass that had a thickness of 5 mm. The coverings were placed at an 11-degree inclination.

PVC pipe collecting channels were constructed under the covers' lower edges to control the output water. In addition, water drainage channels were created with hoses made explicitly to enable the collection of water in containers. Hoses were intended for thermocouple installation, draining the basin, and transporting tainted water. The edges of the still were sealed with silicone sealant. Every effort is made to guarantee the complete air tightness of the still. Water can condense and evaporate on its inner surface as it runs down it.

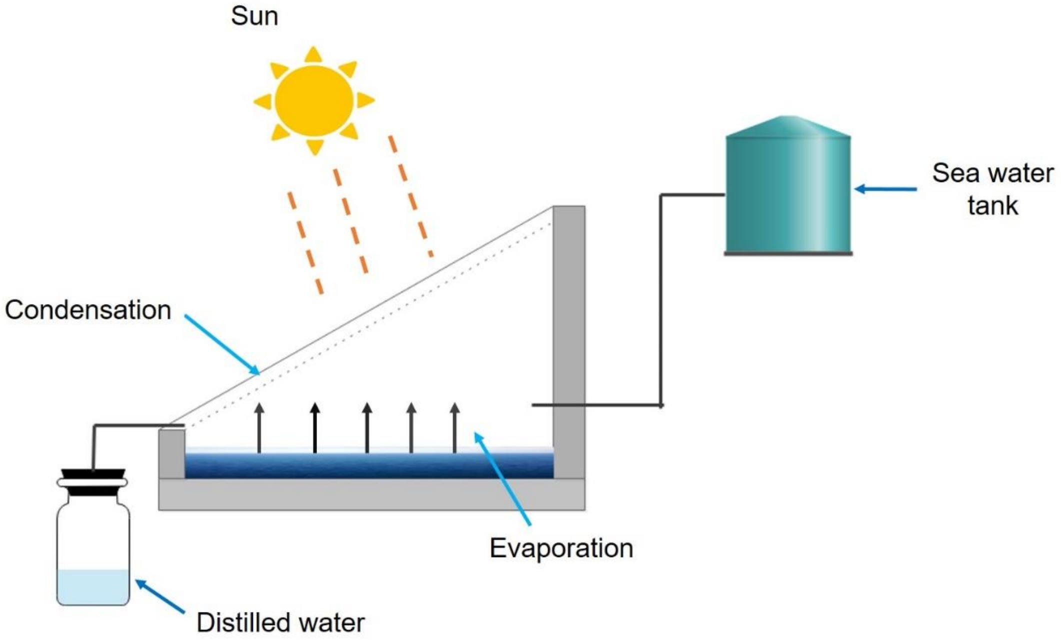

Figure 2. Diagram of a single-slope solar still

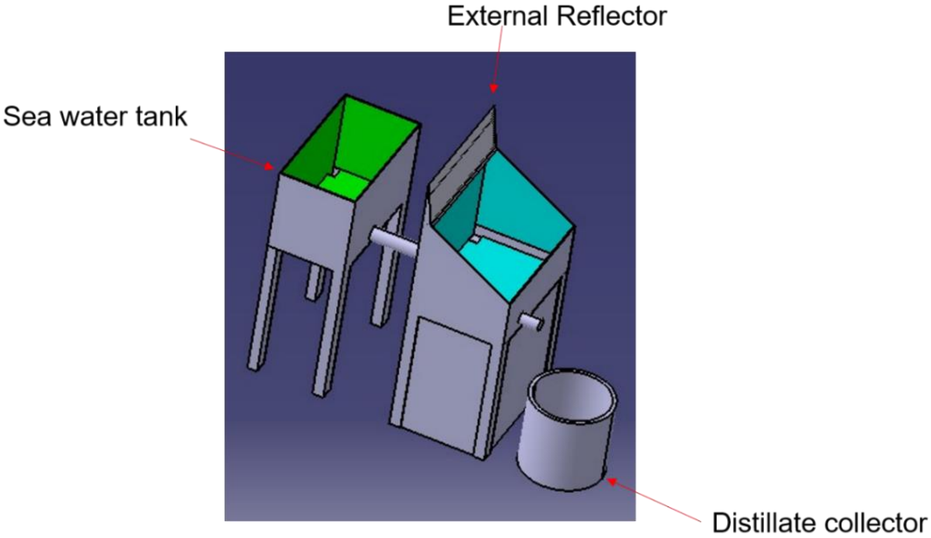

Figure 3. 3D schematic of the proposed system

2.1. Experimental Procedure

From October to November of 2023, the experiment was carried out in Coimbatore, India. To maximize solar radiation absorption, the experimental setup was pointed southward to prevent vapor leakage; a silicone rubber sealant was employed to adequately seal the gap between the body of the still and the glass cover. Four distinct water levels were maintained in the tray throughout the day: 3, 4, 5, and 6 cm, to assess the formation of condensed water. Water was regularly poured into the tray via a hole in the back of the still to maintain the constant. Before being directed toward the solar still, the water is gathered in a tank of around 100 L.

The three instruments that measure the temperature, wind speed, and incident solar radiation are a digital thermometer, a traditional pyrometer, and a digital anemometer. An 8-channel digital display device was utilized, employing K-type thermocouples to gauge various temperatures. These temperatures encompassed the water temperature, water vapor within the tray, glass surface temperature internally and externally, and ambient air temperature. The hourly performance metrics were monitored from 8 a.m. to 5 p.m. Regular cleaning is necessary to prevent dust accumulation