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Design and Experimental Studies on a Single Slope Solar Still for Water Desalination

Saif Salim Saif Al-Mezeini [1], Mohd Asim Siddiqui [1,*], Mohammad Shariq [2,*], Talal M. Althagafi [3], Inas A. Ahmed [4], Mohammad Asif [5], Sultan J. Alsufyani [3], Saud A. Algarni [3], Niyaz Ahamed M.B. [1], Khalda M. A. Elamin [4], Abdel-Nasser M. A. Alaghaz [6] and Mohammed M. Gomaa [7,8]

1 Department of Engineering, University of Technology and Applied Sciences, Shinas 324, Oman
2 Department of Physics, College of Science, Jazan University, Jazan 45142, Saudi Arabia
3 Department of Physics, College of Science, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia
4 Department of Chemistry, Faculty of Science, King Khalid University, Abha 62224, Saudi Arabia
5 Department of Mechanical Engineering, Z. H. College of Engineering & Technology, Aligarh Muslim University, Aligarh 202002, India
6 Department of Chemistry, College of Science, Jazan University, Jazan 45142, Saudi Arabia
7 Department of Architecture, Hekma School of Design and Architecture, Dar Al-Hekma University, Jeddah 22246, Saudi Arabia
8 Department of Architectural Engineering, Faculty of Engineering, Aswan University, Aswan 81542, Egypt
* Correspondence: mohd.siddiqui@shct.edu.om (M.A.S.); mohammadshariq@jazanu.edu.sa (M.S.)

Abstract: Gulf countries experience an imbalance between water supply and demand, which leads to a dramatic decline in the amount of groundwater. Solar energy for water desalination is an attractive option in this region, where the climate is sunny all year. A very basic solar device called a single basin solar still is commonly used to convert available seawater into drinkable water. The issue of producing drinking water may be resolved by using this technique, but because of its low productivity, it is rarely used. The experiments were carried out on a south-facing, single slope solar still with a 23-degree inclination of the condensing cover from October to November 2022, on different days for different water depths. According to the findings, the solar still with 4 cm of depth (as compared to 5, 6, and 7 cm) exhibited the maximum water productivity (2.680 L/day) with an efficiency of 30%. When the solar still was equipped with an external mirror, the temperature in the basin was raised, and water productivity increased to 3.075 L/day with an improved efficiency of 35%. Further, the effects of wind velocity, ambient temperature, inner glass temperature, and intensity of solar radiation on daily productivity have been studied.

Keywords: water desalination; solar still; single basin still; productivity

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1. Introduction

The environment must be safeguarded and protected as a valuable resource. Alternative energy sources must be used to offset the detrimental effects of anthropogenic activities related to the exploitation and burning of fossil fuels [1]. The public and corporate sectors in Oman are growing more interested in the use of renewable energy. Additional study, development, planning, and awareness are required for the present renewable energy resources, which may be employed as energy alternatives and environmentally acceptable energy systems. Some Gulf Cooperation Council (GCC) countries have a vision to lessen reliance on non-renewable resources and effectively utilize resources such as renewable energy to cut production costs and boost competitiveness in various economic sectors [2]. Solar energy has a lot of potential in the GCC, particularly in Saudi Arabia and the Sultanate of Oman, as those countries have one of the highest solar radiation densities in the world [3]. Some countries are hot and arid, where fresh water has always been in short supply. According to research, some countries have several problems, including a double-digit yearly increase in water consumption due to population expansion and economic diversification [4]. The "National Water Resources Master Plan" states that overall, as services are upgraded and expanded, water consumption for household, industrial, commercial, and municipal applications will rise by more than 50% by 2025. New water sources must be sought and other measures implemented to satisfy this growth [5]. Desalination and distillation are two methods for purifying brackish water, but they are technologically complex and require a lot of energy [6]. These techniques rely on fuels derived from oil and gas, which promote environmental deterioration. Additionally, the effects of current fuels on the environment are widely understood [7]. It has been determined that using solar energy in solar-thermal systems can significantly reduce the need for energy sources based on oil and gas. In various areas of the Arabian Peninsula, solar energy is widely available and may be used to cleanse water. Through a technique called solar thermal desalination, this abundant solar energy is used to create drinking water. Saline water desalination is frequently performed with traditional solar stills. On the other hand, one of the key methods for using clean solar energy for clean water production in sunny places with scarce or poor-quality water supplies is solar distillation [8,9].

Solar energy is still widely applicable in dry and salty environments and is generally inexpensive to build and operate. Due to its low protectivity and efficiency (efficiency and productivity are typically 20–30%, 2–3 L/m^2 day, respectively), solar energy is still not widely used [10]. The pace at which water from the basin evaporated and the rate at which vapor condensed on the bottom surface of the glass cover determined the productivity and efficiency of the solar still, respectively [11,12]. However, there is room for improvement in the performance of solar stills to reach greater yields and efficiencies through still design optimization. The factors impacting the solar panel's overall performance are often divided into three categories: (1) climatological conditions; (2) design features; and (3) operational conditions.

It is clear that climatological factors such as speed of air, temperature, and solar radiation intensity have a significant impact on how well the solar still performs, yet these factors are typically out of a researcher's control [13]. On the other hand, design components (such as the slope of the condensing cover, the various cover materials, the different absorber materials and their thickness and aspect ratio of the absorber, insulation thickness, etc.) and operational conditions (such as the feeding water temperature, the impact of water depth, the alignment of the still, etc.) can be controlled and optimized as per requirement [14]. As a result, extensive research studies in the literature have been reported for improved solar still performance [15]. Chaichan et al. described the development of a simple solar distillation system for Omani families. Using that system, three different kinds of water—seawater, wastewater, and tap water—were distilled into pure water that could be used and drunk by people [16]. Abed and his colleagues made a solar-powered system in Iraq for distilling brackish water, which cut the costs of making it by more than 40% [17]. Despite these recent studies, different factors that influence the rate of condensation and evaporation on passive solar still need to be examined. In the Aswan (Egypt) climate, Roshdy et al. investigated the performance of two single slope solar stills with air gap distances of 17 and 37 cm and a fixed water depth of 2 cm. They also used an ultrasonic atomizer to test yield performance and found that reducing the gap distance from 37 to 17 cm increased solar yield by 70%, and that covering the ultrasonic atomizer with a funnel increased yield by 8.5% [18].

