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Enhancement of Pyramid Solar Still Productivity Through Wick Material and Reflective Applications in Iraqi Conditions

Karrar A. Hammoodi[1*], Hayder A. Dhahad[2], Wissam H. Alawee[3], Zakaria M. Omara[4]

[1] Air Conditioning Engineering Department, Faculty of Engineering, Warith Al-Anbiyaa University, Karbala 56001, Iraq
[2] Mechanical Engineering Department, University of Technology, Baghdad 10071, Iraq
[3] Control and Systems Engineering Department, University of Technology, Baghdad 10071, Iraq
[4] Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33511, Egypt

Corresponding Author Email: karrar.al@uowa.edu.iq

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ABSTRACT

The global challenge of water scarcity significantly impacts the socio-economic development of countries, especially in developing regions such as Iraq where accessible potable water is scarce. Solar distillation emerges as a promising technique for desalinating water, particularly through passive solar stills that harness direct solar radiation. This study investigates the performance enhancement of pyramid solar stills, specifically focusing on the employment of wick materials and reflectors under the climatic conditions of Iraq. Wick materials markedly augment the evaporation area and the area for solar radiation absorption, thereby boosting the still's production. Similarly, reflectors play a crucial role in elevating the water temperature in the distillation process, leading to increased evaporation and daily productivity. Results demonstrate that the use of wick materials in the pyramid solar still (CWPSS) significantly outperforms the conventional pyramid solar still (CPSS), with a production increase of 122% and a daily thermal efficiency of 53%, compared to CPSS's 34.5%. Moreover, the application of reflective materials further escalated CWPSS's productivity by 170%, although the distillation efficiency remained constant at 48%. Future research should explore advancements in wick materials, integrated systems, simulation modeling, and field testing to optimize the technology's performance under Iraqi conditions.

1. INTRODUCTION

Water scarcity, a pivotal global crisis, is gaining prominence as a critical contemporary issue. The burgeoning threat to economic growth and development, attributed to escalating population dynamics, rapid urbanization, climate change, and unsustainable water management practices, positions water shortages as a potent destabilizer. The exacerbation of this crisis carries severe ramifications for human health, agriculture, energy production, and industrial activities, consequently impacting economies on local, regional, and national scales. Acknowledging the magnitude of this challenge is paramount, as addressing water scarcity necessitates global coordination and prioritization. This paper underscores the significance of water shortages and their extensive economic implications, emphasizing the urgent call for concerted global initiatives to counteract this pressing concern. Reports suggest that by 2025, acute water scarcity could confront a third of the world's population [1, 2]. Saltwater constitutes a staggering 97% of the planet's surface water. Coupled with this is the energy conundrum, with the drawbacks of prevalent fossil fuel energy including high cost, usage, and pollution [3].

In developing countries, such as Iraq, the paucity of potable water is a recognized impediment. Despite Iraq's abundant river systems, a mere 40% of urban inhabitants have access to potable water, while those residing in rural areas, deserts, and even urban peripheries often lack water access [4]. Potable water scarcity pervades all regions of Iraq, including north [5], central [6], and southern areas [7, 8], and the distance to the nearest potable water source often poses a formidable obstacle. Additionally, Iraq's water consumption has surged significantly post-2003, driven by socio-economic expansion [9].

The solution potentially lies in the deployment of efficient distillation plants or, in some instances, individual distillation systems per household. Conventional distillation plants necessitate substantial fossil fuel consumption, which harbors adverse environmental consequences. Consequently, distillation systems harnessing renewable energy sources, such as solar energy, are advocated as environmentally benign alternatives [10].

During peak summer hours, Iraq receives maximum solar irradiance, reaching up to 1250 W/m2, positioning it among the highest globally. Iraq averages 333 clear days annually [11].