on the top cover, undesirable deposition in the basin, and sufficient radiation absorption. Table 1 presents the information regarding the instruments used. A PVC pipe trough was situated underneath the solar still to assist in the accumulation of potable water. An evaluation was performed on the original water source and the purified water yielded by the solar still. The purified water demonstrated marked enhancements in TDS, salinity, and conductivity.

Table 1. Types of instruments used and % of error [26].

S.No	Instrument	Precision	Range	Inaccuracy (%)
1	Pyranometer	±1W/m^2	0-2500 W/m^2	2.5
2	Anemometer	±0.1m/s	0-45 m/s	10
3	K-type Thermocouple	±1°C	0-100°C	0.25
4	Beaker	±10mL	0-1000ml	10

3. Results and Discussion

This research encompassed the measurement of various parameters. These included the air temperature, vapor and basin water temperature, inner and outer glass temperature, sun radiation, and distillate production. Hourly measurements were taken at different depths within the basin's water. Conductivity, salinity, and TDS were recorded as indicators of the distillate water's quality. The research team successfully conducted an experimental evaluation of the solar still's performance, comparing its effectiveness with and without the presence of an external reflector.

3.1. Observation of Climatic Conditions

Figure 4 illustrates the fluctuations in air temperature and solar radiation on an hourly basis over a span of several days. The experiment, conducted during October and November, revealed variations in the outside temperature and the level of solar radiation received. The temperature ranged from 20 to 30°C. Figure 4 displays the changes in solar intensity and air temperature over time. As seen in Figure 4, these parameters reach their most excellent levels between 12.00 and 14.00 hours. The data indicates a strong correlation between radiation and temperature. The daily fluctuations in atmospheric temperature and solar radiation exhibit a consistent pattern throughout the day, from morning until evening.

