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Research Article

A novel approach to augment stepped solar still productivity using the heat storage characteristics of water

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ABSTRACT

Improvement in freshwater productivity by minimizing the carbon footprint is the main goal paving way to the development and modification of solar stills. The primary objective of this study is to enhance the productivity of the solar still while optimizing construction and maintenance costs. In contrast to other phase change materials and heat storage materials, this study utilizes water as the sensible heat storage medium. This investigation deviates from established protocols by implementing a feed water addition strategy that exceeds evaporated water quantities. The still's performance was enhanced by using a dynamic water depth strategy, where lower depths during morning hours boosted daytime yield, and higher depths later in the day improved night-time output. This process optimizes the use of incident energy, converting it into specific heat energy while minimizing the impact on temperature increase. Experiments in Kochi, India, revealed that the solar still's overall yield, without feed water addition, decreased with increasing initial water depth, yielding 5290 ml/m², 5140 ml/m², and 4800 ml/m² at depths of 0.5 cm, 1.0 cm, and 1.5 cm, respectively. Adding 100 ml of feed water to each tray at the three initial water depths resulted in productivity increases of 2.3%, 2.5%, and 2.9%, respectively, compared to no feed water additions. Furthermore, adding 200 ml of feed water led to more significant improvements in productivity, with increases of 5.9%, 8.2%, and 7.5%, respectively. A solar still with an initial water depth of 0.5 cm and a feed water inlet of 400 ml per tray achieved the highest distillate output of 6330 ml/m²/day, corresponding to a maximum daily efficiency of 66.45%. Experimental values were validated against theoretical energy balance equations, with a deviation of less than 6%. The cost of distillate produced was $0.03, which is approximately one-tenth the price of water available in the regional market. Solar stills offer a viable solution for producing potable water, addressing the drinking water needs of communities and urban areas facing water scarcity. The low cost, simplicity, and eco-friendliness of this desalination process make it ideal for household use. Future research should focus on developing intelligent feed water systems that adapt to solar radiation and ambient temperature fluctuations, optimizing feed water quantity and maximizing daily still output.

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INTRODUCTION

Potable drinking water is the essential commodity ensuring the sustainability of mankind on earth. Population growth combined with technological advancements has increased the per-capita consumption of fresh water. Technological growth has improved the comforts and living standards, but at the cost of a climatic imbalance in the environment. Nine out of ten people lack access to clean drinking water, and by 2025, half of the world's population is predicted to live in water scarce regions [1]. Growing population, urbanization and change in climatic patterns has increased the number of water stressed regions and thus increasing the demand for potable water. Large scale desalination techniques like reverse osmosis, electrodialysis and thermal methods are classified as energy-intensive processes [2] and pose a serious threat to the environment in terms of carbon footprint [3] and salt disposals.

Thermal and membrane-based desalination processes are classified as high specific energy consumption technologies contributing to higher water production costs limiting their utilization [4]. The materials required for the fabrication of the still are produced through energy intensive manufacturing processes. However, the emissions from the manufacturing phase can be considered minimal, taking into account the benefits gained by solar stills. Thus the solar still during its operational period can be considered as a green method compared to other desalination technologies. The need for solar desalination systems gained importance due to environmental risks, posed by burning of fossil fuels [5] and its impact on the carbon footprint. Though solar energy is available intermittently, it is available in abundance at zero cost. Furthermore, even the most isolated, remote and arid regions of the planet, have accessibility to solar energy, which is crucial in harnessing the solar power to meet the energy requirements for water purification. With minimal investment cost and operational expenses for solar stills, the production of potable water comes at an exceptionally low unit cost in comparison to alternative desalination technologies. In addition, simple operation and less maintenance makes this technology more acceptable by the common man. Potable water production using solar stills is most viable for small and arid communities, in spite of its low productivity.