Several techniques exist for desalinating unpotable water to produce drinkable water. These traditional power-driven processes include multi-stage flash (MSF), reverse osmosis (RO), multi-effect distillation (MED), and electrodialysis (ED). However, these methods are increasingly disregarded due to their high cost and environmental impact [12]. Consequently, solar energy emerges as a favorable alternative energy source, given its free availability and environmental sustainability [13].

Solar distillation presents a viable method for treating saline water. This technique, known as passive solar distillation, is contingent upon the direct interaction of solar rays with the distillation basin. A typical passive solar still comprises a water basin, a conduit for introducing saline water, a transparent cover, and channels for distilled water collection [14]. The most prevalent variations of solar stills include single-slope, double-slope, vertical solar segment, conical solar segment, inverted Mutoti solar segment, spherical, v-type solar still, and pyramid solar still [15]. The incorporation of an external energy source such as a solar collector, reflector, or solar tracker transitions the solar still from a passive to a more active system [16, 17].

In summary, despite its abundant rivers, potable water access in developing nations like Iraq remains restricted. Conventional water distillation methods pose significant financial and environmental burdens due to their reliance on fossil fuels. Solar energy, therefore, emerges as an alternative, environmentally-sustainable solution. Given Iraq's high solar intensity and abundance of clear days, the potential for solar distillation is substantial. Solar distillation is a passive method that employs solar rays to treat saline water, with a diverse range of solar stills available. When augmented with solar collectors or trackers, solar distillation evolves into an active, sustainable solution for delivering potable water in regions grappling with water scarcity.

The impetus for this study stems from Iraq's limited fresh water availability due to pervasive water scarcity, which bears significant repercussions across sectors such as agriculture, energy, and industry. The potential of solar stills as a solution for water purification and desalination holds particular intrigue in the Iraqi context. However, there appears to be a dearth of comprehensive research on the performance of pyramid solar stills utilizing wick materials and reflectors under local conditions.

Additionally, the study is primarily driven by the need to optimize the design and performance of solar stills to enhance their efficiency and effectiveness under Iraqi environmental conditions characterized by high temperatures, low humidity, and intense sunlight. The use of wick materials and reflectors in pyramid solar stills represents a novel approach that the author aims to investigate and evaluate within the Iraqi context.

The evaluation of a pyramid solar still's performance, employing wick materials and reflectors under Iraqi conditions, may yield several beneficial outcomes. These include enhanced efficiency, cost-effective water purification, practical design recommendations, and potential contributions to the scientific knowledge on solar still technology, all aimed at addressing Iraq's water scarcity challenges and propelling sustainable water treatment solutions. Moreover, it was observed that the CWPSS displayed superior thermal performance compared to the CPSS under all test conditions. This can be attributed to the wick cords drawing an amount of water equivalent to the evaporated water, without discarding excess or hot water.

2. SOLAR STILLS PRODUCTIVITY

The amount of water produced by a basin area in a day is commonly used to express the performance of solar stills [18, 19]. The productivity of a distiller depends on a number of elements, which can be categorized into three components: meteorological or climate, operational, and design parameters [20, 21].

The first component is comprised of radiation intensity, wind speed, ambient temperature, and the presence or absence of clouds [22]. While operating parameters include water color, waterflow, surfactant additives, salinity and contaminant levels, system maintenance, water feeding, position of solar still, and other effects, water color, waterflow, surfactant additives, salinity and contaminant levels, system maintenance, water feeding, and position of In addition, design considerations include the number of basins and slopes, several types of still designs, the angle of the cover, thermal energy storage, basin absorption rates, reflectors and mirrors, a sun tracking system, insulation thickness, additive materials, and basin depth [23]. Uncontrollable elements that affect performance include the amount of solar radiation, the temperature, the humidity, the wind speed, and the cloud and dust cover. The environment in which a solar still operates cannot be controlled, but the design and operational factors can be easily modified to increase its efficiency [24-26].

Numerous researchers are attempting to improve the performance of a solar distillation system by modifying the distiller's shape and adding components that increase the water's temperature, among other methods [27-31].