In 2015, UNESCO's report on the availability of freshwater resources said that Oman was one of the places where freshwater resources were "totally rare." [19]. Thermal desalination, a phase-change procedure, has been utilized to transform saltwater into drinkable water since the beginning of time. The single-effect desalination technique is another name for the simple thermal desalination system. Technologies for thermal desalination need only minor water treatment and may be utilized with seawater of any salinity [20,21]. As a result, these technologies are widely used in areas where the seawater is highly salinated, and they account for almost 34% of the global and over 64% of the MENA (Middle East and North Africa) installed desalination capacity [22,23].

Saudi Arabia, Oman, and several other GCC countries are required to build desalination facilities that utilize saltwater to generate clean water in order to balance supply and demand due to the continuous pressure on water resources. [24]. The first desalination plant in Oman was built in 1976, at Al Ghubra and Massira. It produced 18,930 m^3 of desalinated water per day and 126 m^3 per day, respectively, using Multi-Stage Flash technology (MSF) [25]. Reverse osmosis technology is used in the Al Khafji desalination facility in Saudi Arabia, which also employs solar photovoltaics to generate energy. The desalination facility can produce 60,000 m^3/day of pure water, with a maximum output of 90,000 m^3/day. Due to the non-renewable nature of oil and natural gas, several GCC countries have established goals for switching their energy sources. Qatar, for example, intends to generate 20% of its energy from renewable sources by 2024 [25]. In Saudi Arabia's Vision 2030, there are water desalination projects that use solar power and make use of the solar resources available in the Kingdom to solve the problem of water sustainability. In order to reduce manufacturing costs and increase competitiveness across all economic sectors, Oman Vision 2040 seeks to reduce the country's dependency on nonrenewable resources [26]. Therefore, as the situation demanded, Oman and Saudi Arabia are among the greatest places in the world to build solar thermal technology, including water desalination. Although it has not yet been carried out, solar thermal offers a lot of promise for the country. So, the current work intends to investigate experimentally the influence of solar water distiller changes in various environmental and operational settings on thermal performance and the distilled water production rate. The focus of the research is on making solar distillers more productive at a lower cost and figuring out how well they work in different climates.

2. Materials and Methods

2.1. Designing and Fabrication of Experimental Device

The mentioned investigation was carried out in Shinas, Oman (24.7242° N, 56.4608° E), at the Mechanical Section of the Engineering Department of the University of Technology and Applied Sciences. Figure 1 depicts the actual setup of the experiment, which is a standard single slope basin type solar still. A single-basin solar still with a base size of 90 cm × 75 cm was made from galvanized iron sheet and covered with an inclined glass cover. To accommodate rising solar radiation, three internal and one external mirrors are used. Five thermocouples are attached at various locations to find the ambient temperature, the temperature of the inner surface of the glass, the temperature of the outer surface of the glass, the vapor temperature, and the water temperature tray, respectively.

Figure 1. Typical pictures of used solar still.

The internal structure and design of the solar still setup used in the current study are given in Figure 2a–d. Figure 2a–d illustrates the front view, side view, top view, and back view of the solar still, respectively. The solar still was built using plywood sheets that were 20 mm thick. External and internal reflectors were put on the inner walls (two sides and the back wall) of the solar still to boost solar radiation and get more intense radiation. According to Tanaka et al. [27], it was discovered that an external reflector would direct sunlight toward the basin, thus boosting the device's effectiveness. The basin is composed of galvanized iron and measures 90 cm × 75 cm × 10 cm. To maximize radiation absorption, the whole basin area was coated in black. To reduce heat losses, the solar still device was insulated on all inside surfaces with a 50 mm thermocol sheet. Transparent coverings were made of 5 mm thick window glass. The coverings were angled at 230 degrees. Shinas Oman's geographical location at 24° in the northern hemisphere makes it ideal for receiving maximum sun energy. To collect the output water, collection channels constructed of PVC pipes were installed beneath the lower margins of the covers. In addition, outlets were constructed for draining the water through drilled hoses and storing it in jars. Hoses were created to deliver polluted water, empty the basin, and insert thermocouples. The still's edges were sealed using silicone sealant. All of this is done to ensure that the still is airtight. Water evaporates and condenses on the inside of the glass lid. It runs down the bottom of the glass cover.