Energy storage elements store the solar energy received and release this thermal energy when the incident solar radiation is low. Attaining a steady pattern of hourly yield during cloudy and rainy days is desirable and can be accomplished with the inclusion of heat storage elements. Sandy beds were used as the heat storage element in stepped trays, and it was observed that, as the depth of the bed increased the productivity decreased [6]. Jathar and Ganeshan [7] have used different masses of sand, broken bricks and broken concrete to evaluate the productivity of concave stepped trays. It can be observed that, the productivity improved with mass and specific heat capacity of the stones. Black poly propylene plastic tubes with 6 mm diameter and 2.25 cm height has been used to form honeycomb matrix in the flat basin to reduce the reflection losses to augment the distillate output [8]. Usage of conch biomaterial shells as energy storage in the still achieves a yield 10.8% more than that of the conventional still [9]. Ramalingam et al.[10] used copper scraps coupled with coconut coir disk in stepped still to produce 44.24% increased yield compared to the one without them. Researchers also used aluminum fillings [11], pin fins [12], copper scraps [10] and fins [13] as heat sensible materials.

Some researchers have also utilized water as a sensible heat storage medium due to its larger heat capacity. Due to the presence of high energy hydrogen bonding (10–30 kJ/mol) in water, it shall be considered the best possible thermal fluid at an operating range of 0°C to 100°C [14]. The quantum of sensible heat energy stored in water is augmented, when there is an increase in the temperature of water or by increasing the mass of water exposed to solar radiation [15]. In the absence of solar energy, the stored sensible energy is further utilized to assist the evaporation of water to achieve a steady productivity [16]. According to Kabeel et al. [17], the productivity of the still is dependent on the mass of the sensible heat storage material and depth of water.

The addition of feed water can be classified into static and dynamic mode [18]. In static mode, the feed water is introduced into the still once at the start of the day, whereas in dynamic mode the feed water is fed periodically. Few researchers abstained from feed water addition [19–21], while most researchers added makeup water on an hourly basis [13] or in half hour intervals [7,22,23] to compensate the evaporated water. Abujazar et al. [24] used water level sensor to maintain a constant depth of water in the triangular trays. In the case of inclined and weir type stills, the feed water is allowed to overflow the absorber plate at a constant flowrate [10].

Siddula et al. [16] compared the productivity of a triangular shaped and conventional still with different depths of water. It was recorded that, as the depth of water was increased from 1.5 cm to 3.0 cm in the triangular and conventional still, the output declined by 19.09% and 35.92% respectively. At very low depths of water in the basin, chances of dry spots been developed can reduce the productivity [19]. Hence it is advised to always keep the tray water levels at least minimal. Kabeel et al. [25] tested extended type trays with water depths 5 mm, 10 mm and 20 mm and observed that the productivity decreased with the increase in depth of water. According to Omara et al. [26], the extended type trays have more surface area and for a given depth of water, they can contain more mass of water compared to a conventional still. As the water depth increases and due to the high specific heat capacity of water, a greater amount of heat is stored in the water, which promotes the formation of vapors during the nocturnal hours [27]. Due to the small quantity of water in the trays of the stepped solar still, the evaporation rate is more due to the less time consumed to convert water particles to vapor [28]. The hourly efficiency of the still gradually increases from the start of the day to reach its maximum and then gradually declines thereafter [29].

Abdullah et al. [30] in their recent review, found that increasing the water depth in stills leads to a decrease in distillate production, indicating an inverse relationship. A study by Alwan et al. [31] investigated the relationships between climatic, operational, and design parameters and still productivity, concluding that increased water depth in the still leads to decreased productivity. Nougriaya et al. [32] found that stills with 1-2 cm water depth produce more distillate efficiently. Research by Siddula et al. [16] on single slope solar stills with varying water depths (1.5-3 cm) revealed that shallower depths produce higher hourly yields in the morning, whereas deeper depths yield more in the afternoon.