The temperature of the glass cover can be decreased by a layer of continuously flowing water [32]. Using an intermittent flow of cooling water on the lid [33] achieves the same result. Wind velocity also influences the temperature of the surface. When air movement increases, convective heat transmission from the cover to the atmosphere increases. This impact increases the condensing and evaporation rates of the still, as well as its production [34].

Researchers have developed solar stills with solar collectors [35], with condensers, solar stills operating under low pressure, those with heat recycling, their configuration, color multi-stage/multi-effect solar stills, those with heat storage, and hybrid solar still/PV systems to increase productivity. Due to their limited production, however, solar distillates are not yet commercially viable. The application of variable phase change materials (PCM) with a high latent heat capacity to absorb a substantial quantity of energy has been investigated [36]. Using phase change materials (PCM) with a high latent heat capacity to absorb energy has been studied [37]. Other researchers analyzed a graded solar still and a simple solar distiller with a single basin, employing a PCM to store energy. Continuing distillation after dusk increased PCM storage distillation productivity. A large temperature difference between the water and the glass cover, which was cooler, helped [38].

Numerous studies have been conducted throughout the world in an effort to identify viable technologies, but none have been specifically intended for developing nations [8, 10, 39-42]. In this investigation, a passive solar still in the shape of a pyramid was constructed and tested using wick materials with reflectors. The surface of the pyramid-shaped solar still had a rough texture. Using a wicked concave still design is intended to enhance the evaporation area and solar radiation absorption area in order to increase the still's production. Glass is used on all sides of the concave still, so it doesn't cast shadows like a conventional solar still does.

3. EXPERIMENTAL SETUP

In recent years, Testing equipment was set up on the roof of the University of Technology Baghdad training and workshop building in latitude 33.3° N, longitude 44.5° E and a height of 33 meters above sea level.

3.1 Description of the experimental setup

Both the conventional pyramid solar still (CPSS) and the wick-type pyramid solar still (WPSS) were used in this investigation. Figures 1 and 2 depict the experimental setup for these two solar still models. We used the same dimensions and parameters for operation in order to do a comparison of their thermal performance. The volume of the feeding tank was 50 cm by 50 cm by 100 cm. In order to build both solar distillers, galvanized sheets with a thickness of 1.5 mm were bent and then welded together. As can be seen in Figure 2, the outside dimensions of solar stills were as follows: 70 cm by 70 cm by 15 cm. Additionally, the cover of the solar distillers was constructed out of four triangle-shaped pieces of glass.

Figure 1. Experimental test-rig: (a) Solar stills without mirrors; (b) Solar stills with mirrors

An inclination angle of 49 degrees was present in the glass cover. The body of the basin was insulated from the environment using fiberglass that was 5 cm thick. At the bottom corners of the four triangle-shaped glass sheets, four slanted troughs were mounted at an angle in order to collect and direct the condensed droplets that formed on the exterior of the distiller. Silicone was utilized to create a seal along the contact edges of the solar still in order to prevent any leaks. The feeding reservoir was used to provide the stills with salty water, while the flasks located outside the still were used to collect the freshwater distillate. The WPSS was exactly the same size as the CPSS, and its surface area was exactly the same as well.

In order to maximize the effectiveness of the incident sun rays, two exterior reflectors were utilized. The exterior front reflector of one mirror was attached to the front of the distillers, while the second mirror was attached to the back of the distillers. Both the rear and the front mirrors measured 70 cm by 70 cm. The angle of the external reflector can be adjusted either backwards or forwards [43], depending on the month of the year. The top mirror is adjusted so that it is either inclined backwards or forwards according to the season. During the winter, you should tilt the top mirror slightly forward, and during the summer, you should tilt it slightly back. Additional information regarding reflector inclination angles can be found in the study [44]. The inclination angles for the external top reflector and the front reflector are shown in Figure 2.