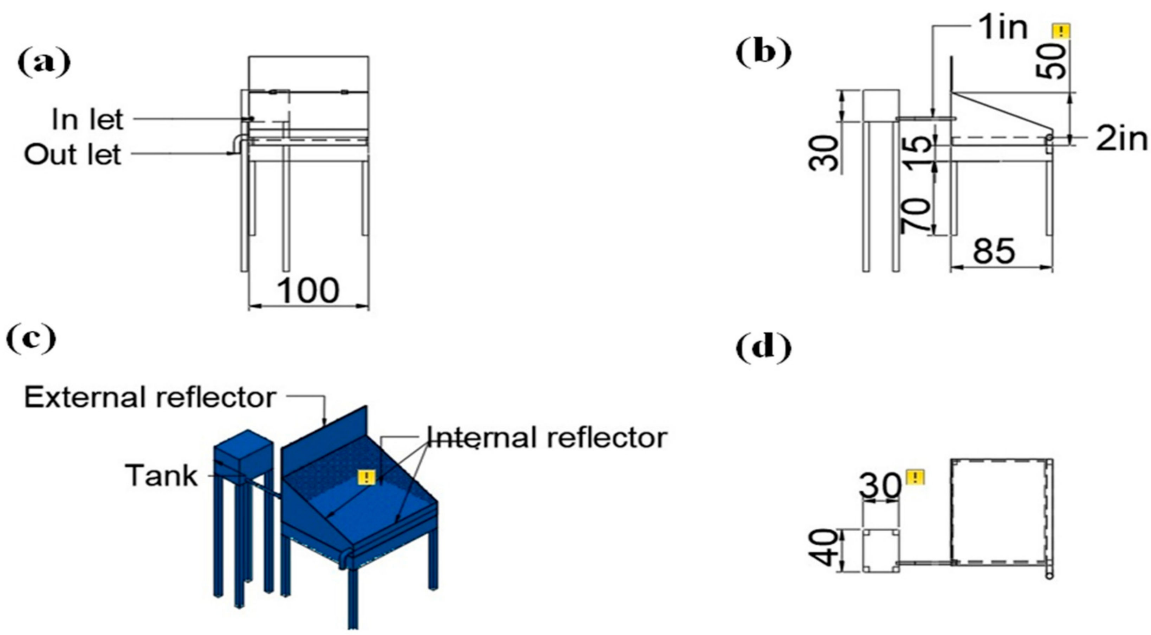

Figure 2. AutoCAD designing of fabricated solar still (**a**–**d**).

2.2. Used Instrumentations

Various types of equipment were utilized to measure different performance metrics. Using K-type thermocouples, the temperatures at various places of the still, such as the water inside the tray, vapor, exterior glass surface, inner glass surface, and ambient temperature, were monitored. The thermocouples were linked to a digital temperature reader (8 channels). A standard digital thermometer was also utilized to find the atmospheric temperature. The collected effluent water was measured using a flask with a capacity of 900 mL and a minimum count of 10 mL. The solar radiations were measured using a standard pyrometer with a minimum count of 1 W/m^2 and a range of 0–2000 W/m^2. A digital anemometer was utilized to observe the velocity of air. In addition to that, a TDS, salinity, and conductivity measurement meter was used to check the quality of the supply and condensed water.

2.3. Experimental Procedure

The experiment was carried out at UTAS Shinas in Oman from October to November. To get the most solar energy, the experimental setup was left oriented toward the south.

To avoid vapor leakage, a silicon rubber sealant was employed as the sealing interface between the body of the still and the glass cover. The productivity of condensed water was assessed by maintaining a constant water depth in the tray of 4.0 cm, 5.0 cm, 6.0 cm, and 7.0 cm throughout the day. This constant was maintained by feeding water into the tray every hour through a drilled hole on the rear side of the still. The input water is initially collected in an iron tank (about 50 L in capacity) and then sent to the solar still. A conventional pyrometer, a digital anemometer, and a digital thermometer were utilized to find the incident solar radiation, wind speed, and the surrounding temperature. K-type thermocouples and a multi-channel (8-channel) digital display unit were utilized to find the water temperature in the tray, the water vapor, the inside surface of the glass, the outer surface of the glass, and the ambient temperature. Performance parameters were monitored on an hourly basis beginning at 8 a.m. and ending at 5 p.m. (Oman Standard Time). For proper radiation absorption, unwanted deposition in the basin and dust in the top cover must be cleaned on a regular basis. Table 1 provides the details of the instruments that were utilized. The clean water was collected via the trough installed (made of PVC pipe) on the solar still's lower side. The quality of supply water and clean water generated by the solar still was examined; significant improvements were observed for properties such as TDS, salinity, and conductivity of pure water.

Table 1. Specifications of used instruments.

Sr. No.	Name of Instrument	Range	Accuracy	Errors
1	K-type thermocouples	0–100 °C	±1 °C	0.50%
2	Standard pyranometer	0–2000 W/m^2	±1 W/m^2	2.50%
3	Digital anemometer	0–20 m/s	±0.1 m/s	10%
4	Collecting flask	0–9000 mL	±10 mL	10%
5	TDS, salinity, and conductivity meter	TDS: 500 g/L Conductivity: 800 ms/cm Salinity: 200 PPT	±20 mg/L ±10 µs/cm ±10 PPT	10%

3. Results and Discussions

In this project, different parameters, including air temperature, the basin water, the vapors, the inner glass, the outer glass, the solar radiation that hits the surface of the glass, and the distillate output, have been measured every hour at different basin water depths. In addition, some parameters related to checking the quality of distillate water (such as TDS, salinity, and conductivity) were observed. The experimental comparison research for the performance evaluation of a solar still with and without external reflectors has been completed.

3.1. Climatic Observation

Figure 3 depicts the hourly observation of sun radiation and atmospheric temperature with time on specific days. The daily solar radiations received for October and November were found in the range of 0–850 W/m^2, and the atmospheric temperature observed during the experiment varied from 28–31 °C. The highest magnitude of these parameters is between 12.00 and 14.00 h, as shown in Figure 3. The figures show that both radiation and temperature are nearly proportionate. The variation in atmospheric temperature and solar radiation during the day follows the same pattern from morning to evening.