It can be concluded from the extensive literature that, distillate output of a solar still can be augmented by utilizing more radiant energy through heat storage methods. The liquid in solar stills can also serve as a heat storage medium, and the dynamic impact of this sensible heat storage approach has received limited attention in the existing literature. Diverging from the conventional approach of adding feed water to replenish evaporated water, this research explores the addition of a fixed volume of water at fixed intervals to enhance the water depth in the trays. It is worth observing that the amount of water added exceeds the quantity of water evaporated. This feeding mechanism increases the water depth in the trays compared to the initial water depth. This gradual increase in water depth facilitates more efficient utilization of solar energy from the sun, primarily through sensible heat storage.

Theoretical Model of the Solar Still

A theoretical model of the stepped solar still is developed in this section, based on energy balance at the basin, water, and glass cover [33]. Glass accumulates the solar energy from the sun in the specific heat capacity which raises its temperature. A part of the energy is lost to the ambient through convection and radiation from the condensate surface. The solar energy transmitted by glass is received by the water body in the trays. The energy absorbed by water is accumulated in the water contributing the increase in temperature. The temperature difference between the water and the glass cover causes the vapors to advance towards the lower temperature condensate cover. The vapors condense at the glass surface and this energy is transferred to the condensate cover. Similarly convective and radiation energy is transferred between the water body and the glass cover. A portion of the energy transmitted through water is absorbed by the trays. The trays heat at a faster rate achieving the highest temperatures due to its high absorptivity character. Convective heat energy exchange occurs from the tray surface to the water in the trays and similarly from the tray to the ambient. The model is evaluated for water depths ranging from 0.5 cm to 2.0 cm. The thermal network of the solar still is depicted in Figure 1.

The energy balance equation at node 1 (condensate cover) comprises of the energy received from the sun, condensation of vapors, convective and radiation heat transfer from water, energy accumulated in the form of specific heat and the energy lost to the ambient. Similarly at node 3 (trays) the energy is received from the sun and accumulated in the form of specific heat, while convective energy is lost both to water and ambient. The energy balance at node 2 (water) constitutes the energy received from the sun and the trays, accumulating in the form of specific heat. It constitutes the evaporative energy producing the vapors and the convective and radiation heat loss to the glass cover. The energy balance equations for the glass (node 1), water (node 2), and trays (node 3) are expressed in matrix form, as presented in Equation 1. The temperature of tray, water, glass and the distillate output for unit area of the tray from the stepped solar still can be predicted by solving this matrix.

$$\begin{bmatrix} 0 & -h_{twg} & (h_{tga} + h_{twg}) \\ -(h_{tbw}) & (h_{twg} + h_{tbw}) & -h_{twg} \\ 0 & -(h_{tbw}) & (U_b + h_{tbw}) \end{bmatrix} \times \begin{bmatrix} T_b \\ T_w \\ T_g \end{bmatrix} = \begin{bmatrix} I_g(t) - m_g C_{pg} \frac{dT_g}{dt} + h_{tga} T_a \\ I_w(t) - m_s C_{pw} \frac{dT_w}{dt} \\ I_b(t) - m_b C_{pb} \frac{dT_b}{dt} + U_b T_a \end{bmatrix} \quad (1)$$

Where total heat transfer coefficient between water and glass (h_{twg}), between glass and ambient (h_{tga}) and basin and water (h_{tbw}), and can be found out from the following equations [33],

$$h_{twg} = 0.884 \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{1/3} + \frac{(16.28 \times 10^{-3}) h_{cnv} (P_w - P_g)}{(T_w - T_g)} + \frac{\varepsilon_{eff} \, \sigma \left[(T_w + 273)^4 - (T_g + 273)^4 \right]}{(T_w - T_g)} \quad (2)$$

$$h_{tga} = \frac{\left[\varepsilon_g \sigma (T_g + 273)^4 - (T_{sky} + 273)^4 \right]}{(T_g - T_{sky})} + (2.8 + 3.0 V_w) \quad (3)$$