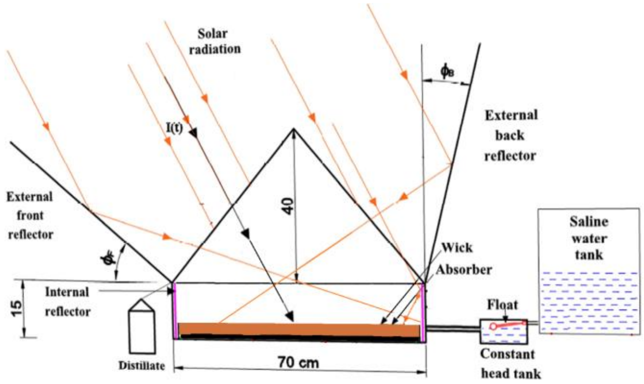


Figure 2. 2-D drawing of the experimental test-rig

As can be seen in Figure 3, the WPSS conducted the experiment using a variety of wick materials, including light cotton and velvet. Each wick has dimension as 68 cm across and 68 cm in length. The wicking materials that were linked to the water in the basin were dark in color so that they could absorb as much sunlight as possible.

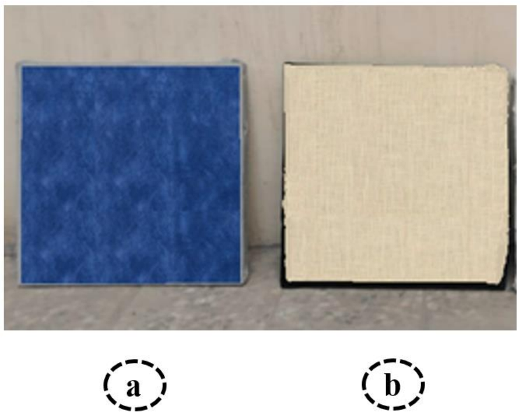


Figure 3. Photograph of various wick materials: (a) Velvet fabric; (b) Light cotton

3.2 Measurement instruments

The effectiveness of a solar still is mostly determined by the water temperature, the amount of solar irradiation, the amount of wind speed, and the amount of water that can be distilled. Solarimeters were employed to measure the strength of the sun's rays, and thermocouples of the K type were utilized in order to take temperature readings at various spots throughout the still. During the course of the experiment, wind speed was employed to record wind speed, and a (sensitive scale) was utilized to weigh the amount of freshwater produced at each hourly interval. The details of the measurement instruments are included in Table 1.

Table 1. Measuring device with the accuracy and range

No.	Instrument	Range	Accuracy	% Error
1	Thermocouple K-Type	0-100℃	±0.2℃	0.25%
2	Thermometer	0-100℃	±1℃	0.5%
3	Solarimeter	0-2500 W/m^2	±2 W/m^2	2%
4	Measuring beaker	0-2000 ml	±3 ml	1%

3.3 Experiment procedure

Testing occurred during the months of January and February. For a period of 10 days in total, each solar still had a unique wick made out of a variety of materials. The present data was gathered on days that had the greatest number of hours of daylight. The glass of the solar still was wiped down just before daybreak, and the trial installation was finished well before 8 in the morning. Before beginning to take measurements, the pyranometer, thermocouples, digital temperature indicator, and anemometer were all subjected to testing. Beginning at 8:00 in the morning, once per hour to 5 p.m. On each and every day of the experiment, experimental data was acquired, consisting of basin water, ambient temperature, temperature of the glass cover, amount of solar radiation, wind speed, and productivity. Following collection of the condensate in a trough, it is pumped away from the solar still and into a container.

4. RESULTS AND DISCUSSIONS

It was observed that both the thermal efficiency of the solar still and the daily productivity increased. Productivity in a pyramid solar still refers to the amount of water collected over a given period. Calculating the daily productivity gain is feasible by using the following formulas:

$$\tau_d = \frac{\textit{The daily productivity x Vaporization latent heat}}{\textit{The daily solar radiation}}$$

where, η_d is daily thermal efficiency.