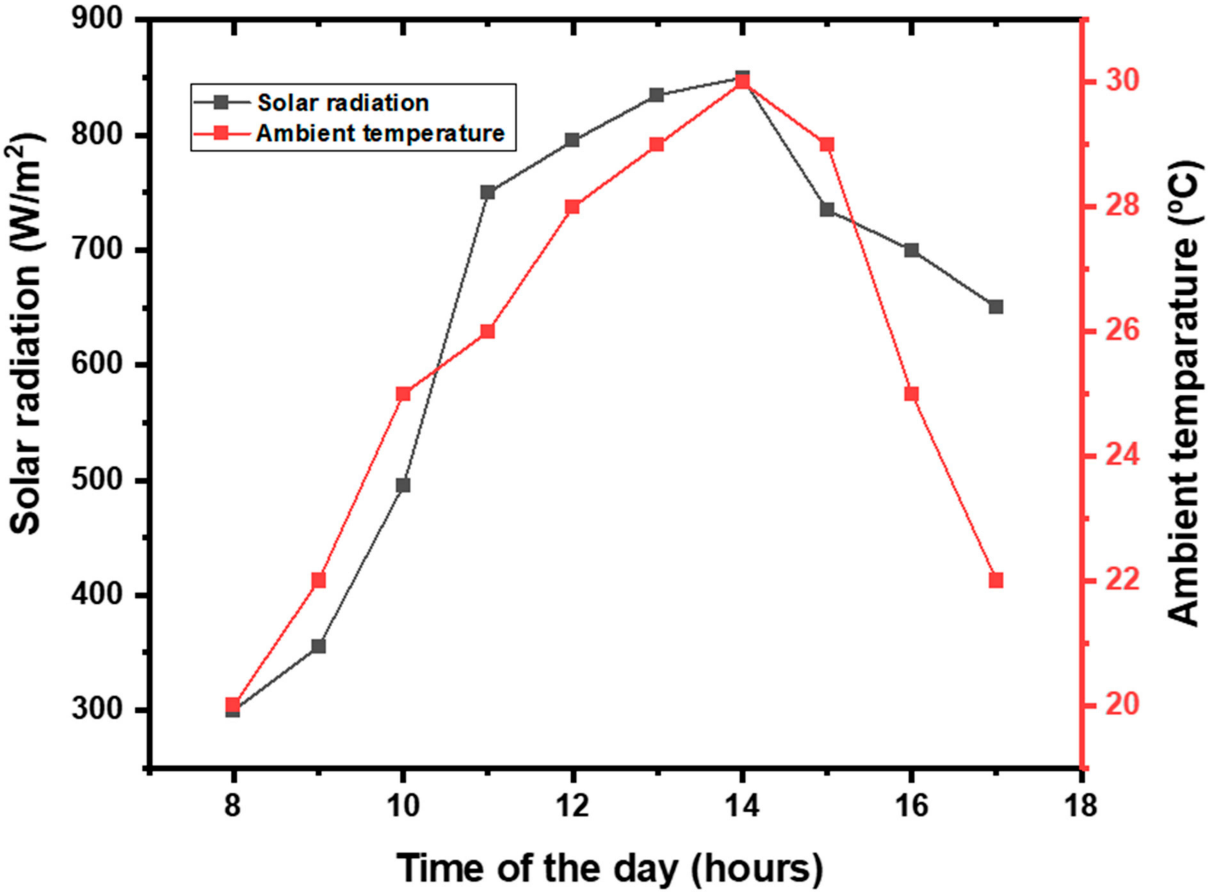

Figure 3. Hourly variation of atmospheric temperature and sun radiation at daytime.

3.2. Sun Radiation Effect on Various Temperatures

The experiment was conducted with four different water depths in the solar still and named Case 1–4. Case 1: water depth = 4.0 cm, Case 2: water depth = 5.0 cm, Case 3: water depth = 6.0 cm, Case 4: water depth = 7.0 cm.

Figure 4 shows the variation of temperatures for all observed Cases 1–4 (water temperature, vapor temperature, glass inner temperature, glass outer temperature, and atmospheric temperature) versus the time of the day. According to these graphs, various performance temperatures rise with the intensity of solar radiation, which is highest between 12.00 and 14.00 p.m. After that, as solar radiation intensity decreased, various temperatures also followed the same trend. Figure 4 shows that the vapor temperature curve is always higher than the water temperature curve. This may be because the vapor absorbs more energy in the form of latent heat of vaporization than the water. The inner glass cover temperature also increases as vapors begin to condense and release the latent heat of condensation at the inner surface of the glass cover [28].

3.3. Effect of Various Water Depths on Productivity and Efficiency of Solar Still

In Section 3.2, the experiment results show that the water depth significantly affects increased productivity. Four different basin water depths (4.0 cm, 5.0 cm, 6.0 cm, and 7.0 cm) were tried in the experiment, and the outcomes from each time were compared to those from the other tested water depths. According to Table 2, the experiment was conducted in October 2022.