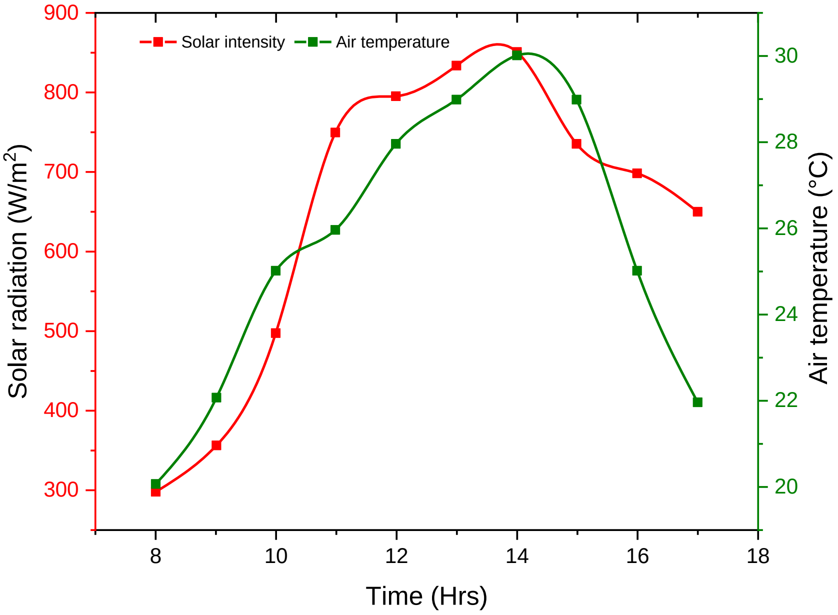

Figure 4. Air temperature and solar intensity variations throughout time

3.2 Impact of Solar Radiation on Water, Vapor, And Inner and Outer Glass Temperatures

The investigation utilized four distinct water depths within the solar still designated as Case 1 to Case 4. In Case 1, the water depth was set at 3 cm, while in Case 2, it was adjusted to 4 cm. Similarly, Case 3 involved a water depth of 5 cm, and Case 4 entailed a water depth of 6 cm. The temperature fluctuations of different variables, including water temperature (Tw), vapor temperature (Tv), glass inner temperature (Tgi), and glass outer temperature (Tgo), are depicted in Figure 5. According to the graph, there is a clear correlation between the increase in performance temperatures and the intensity of solar radiation, with temperatures reaching their highest point between 12.00 and 2.00 p.m. Subsequently, as solar radiation intensity decreases, temperatures also decrease. The comparison of the vapor temperature curve with the water temperature curve in Figure 5(a-d) reveals a consistent pattern of the former exceeding the latter. This discrepancy can be explained by the higher absorption of energy in the form of latent heat of vaporization by the vapor as opposed to the water.

Consequently, the temperature of the inner glass cover rises as the vapors condense and release the latent heat of condensation at the inner surface of the glass cover [27]. The temperature of the condensed water in a single-slope solar still exhibits a progressive increase, culminating at around 14:00 hours. This phenomenon arises due to the maximum solar intensity coinciding with the peak daylight hours, resulting in heightened rates of evaporation and condensation.

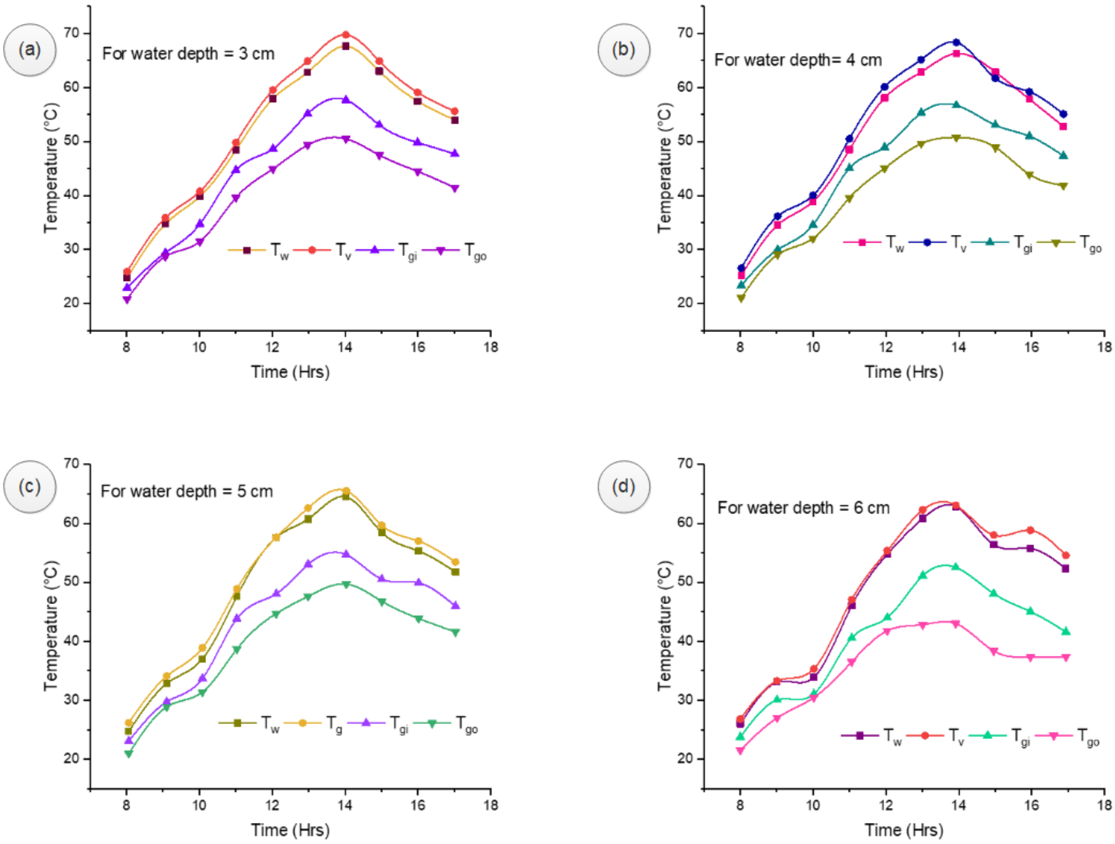

Figure 5. (a-d) Water, vapor, and glass inner and outer temperatures change over time for varying water depths