The choice of wick material can affect the productivity of the solar still as below:

Velvet Fabric: The high absorbency of velvet fabric may result in increased water capture from the air, potentially leading to higher productivity in terms of water collection.

Light Cotton: Light cotton, being a thinner and lighter fabric, may have moderate absorption properties, resulting in moderate productivity in terms of water collection.

Based on that, the productivity vs. wick material comparison shows that velvet fabric leads to higher productivity compared to light cotton, with the productivity increasing as the absorbency of the wick material increases.

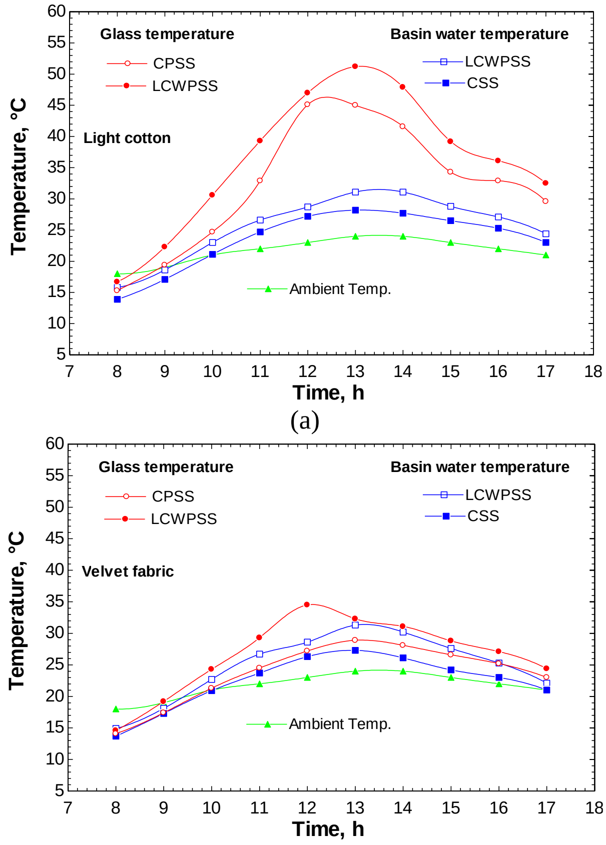
4.1 The wick solar stills' thermal performance

The hourly temperature fluctuations that occurred at several areas on the solar still are depicted in Figures 4a and 4b below.

In order to prevent unnecessary reiteration, the findings of one day's worth of tests for every different kind of wick that was utilized are reported here. Figure 4 demonstrates that the utilization of a variety of wick materials, in comparison to the conventional pyramid solar still (CPSS), results in an increase in temperature in the WPSS. This is the case regardless of the type of wick that is employed.

It was found that the temperature of the glass on the WPSS was 0-12℃ higher than that of the CPSS for LCWPSS and 0-2℃ higher for VWPSS. This is due to the fact that the WPSS resulted in a greater rate of evaporation when compared to the CPSS. As a direct consequence of this, the glass temperatures of the LCWPSS, VWPSS, and CPSS were 41.6℃, 28.2℃, and 27.1℃, respectively, at 15:00.

Figure 4 shows that the WPSS had a water temperature that was 0-18℃ greater than the CPSS for two different wicks. This is because the convexity of the basin allowed more sunlight to reach the water in the basin, which led to the observed result. At one o'clock in the afternoon, the water in the LCWPSS, VWPSS, and CPSS had respective temperatures of 47.9, 31.4, and 30.1℃. At 14:00, the solar intensity was 1150 W/m^2, and the temperature of the air was 24℃.



(b)

Figure 4. Temperatures for the conventional and wick solar stills with different wicks materials: (a) Light cotton; (b) Velvet fabric

Figures 5 (a) and 5(b) illustrate the variations in the hourly and cumulative yield of both solar stills when using two different wick materials. It is clear that LCWPSS productivity improved rapidly as a result of the lower basin liner's high temperature, while the CPSS requires more time to heat the water and produce vapor. Furthermore, the VWPSS had higher freshwater productivity than the CPSS. The cumulative yield of WPSS was greater than that of CPSS. The LCWPSS, VWPSS, and CPSS produced a total distillate of 1461, 830, and 620 mL/m^2 per day, respectively. As a result, productivity increased by roughly 136.6%, and 33.8% for the LCWPSS and VWPSS. This increase in productivity is attributed to the LCWPSS's higher evaporation rate.