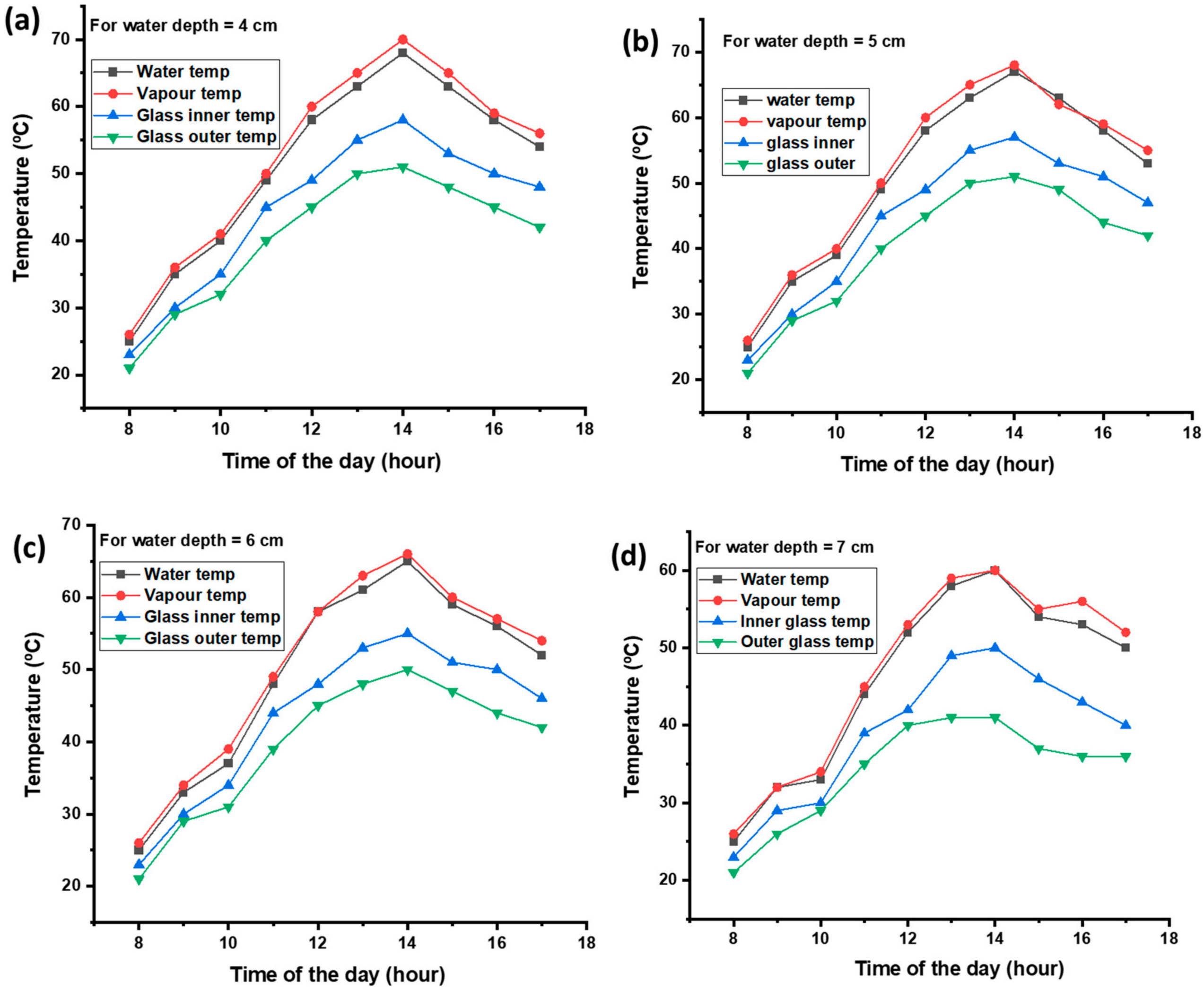

Figure 4. Hourly observation of temperature variations vs. time of the day with water depth = 4.0 cm (**a**), water depth = 5.0 cm (**b**), water depth = 6.0 cm (**c**), and water depth = 7.0 cm (**d**).

Table 2. Table of testing the water depths with productivity.

Brackish Water Depths Were Tested	Month of Measurement: October–November 2022. Average Daily Sunlight Used Hours: 9 h. Solar Radiation Density Range: 0 to 850 W/m^2. Productivity (Liters per Day)	% Productivity Rise
Case 1: 4.0 cm	2.68	10.27%
Case 2: 5.0 cm	2.43	8.25%
Case 3: 6.0 cm	2.24	18.78%
Case 4: 7.0 cm	1.89	-

The results of the experiments with all water depths are shown in Figure 5a and Table 2. The most extraordinary productivity is reached at 14.00 p.m. for all depths, as the maximum magnitude of solar radiation is received at this time, as shown in Figures 4a and 5a. Furthermore, Figure 5c shows that the lowest water depth yields the highest production (L/day), i.e., 4 cm, because increasing the depth of the basin's water volumetric heat capacity results in a lower temperature of the water at the same sun radiation intensity and eventually decreases productivity. Furthermore, the evaporative heat transmission coefficient is greater at lower depths and gradually reduces as the basin's water depth increases [29]. Figure 5d compares the productivity attained between 8 a.m. and 5 p.m. for water depths of 4, 5, 6, and 7 cm. A water depth of 4 cm produces 10.27% more than a water depth of 5 cm. and there is a rise of 8.25% in water productivity compared to a water depth of 6 cm. Case 3 has the highest percentage of productivity increase (18.78%) when compared to Case 4. This may be because of a significant decrease in vapor temperature in Case 4.