3.3. The Effect of Water Depth on a Single Basin Solar Still's Productivity and Efficiency

This experiment included measuring and comparing the results of four distinct water depths in the basin: 3, 4, 5, and 6 cm. Figure 6 illustrates that the maximum production for all depths happens around 2.00 p.m. since this is when the most solar energy is received. Furthermore, the findings depicted in Figure 6 emphasize the importance of considering water depth and the productivity of solar still. The highest production rate (2.68 L/day) is achieved at the lowest water depth of 3 cm. The increase in the water volumetric heat capacity of the basin can explain the decrease in water temperature and subsequent decline in productivity. This alteration in heat capacity causes a reduction in temperature despite the constant solar radiation intensity, resulting in reduced productivity. Therefore, it is crucial to carefully manage the water depth to maximize production in this scenario.

In addition, the coefficient of evaporative heat transmission showcases a more significant value at lesser depths and undergoes a gradual reduction as the water depth of the basin increases. [28]. The daily yield of solar still under different water depths is shown in Figure 7. Findings demonstrate a substantial 10.28% enhancement in production when the water level is lowered from 4 cm to 3 cm. The basin's water volume is at its minimum when the water depth is 3 cm, as opposed to 4 cm. This reduction in water volume allows more energy to be utilized in evaporation, given the constant solar intensity. As a result, the solar system's heat transfer rate and efficiency are significantly enhanced. Similarly, there is an 8.83% improvement in water production when the water depth is reduced to 5 cm. Case 3 exhibits the most significant increase in productivity (19.04%) compared to Case 4. One possible explanation for this phenomenon is a notable reduction in the vapor temperature in Case 4.

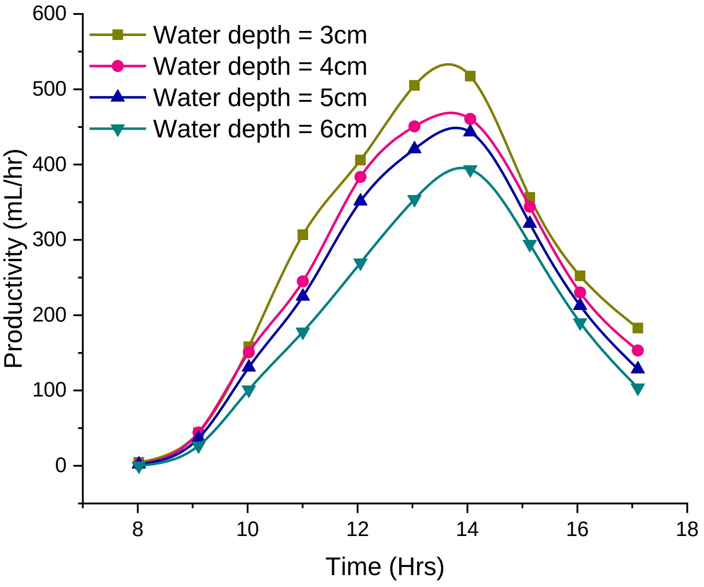

Figure 6. The solar still's productivity over time for different water depths

The daily thermal efficiency represents the proportion of solar radiation utilized for evaporating basin water. Equation (1) may be used to calculate the solar still's daily thermal efficiency, as shown in Figure 8 [29].

$$\eta_{still} = \frac{\Sigma_{m_w} L}{\Sigma_{Ig} A\, 3600} \tag{1}$$

Where L is the latent heat of vaporization (J/kg), A is the glass cover area, Ig is the day average radiation (W/m^2), and m-w.mw is the hourly distillate output (kg)(m^2). When Case 4 and Case 1 are compared, it can be seen that the daily efficiency has gone up, which means that the distillate production is more significant for a certain quantity of incident solar energy. The drop in water temperature brought on by Case 4's larger water mass is responsible for this efficiency gain. Based on the calculations, the daily efficiencies for Case 1, Case 2, Case 3, and Case 4 are about 31.34 %, 28.12 %, 25.23 %, and 21.78 %, respectively.