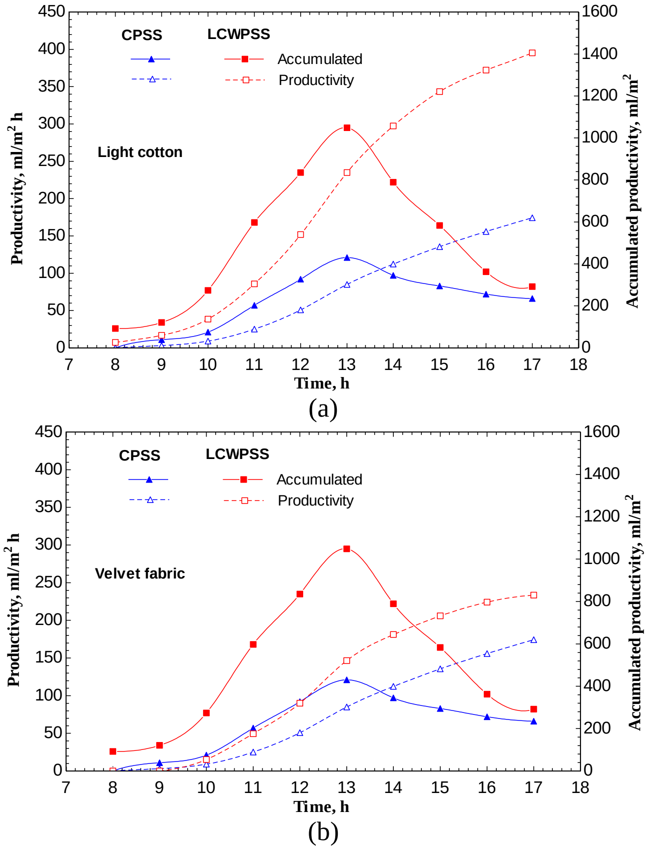


Figure 5. The hourly productivity fluctuation and overall accumulated productivity of two solar distillers with various wicks: (a) Light cotton and (b) Velvet fabric

The LCWPSS solar still, which had the highest total amount of collected distillate, was selected as a model to investigate the impact that reflecting mirrors have on the performance of wick-type solar stills. The LCWPSS intends to make use of the mirrors in order to maximize the quantity of solar energy that it can absorb. This is performed by the front and back external mirrors reflecting dispersed sun rays onto the CWPSS, which ultimately leads to an increase in the temperature of the water, the glass, and the upper liner. As a direct consequence of this, the rates of evaporation and condensation that occur within the CWPSS have accelerated. The inside mirrors prevent heat from escaping through the walls to which they are attached, which in turn raises the temperature of the water, the glass, and the upper liner. Because of this, both evaporation and condensation happen much more quickly.

Figure 6 shows how the amount of sunlight and temperature change at different places on the LCWPSS with external and internal mirrors (basin liner, water, glass, and normal). The temperature of the glass was 0-8℃ lower than the CPSS because the LCWPSS generates more evaporation than the CPSS. At 14:00, the LCWPSS and CPSS had glass temperatures of 45.8°C and 27.5°C, respectively.

At 14:00, the LCWPSS and CPSS had water temperatures of 53.6℃ and 30.5℃, respectively, indicating that using mirrors increased the difference between the LCWPSS and CPSS water temperatures.

The results revealed that the difference in water temperatures between the LCWPSS without mirrors and the CPSS was around 0-16℃, but the difference was roughly 0-22℃ when mirrors were utilized. When mirrors are utilized, the basin liner's temperature rises, causing the LCWPSS water temperature to rise. This contributed to the improved evaporation rates of the LCWPSS. At 14:00, the intensity of the sun was 830 W/m^2 and the temperature of the air was 25℃.