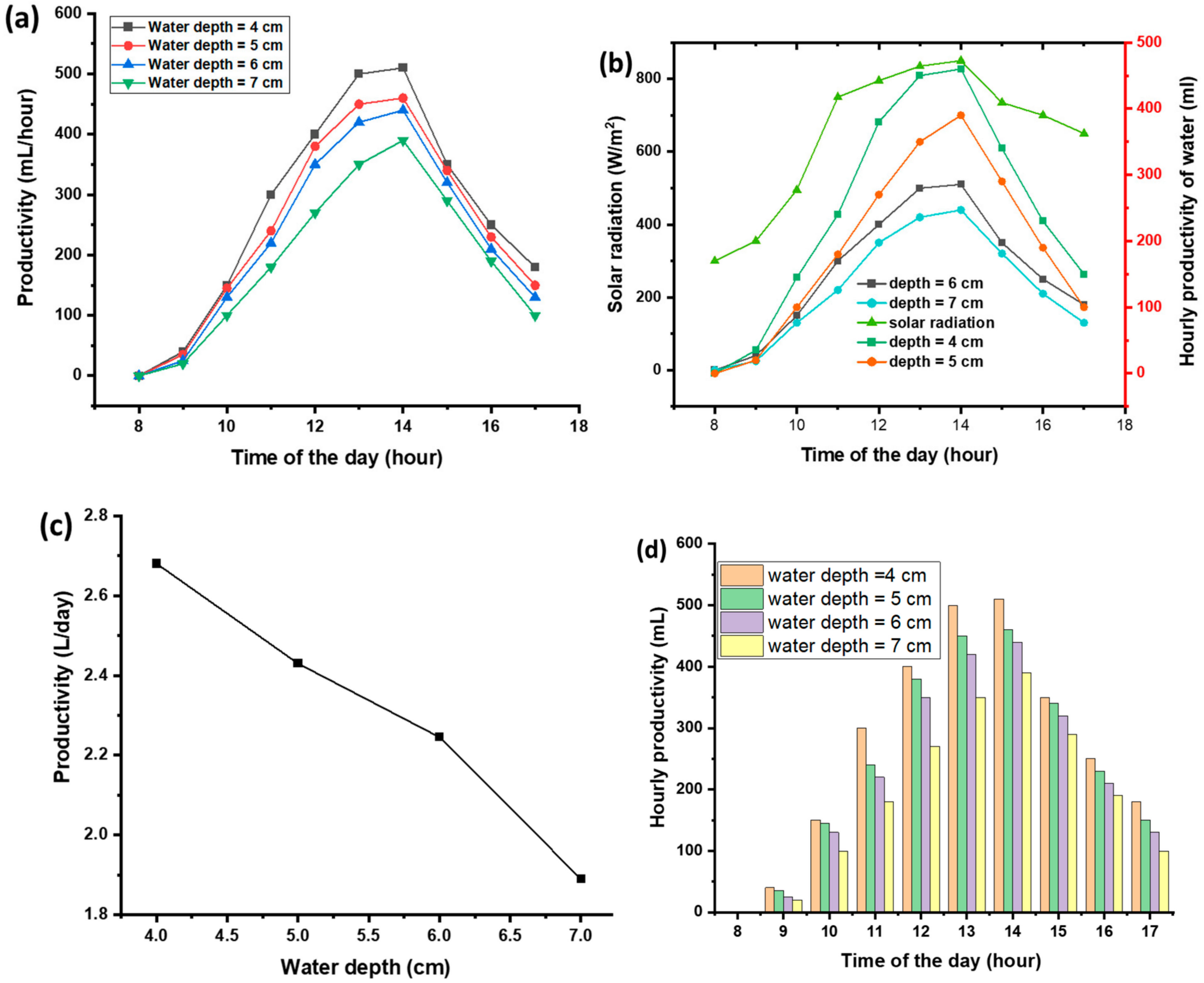

Figure 5. Productivity varies with water depth and time. Productivity with daytime (**a**), solar radiation with daytime (**b**), productivity per day with water depth (**c**), Bar diagram of hourly productivity at different water depths (**d**).

The ratio of thermal energy used in the evaporation of basin water to incident solar energy is known as daily thermal efficiency (η_{still}). Equation (1) [28] calculates the daily thermal efficiency of a solar still and is depicted in Figure 6.

$$\eta_{still} = \frac{\Sigma m_w \times L}{\Sigma Ig \times A \times 3600} \quad (1)$$

where m_w denotes hourly distillate production (kg), L denotes latent heat of vaporization (J/kg), Ig denotes daily average radiation (W/m^2), and A denotes glass cover area (m^2). The daily efficiency increased from Case 4 to Case 1, resulting in more distillate for a similar amount of incident solar energy. Because the mass of the water was greater for the same incident radiation in Case 4, the water temperature decreased, affecting the daily efficiency.

The daily efficiencies for all cases have been determined and found to be ~31% (for Case 1), ~28.5% (for Case 2), ~25% (for Case 3), and ~21% (for Case 4).

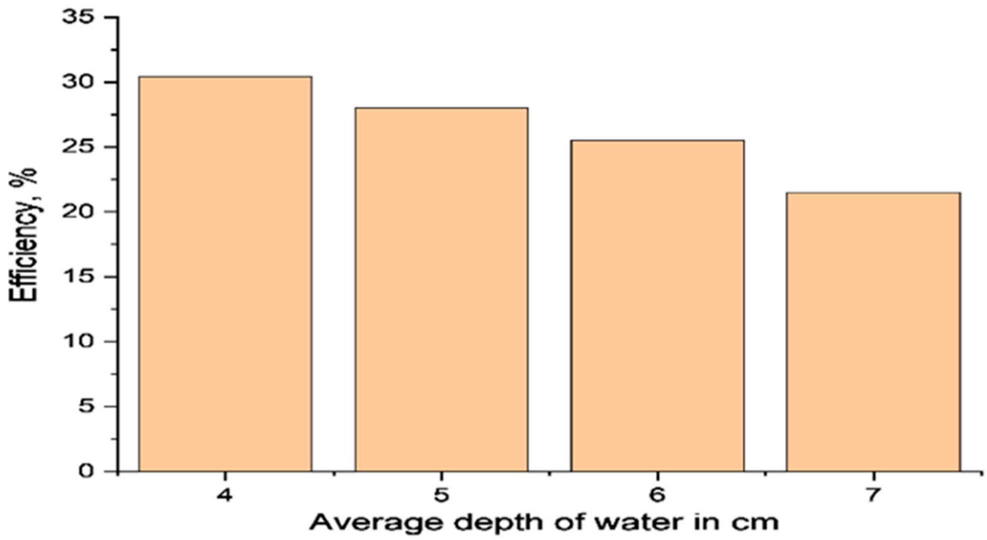

Figure 6. Daily efficiency with basin water depth.

3.4. Effect of External Reflector on Productivity and Efficiency

In the experiment, the effect of the external reflector was also evaluated, and the corresponding outcomes are shown in Figure 7a (for case 1) and Figure 7b (for case 2), respectively. Daily production and efficiency for the solar still without and with an external reflector have been studied, and it was found that significant improvements are observed for the still with an external reflector. This could be because a rise in the water basin temperature leads to a rise in the temperature difference between the glass cover and the water basin, ultimately enhancing the productivity and efficiency of solar stills with external reflectors (Figure 8). These observed results are fairly consistent with the theoretical and experimental analysis reported by researchers [29]. The overall impact of the external reflector on efficiency and productivity has been evaluated and tabulated in Table 3. The bar graph (Figure 8) and Table 3 show a significant increase in efficiency of almost 17% for Case 1 (Figure 7a) and 11% for Case 2 (Figure 7b).