$$h_{tbw} = f(h_{cbw}, h_{cvbw}) \quad (4)$$

Experimental Setup

Various configurations of the stepped solar still and the characteristics that enhances the distillate output is discussed in our earlier work [27]. Studies of solar still using flat, convex and convex stepped trays reveal that, the productivity of the still has improved compared to single basin due to the increase in the surface area of contact between the water and basin surface [34]. It can be observed that the still with tray width of 120 mm produced 26.9%, 11.7% and 5.7% respectively more distillate output compared to that of tray widths 100, 110 and 130 mm [25].

The stepped tray was designed to maintain a constant air cavity between the central axis of each tray and the condensate cover. Compared to the conventional still, the cavity space between the trays and the condensate cover

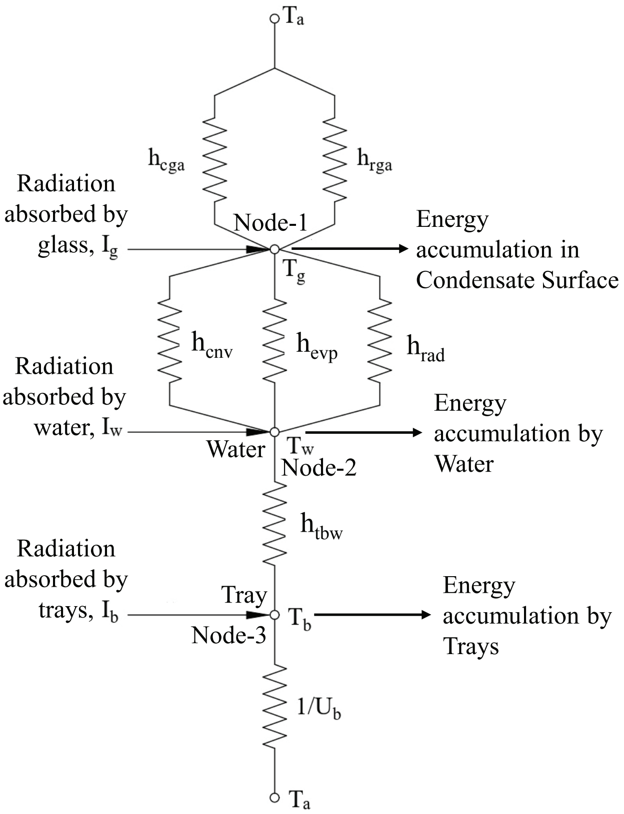


Figure 1. Thermal network and temperature nodes in the solar still.

in stepped still is comparatively less. Thus a stepped solar still with extended type tray made of galvanized steel is selected for the proposed experiments. For obtaining a total projected area of 0.5 m^2, a set of five trays with dimensions 1000 x 20 x 120 mm was used to build the stepped still. Each tray could hold a maximum capacity of 2400 ml of water. Trays were painted black to increase its absorptivity to 0.9.

The difference in temperature between the water in the trays and the condensate cover is one of the governing parameters in improving the cumulative output from the still [35]. The specific height of the still equals the distance between the center of the absorber surface and the condensate surface. For achieving higher distillate output, evaporating and condensing surfaces are required to be parallel [36]. Reducing the distance between the water surface and condensate cover increases the convective heat transfer between the duo and improves the daily productivity [37]. This is evident from the Dunkle equation and it enhances the convective heat transfer coefficient [38]. Thus a specific height of 120 mm with a cavity ratio of 4.16 was selected for the still design.

A transparent glass cover of 4 mm thick was used as the condensate surface to ensure optimal sunlight reception during the bright sunny days in Kochi, India (9.93°N, 76.26°E) as shown in Figure 2. Glass inclination was set at an angle of 25° to maintain an equal cavity space between the cover and the consecutive trays. The reflectivity and transmissivity of the selected glass is 0.05 and 0.9.