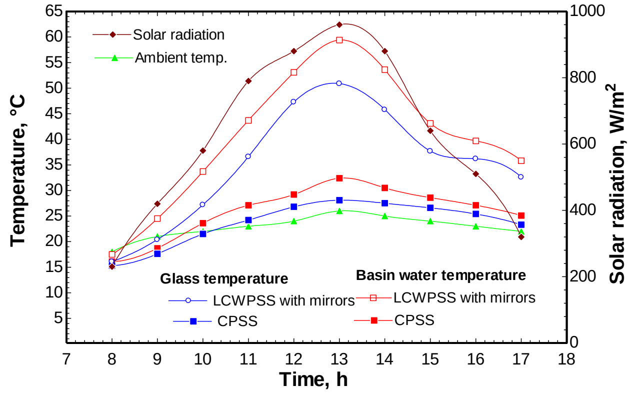


Figure 6. Variations in solar irradiance and temperature for the CPSS and LCWPSS with reflectors

As intended, the CWPSS performs significantly better when both internal and external (front and rear) reflectors are utilized in conjunction with the solar still. Figure 7 (hourly data) displays CPSS and LCWPSS data with internal and external mirrors, which clearly demonstrates that the LCWPSS with mirrors produced more distillate than the CPSS. At 13:00, the LCWPSS and CPSS obtained their maximum hourly yields of 320 and 121 mL/m^2.hr, respectively. Using mirrors, the CPSS and LCWPSS gathered daily freshwater at rates of 1,525 mL/m^2 and 620 mL/m^2, respectively.

Using mirrors with the LCWPSS enhanced productivity by around 155% relative to the CPSS, and by 136.6% relative to the CWPSS without mirrors. When mirrors are utilized in the CWPSS, evaporation and condensation processes operate more efficiently, resulting in an increase in freshwater.

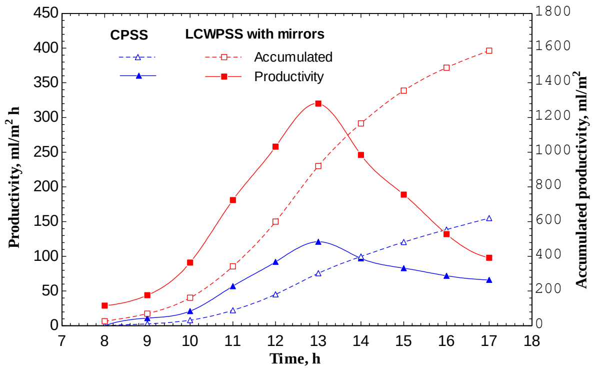


Figure 7. The hourly fluctuation and total accumulated productivity of both CPSS and LCWPSS with reflectors

4.2 The comparison of this study to previous studies

Table 2 provides a comparison of the current results with those of previous studies. The purpose of this comparison is to assess how much better the solar distiller will operate following the modifications. Solar stills with a light cotton wick and reflectors performed far better than those described in prior publications.

Table 2. Comparing the current findings with those of previous investigations

Reference	Modifications	Efficiency	Productivity Improvement
Kabeel [43]	Pyramid-type solar still with concave wick	30%	95%
Tuly et al. [45]	Double slope solar still + solid rectangular fin + paraffin wax + black cotton cloth + external condenser	39.74%	22.33%
Agrawal and Rana [46]	Solar still + multiple V-shaped, floating wicks (black jute cloth)	56.62%	26%
Saravanan and Murugan [47]	Pyramid still with woollen cloth wick material and 2 cm water depth	40.3%	29.57%
Ahmed [48]	Twelve mesh wires Jute, sheet mesh, cotton, sponge	-	26.9%
Rajaseenivasan et al. [49]	Cotton, waste cotton pieces, and jute	-	20%
Rajaseenivasan and Srithar [50]	Wicks and square and circular fins	Increased by 15%	45.8%
El-Agouz [51]	Continuous water, circulation using cotton wick	70%	48%
Sharshir et al. [31]	V-corrugated absorber ba sin with wick and nano materials	--	72.95%
Alawee et al. [52]	Nano and wick materials	--	176%
Present study	Cords wick pyramid solar still with mirrors	53%	195%