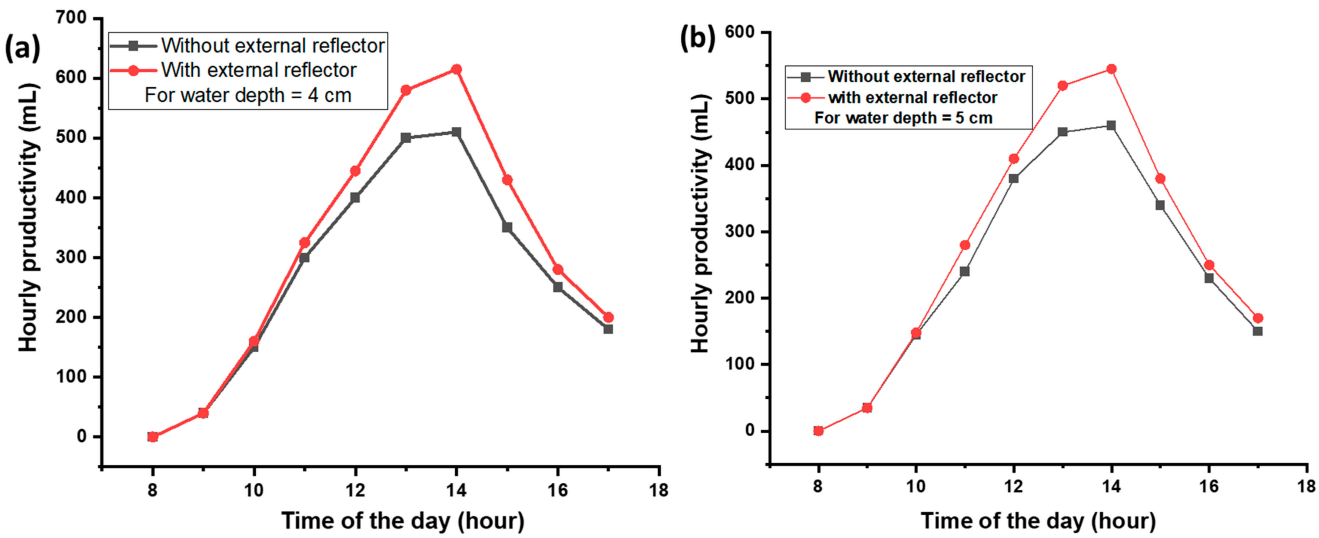

Figure 7. Hourly productivity observations with time (hour) for Case 1 (**a**) and for Case 2 (**b**) with and without an external reflector.

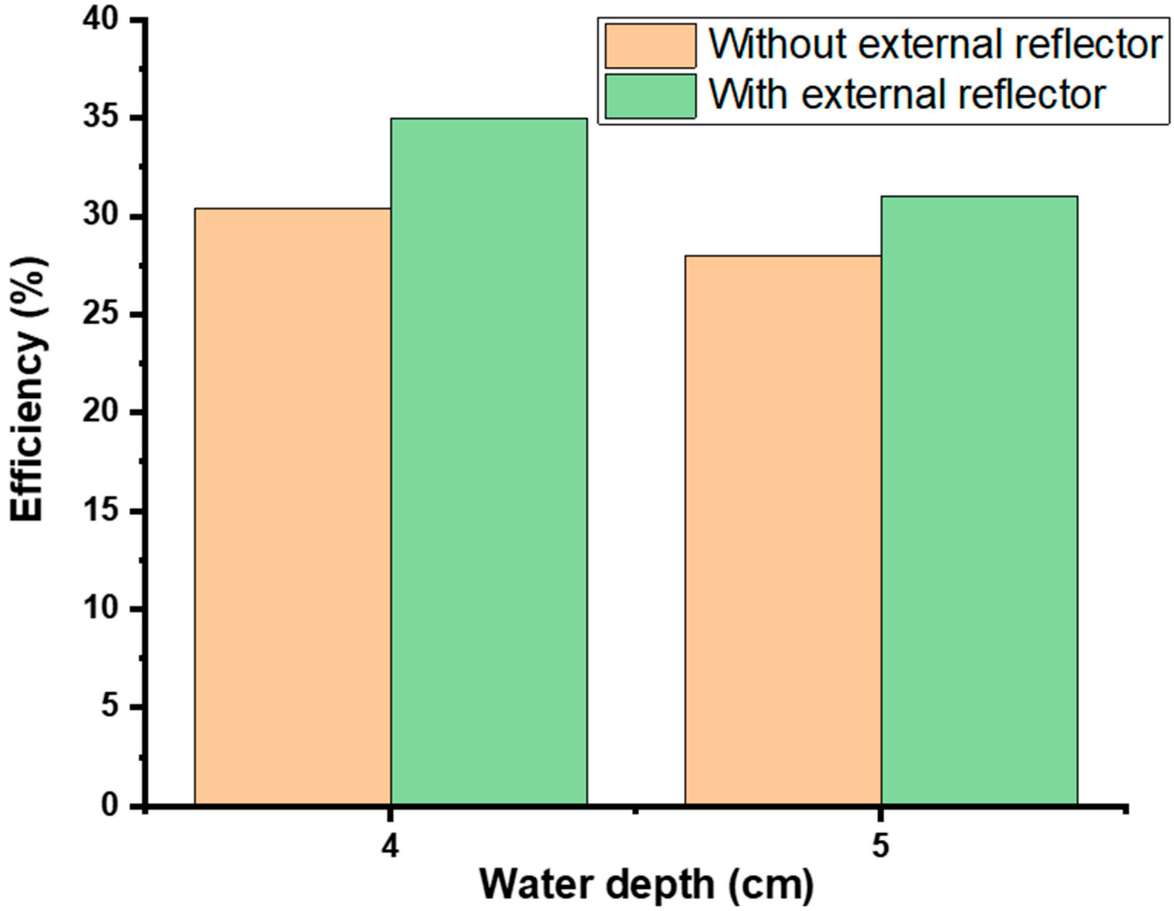

Figure 8. Comparison of efficiency with and without reflector for Case 1 and Case 2.

Table 3. Overall productivity and efficiency of solar still with and without external reflectors.

Tested Depths of Brackish Water.	Without External Reflector Average Solar Radiation 719 W/m^2		With External Reflector Average Solar Radiation 719 W/m^2		Percentage Increase in Efficiency Due to an External Reflector
	Productivity (L/day)	Daily Efficiency (%)	Productivity (L/day)	Daily Efficiency (%)	
Case 1 (water depth = 4 cm)	2.680	30.40	3.075	35	16.67%
Case 2 (water depth = 5 cm)	2.430	28	2.738	31	11%

Figure 9a,b shows the variation of water and vapor temperatures in the presence of external reflectors for Cases 1 (Figure 9a) and 2 (Figure 9b). The temperature of condensed water vapor gradually rises, with the maximum temperature discovered at 14.00 p.m. for Cases 1 and 2, as seen in Figure 9a, b. Similarly, the inside and outside temperatures of the glass cover increased with time, with maximum temperatures observed at 13 p.m. and 14 p.m. in the afternoon for Cases 1 and 2, respectively. These results also support the above observations, and maximum efficiency is exhibited by the solar still with a water depth of 4 cm in the tray.