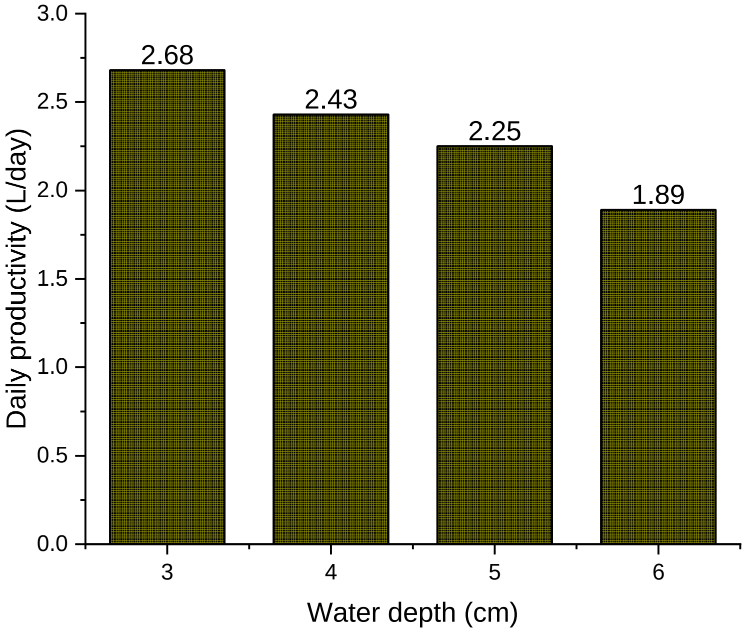

Figure 7. The solar still's daily productivity at different water depths

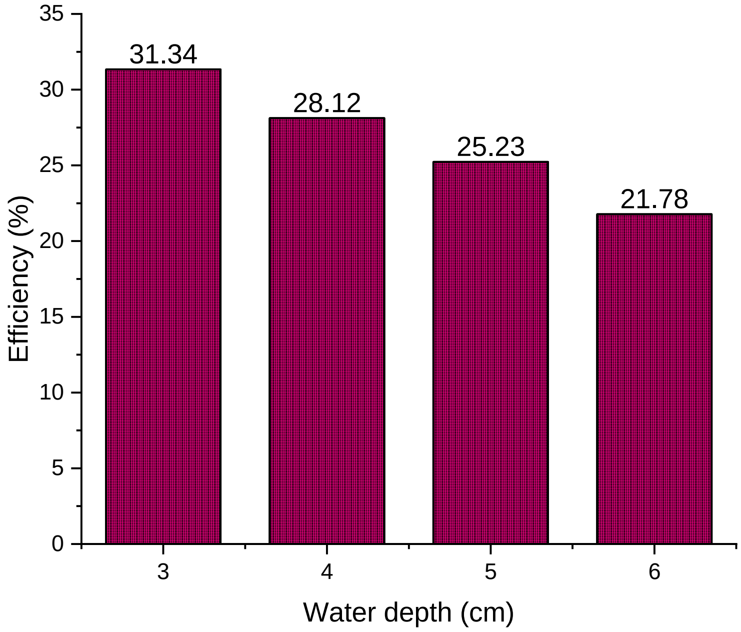

Figure 8. The solar still's efficiency at different water depths

3.4. Effect of the External Reflector on Water, Vapor, and Inner and Outer Glass Temperatures at an Optimal Water Depth

The experiment also assessed the impact of the external reflector at the optimal water depth of 3 cm. Figure 9 illustrates the fluctuation of various temperatures when an external reflector is present. The temperature of evaporated condensed water rises steadily, peaking around 14.00 hours. Similar to this, the temperature of the glass cover increased gradually over time, peaking between 1 and 2 p.m. These findings further validate the observations above, with the solar still achieving optimal efficiency when the water depth is set at 3 cm.