5. CONCLUSIONS

Solar energy, one of the most potent forms of energy, is an efficient renewable energy source, available in abundant and environmentally conducive regions across the globe. Wick materials significantly augment the evaporation and solar radiation absorption areas, thereby enhancing the still's productivity. Additionally, reflectors play a pivotal role in elevating the temperature of incoming water to the distillate, leading to an increased evaporation process and subsequently, increased daily production. In this study, pyramid solar stills equipped with wick materials and reflectors were used to evaluate the performance of solar stills under Iraqi climatic conditions. The research yielded the following conclusions:

Solar radiation intensity exerts a positive impact on the production efficiency of the solar system (the water distillation apparatus). It was demonstrated that a surge in radiation intensity corresponded with increased productivity and efficiency.

The CWPSS exhibited superior thermal performance relative to the CPSS under all test conditions. This can be attributed to the wick cords drawing an amount of evaporated water without discarding surplus or heated water.

In the absence of reflectors, the CWPPS achieved optimal performance, with a 122% surge in production and a daily thermal efficiency of 53%, in contrast to the CPSS's 34.5%.

The incorporation of reflectors resulted in a 170% increase in the CWPSS's production, while maintaining the distiller's efficiency at 48%.

In conclusion, the study underscores the importance of judicious material selection, such as wicks and reflectors, to enhance the performance of pyramid solar stills under Iraqi conditions. This suggests that decision-makers and practitioners involved in executing solar distillation projects in Iraq should meticulously select and evaluate the materials utilized in constructing solar stills to optimize their performance and efficiency, ensuring the technology's suitability for local environmental conditions. Nonetheless, the evaluation of the performance of pyramid solar stills using wick materials and reflectors under Iraqi conditions carries certain limitations, including restricted efficiency, weather condition dependency, and the quality of the distilled water produced. Future research avenues could explore advanced wick materials, integrated systems, modelling and simulation, and field testing and monitoring to further deepen our understanding of this technology and enhance its performance under Iraqi conditions.

6. FUTURE RESEARCH DIRECTIONS

1. Wick Material Optimization: Future investigations could focus on identifying and developing locally available, cost-effective, and sustainable wick materials suitable for use in pyramid solar stills in Iraq. Studies could delve into the capillary action, water retention capacity, and durability of various wick materials to optimize their performance and amplify the still's efficiency.
2. Reflector Design Optimization: Research could be directed towards exploring different reflector shapes, sizes, and angles for their efficacy in directing sunlight towards the wick materials. The potential of advanced reflector materials or coatings that can enhance solar radiation absorption and mitigate reflector degradation due to extended exposure to harsh weather conditions could also be examined.
3. Performance Modeling: Mathematical models predicting the performance of pyramid solar stills using wick materials and reflectors under diverse weather conditions in Iraq could be developed. Such models could incorporate parameters like solar radiation intensity, temperature, humidity, and wick material properties to optimize the design and operation of the stills.
4. Cost-Benefit Analysis: A comprehensive cost-benefit analysis of pyramid solar stills using wick materials and reflectors in the Iraqi context could be undertaken. This would involve evaluating the economic feasibility, environmental impact, and societal acceptance of such stills to ascertain their viability as a sustainable and practical solution for addressing water scarcity in Iraq.
5. Field Testing and Validation: Long-term field testing of pyramid solar stills fitted with wick materials and reflectors in Iraq could be conducted to validate their performance, durability, and effectiveness under real-world conditions. Data on still performance could be collected for further analysis and study.

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