3.5. Water Quality Testing

The quality of the sea water (input water) and output water collected from the solar still was evaluated using many parameters such as TDS, salinity, and conductivity. Table 4 shows the measured values of the feed water and output water samples, as well as the permitted limits.

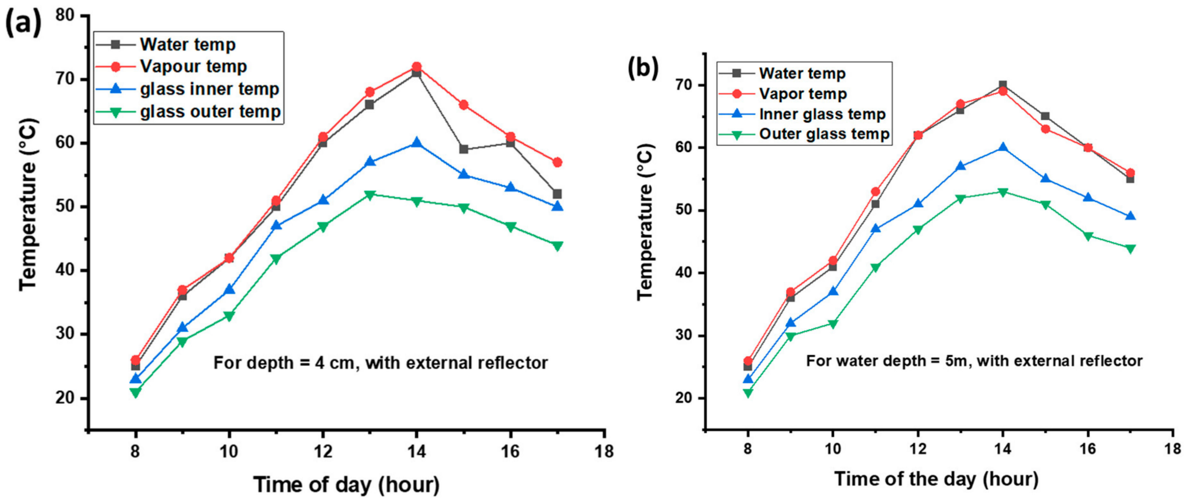

Figure 9. Variation of water and vapor temperatures in the presence of external reflectors for (**a**) depth of 4 cm (**b**) depth of 5 cm.

Table 4. Concerning the qualities of input and output water.

Property of the Water	Feed Water (Sea Water)	Output Water (Collected from Solar Still)	Acceptable Limits
TDS (mg/L)	35,000	41	<300
Conductivity (µs/cm)	65,000	88	50–800
Salinity (ppt)	35	0	<0.5

3.5.1. Conductivity

The conductivity of water measures its capability to transmit electrical current. This ability is proportionate to the ion concentration in the water. These conductive ions are made up of inorganic components such as alkalis, chlorides, sulfides, carbonate compounds, and dissolved salts. A greater conductivity value implies that the water contains more compounds dissolved in it. Fresh drinking water has a conductivity ranging from 50 to 800 µs/cm. Pure, distilled water is a poor electrical conductor. Table 4 shows that the conductivity of the water from the solar still is within acceptable limits. As a result, water collected using a solar still has dramatically increased quality and can be used for potable purposes.

3.5.2. Salinity

Salinity refers to the concentration of salts in water or soil. The acceptable salinity of fresh water is less than 0.5 parts per thousand (ppt). Large rivers' salt levels can fluctuate along their course, ranging from 0.5 to 30 ppt depending on their closeness to river inflows or the ocean. Salinity varies from place to place in the oceans. The average salinity of ocean water is 35 ppt. The solar still's output water has zero salinity, as shown in Table 4. Hence, the quality of the solar still output water is suitable for drinking.

3.5.3. TDS

The total dissolved solids (TDS) test is used to assess water quality. TDS is calculated as the sum of a sample's magnesium and calcium hardness. As a result, although the TDS test does not assess the kind of ions in a sample, measured data demonstrates an increase in water quality derived from a solar still. The acceptable limit for drinking water should be between 50 and 300 mg/L. TDS readings observed show an increase in water quality derived from the constructed solar still, as given in Table 4. Hence, all parameters, including TDS, are within reasonable limits for the water collected from our constructed solar still. Accordingly, the constructed solar still in the current study can be scaled up for commercial use.

4. Conclusions

The concept of utilizing solar stills to acquire clean water was observed to be particularly interesting because of financial and technological advantages, including the low-cost technology, raw materials, and production. The highest magnitudes of solar radiation and ambient temperature were observed between 12.00 and 14.00 h. Case 1 with the lowest water depth (4 cm) yielded the highest production (L/day). When Cases 1 and 4 are compared, the productivity percentage rises to 41%. Daily efficiency increased by almost 16% for Case 1, and an 11% increment was observed for Case 2 if compared with and without external reflectors. By lowering the water depths on the basin plate, the solar still used in the current study proved more efficient. A basin type's daily production can still be increased by 15% to 20% with a simple change involving external reflectors. Higher solar radiation improves the productivity and efficiency of a solar still; hence, utilizing this simple technology on summer days, especially from March to October, could be more beneficial in countries such as Oman and Saudi Arabia. The quality of the feedwater and output water generated by the solar still was examined, and considerable improvements were discovered. The quality of distilled water totally complies with WHO standards. More research is needed to scale up the process on a commercial basis, particularly in countries such as Oman and Saudi Arabia, which receive a lot of sunlight. This would assist the nation in reaching its vision goals. According to various researchers, nanotechnology could improve this technique. In isolated places where freshwater is scarce, this method could be used.

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