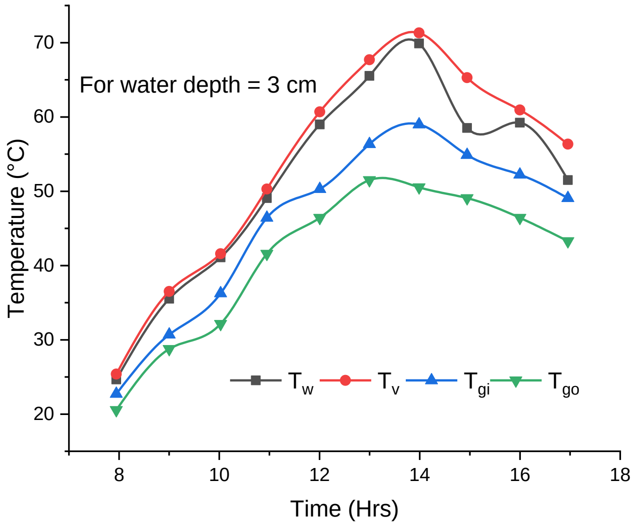

Figure 9. Effect of the external reflector on various temperatures at a water depth of 3 cm

3.5. Effects of an External Reflector on Solar Still Productivity and Efficiency

The primary objective of the investigation was to examine the daily production and efficiency of solar stills, specifically comparing those that lacked an external reflector to those that were equipped with one. The results are presented in Figure 10, which displays the productivity of solar stills with and without a reflector. Figure 11 exhibits the efficiency of solar stills with and without an external reflector. The findings of this study revealed that solar stills with an external reflector exhibited notable enhancements in production and efficiency. This improvement can be attributed to the increase in temperature within the water basin, subsequently amplifying the temperature difference between the glass cover and the water basin. As a result, the productivity and efficiency of solar stills with external reflectors were significantly enhanced, as depicted in Figure 10. These empirical findings closely align with the theoretical and experimental analyses previously conducted by researchers [30].

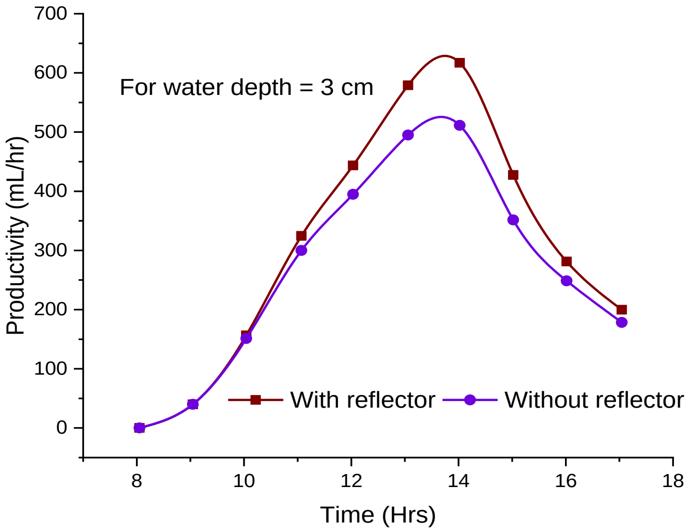

Figure 10. Productivity of solar still with and without external reflector

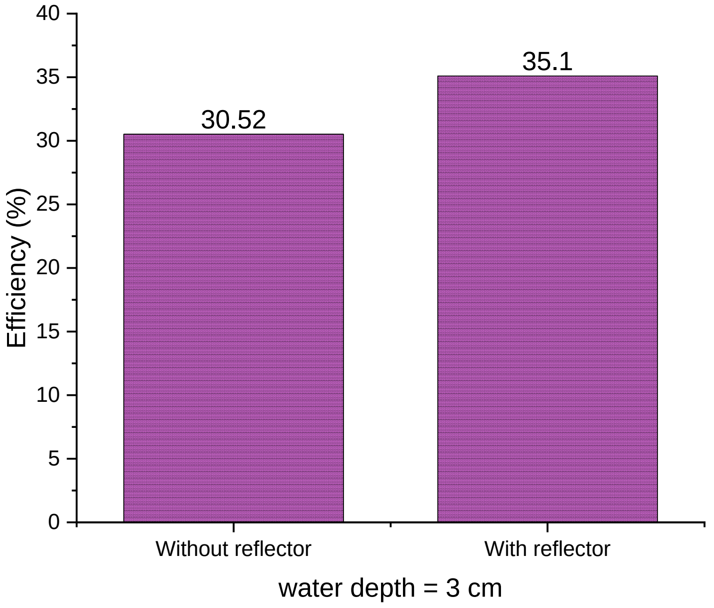

Figure 11. Solar is still efficient with and without an external reflector

Table 2. Comparison of productivity and efficiency with and without reflector

S.No	Water depth (cm)	Without reflector		With external reflector		% increase in efficiency due to reflector
		Productivity (L/day)	Efficiency (%)	Productivity	Efficiency	
1	3 cm	2.68	30.52	3.085	35.1	15.11%