Table 1. Dimensions of stepped solar still

Design Element	Parameter	Value
Still Box	Length (m)	1.12
	Front wall Height (m)	0.21
	Rear Wall height (m)	0.54
	Projected Area (m^2)	0.77
Tray	Length (m)	1.0
	Width (m)	0.12
	Height	0.02
	Projected Area (m^2)	0.52
	Mass / Tray (Kg)	2.89
	No. of Steps/Trays	5
Glass	Thickness (mm)	4
	Area (m^2)	0.645
	Mass (Kg)	6.45
	Angle	25°
Insulation	Thickness (m)	0.04

A graduated steel scale is fixed onto the middle tray to measure the level of water. Table 1 provides the dimensional specifications for the stepped solar still employed in this study. Saw dust was used as insulation with 4 cm thickness. Provisions are provided to ensure uniform supply of feed water at constant heads into each of the trays.

Experimental Procedure

Experiments were conducted in the sunny days of March to May 2024 at Kochi, India with coordinates 9.93°N, 76.26°E. Each day, the tests commenced at 08.00 am and extended beyond dusk till midnight or when the yield seizes. The orientation of the stepped solar still was located facing south, since the location of Kochi is above the equator. Experiments were conducted with three different initial depths of water (dw) 0.5 cm, 1.0 cm and 1.5 cm. Each case of dw was tested by different conditions of feed water addition including (1) no feed water added, (2) 100 ml of feed water added into each tray at 09.00 am, 10.00 am and 11.00 am and (3) 200 ml of feed water added into each tray at 09.00 am, 10.00 am and 11.00 am. In addition, 400 ml feed water was added to initial depths of 0.5 cm and 1.0 cm to study its sensible storage effects. Surface cleaning of the condensate cover was performed daily to prevent any hindrance of heat transfer through the glass due to the presence of foreign elements.

Thermocouples coupled with a 4-channel data logger was used to measure the basin, water and glass temperatures, while the ambient temperature was measured using

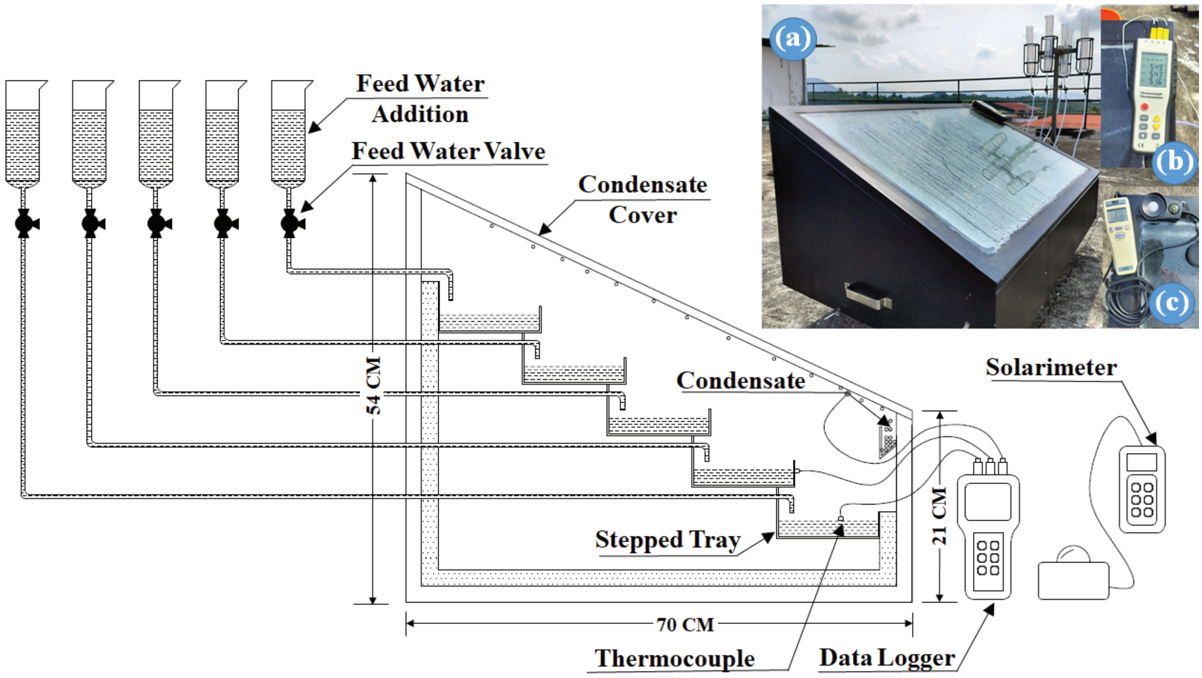


Figure 2. Schematic diagram of experimental setup for extended tray type solar still (Insert image of (a) stepped solar still with feed water system, (b) data logger, (c) solarimeter.

Table 2. Combinations of depth of water and feed water quantities

Depth combination	Initial Depth of Water (cm)	Quantity of water (ml) added at each hour given		
		09.00 AM	10.00 AM	11.00 AM
$dw_{0.5}$	0.5	0	0	0
$dw_{0.5-100}$	0.5	100	100	100
$dw_{0.5-200}$	0.5	200	200	200
$dw_{1.0-0}$	1.0	0	0	0
$dw_{1.0-100}$	1.0	100	100	100
$dw_{1.0-200}$	1.0	200	200	200
$dw_{1.5-0}$	1.5	0	0	0
$dw_{1.5-100}$	1.5	100	100	100
$dw_{1.5-200}$	1.5	200	200	200

Table 3. Maximum quantity of water in the stepped still for different dw and feed water input, assuming no evaporation from the tray

Initial Depth of Water (cm), dw	Feed water quantity added hourly per tray at 09.00 am, 10.00 am and 11.00 am			
	0 ml	100 ml	200 ml	400 ml
	Final Quantity of water in the trays after feed water addition			
0.5	3000	4500	6000	9000
1.0	6000	7500	9000	12000
1.5	9000	10500	12000	-

Table 4. Measuring instrument specifications

Sl. No.	Measuring Instrument	Range	Accuracy	Standard Uncertainty (σ)
1	Solarimeter (MECO)	0-1000 W/m^2	±1 W/m^2	0.5773
2	Multi-channel digital temperature indicator	-50 °C to 110 °C	0.1 °C	0.0577
3	Calibrated Thermocouples	0 °C to 100 °C	±0.5 °C	0.2886
4	Measuring Flask-2	0 - 30 ml	5 ml	0.0028
5	Anemometer (MECO - 961P)	1- 25 m/sec	±0.2 m/sec	0.1154

a conventional thermometer. Solar radiation intensity was recorded using the solar meter (MECO, India), placed on the inclined surface of the glass. The air velocity was recorded using an anemometer (MECO, India) and the distillate output was measured using graded bottles.

The measurement uncertainties were determined based on the specifications provided by the instrument manufacturers. Error analysis was conducted for a solarimeter, a multi-channel data logger, thermocouples, and an anemometer. The errors could get accumulated due to the limited precision of the instruments, human errors and uncertainty of the measuring technique during the experimentation. The error values of each measurement were calculated from the least count of the instrument and the minimum output to be measured and are reported in Table 4. Experimental uncertainty is calculated by considering the standard uncertainties of each measuring instrument. The standard uncertainties provides the possible errors in the experimental values measured [39,40]. The mathematical expression for percentage of uncertainty is given by [41],