Table 2 displays the productivity and efficiency comparison between the reflector and the absence of one. With an efficiency of 30.52 percent, the solar still without a reflector generated 2.68 L/day at a water depth of 3 cm. Production increased significantly to 3.085 L/day, and efficiency improved to 35.1% with the addition of a reflector. The efficiency increase resulting from the reflector is determined to be 15.11%. Based on the data, incorporating a reflector into the solar still notably impacts its performance, resulting in increased productivity and efficiency. The findings indicate that the reflector plays a crucial role in enhancing the solar still's water distillation capabilities, highlighting its potential for improving water desalination methods, especially in situations with limited water depths.

4. Water Quality Test

The measured values for the input and output water samples are shown in Table 3, together with the permitted limits for the water (output water) and saltwater (input water) collected from the solar still. Numerous factors were considered in the evaluation, including conductivity, salinity, and total dissolved solids (TDS).

Table 3. Quality water before and after Desalination

S. No	Property	Sea water	Distillate water obtained from the conventional method	Distillate water obtained from the proposed method	Acceptable limit
1	TDS (mg/L)	36000	48	43	<300
2	Conductivity (µs/cm)	66000	90	57	50-800
3	Salinity (ppt)	38	0.2	0	<0.5

The conductivity of water is a result of its capability to carry electrical current, which is directly influenced by the amount of ions present in the water. These conducting ions comprise inorganic compounds like carbonate complexes, dissolved salts, alkalis, chlorides, and sulfides. A higher conductivity value in water indicates a more significant concentration of dissolved substances. Drinking water typically exhibits a conductivity range of 50 to 800 µs/cm. Water that is pure and free from impurities has a low conductivity for electricity. The water from the solar still has a conductivity that is within an acceptable range, according to the data shown in Table 3. As a result, drinking-grade water that is collected in a solar still has much higher purity. The amount of salt present in soil or water is measured as salinity. For fresh water, the salinity level should be maintained below 0.5 parts per thousand (ppt). The salt concentration in large rivers can fluctuate between 0.5 and 30 ppt, influenced by factors such as flow rate and proximity to ocean or river inflows. Ocean salinity levels exhibit spatial variability, with an average of 38 ppt. Water generated by a solar still is entirely salinity-free, making it a safe option for drinking.

The evaluation of water quality is conducted using the TDS test. This test involves the addition of calcium and magnesium hardness quantities to determine the total dissolved solids (TDS) present in a given sample. Therefore, practical data suggests that using solar energy improves water quality even when the TDS test cannot pinpoint the precise ions in a sample. For drinking water, the recommended range is 50 to 300 mg/L. The TDS measurements in Table 3 demonstrate that adding the built-in solar still has enhanced the water's quality. The water from our fabricated solar system fulfills all the requisite standards, encompassing TDS, and remains within acceptable parameters. Consequently, the solar still formulated in this research demonstrates potential for commercial expansion.

5. Conclusion

The single basin solar's performance was still significantly enhanced by manipulating the water's depth and adding an external reflector. It has been established that the productivity of solar energy is still inversely correlated with water depth. Specifically, decreasing the depth of saline water leads to a rise in productivity due to increased water temperature, which enhances the evaporation rate. This relationship was demonstrated in several experiments, where the still with a water depth of 3 cm reached the highest output of 2.68 L/day, significantly outperforming other setups with deeper water.

Additionally, using external reflectors has further improved the production and efficiency of solar stills. This improvement is mainly attributed to the elevated temperatures within the water basin, which create a greater temperature differential between the water surface and glass cover, thereby boosting evaporation. When reflectors were used, the efficiency of a still with a water depth of 3 cm improved by approximately 15.11%, confirming the effectiveness of this modification.

Moreover, the investigation highlighted the notable enhancement in the quality of the distilled water, which meets the stringent standards set by the World Health Organization. The potential for commercial application of this technology is vast, particularly in sun-rich countries like India, where such innovations could significantly address freshwater shortages. Implementing this technology, particularly from March to October, could substantially increase the output and efficiency of solar stills, thus helping the government meet its long-term water sustainability goals. Further research is necessary to refine these techniques and expand their commercial viability.

Declaration of Competing Interest: The authors declare they have no known competing interests.

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