$$\%\,Uncertainty = \frac{U_i}{B} \times 100 \tag{5}$$

$$U_i = \frac{\sqrt{\sigma_1^2+\sigma_2^2 \ldots +\sigma_n^2}}{n^2} \tag{6}$$

$$\sigma = \frac{\sqrt{\sum(X-\bar{X})^2}}{n_o} \tag{7}$$

The percentage of experimental uncertainty was estimated to be less than 1.5%. Water in the trays absorb a portion of the solar radiation received by the stepped still. A part of energy is used for evaporation of water molecules and other part of energy is stored in the form of sensible heat. The magnitude of solar energy stored depends on the mass of water in the trays and temperature rise. With less quantity of water in the trays, most of the absorbed energy is utilized for the phase change of water molecules. An increase in the initial depth of water in the trays shall also delay the evaporation process [19].

RESULTS AND DISCUSSION

As indicated in Table 2, a predetermined measured quantity of feed water is added at 09.00 am, 10.00 am and 11.00 am to three initial depth conditions including 0.5, 1.00 and 1.5 cm. The maximum quantity of water that the still can accommodate is limited to 12000 ml. The maximum quantity of water in the trays after the addition of feed water under the circumstance of extreme cloudy and rainy days when no evaporation occurs is depicted in Table 3.

Effect of Solar Radiation Intensity

The variation of solar radiation intensity with time is plotted in Figure 3 for nine different combinations of depth of water and feed water quantities (Table 2). It is noticeable that solar stills under different experimental combinations received identical solar energy inputs throughout the day of the experimentation. The still performance was dependent on the intensity of solar radiation. Thus peak hourly productivity was achieved just at after noon (between 12.00 pm and 01.00 pm), when the solar radiation intensity was maximum. The peak of radiation intensity was received during noon and the maximum and minimum cumulative radiation received during the days of study were 19.56 MJ/m^2 and 21.95 MJ/m^2. The average value of cumulative solar energy received during the first hour (08.00 am to 09.00 am) from the commencement of experiment was 1.715 MJ/m^2 and the maximum average energy received between 11.00 am and 12.00 pm were 3.09 MJ/m^2. This increasing trend in cumulative energy ensures the feasibility to increase the quantity of water in the tray to store the increased input energy radiated from the sun.

Effect of ambient conditions

The average ambient conditions of the still during the days of experimentation, ranges from 30.9°C to 32.2°C. The ambient temperature characteristics followed a similar trend that of the solar radiation as shown in Figure 4. The curve profiles of ambient temperature and solar radiation were similar, indicating the dependency of ambient temperature on the energy received from the sun. The increased ambient temperature during the noon session was favorable in reducing the heat loss between the condensate cover and the ambient. During these days the highest ambient temperature recorded was 37.9°C at 02.00 pm.

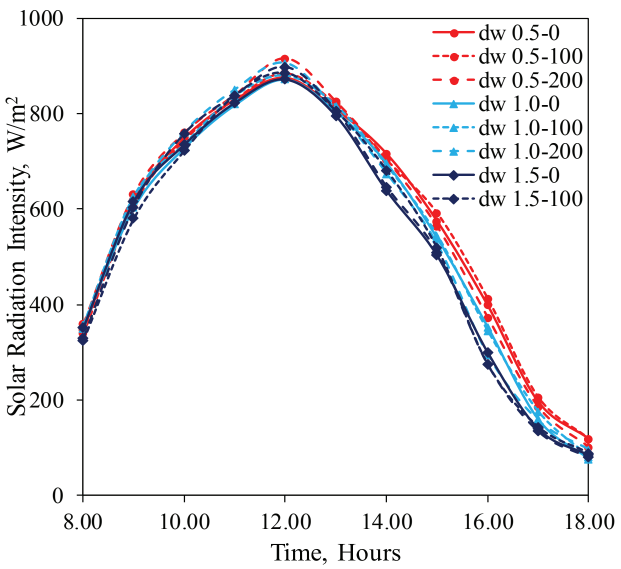


Figure 3. Variation of intensity of solar radiation for different initial depth conditions and feed water input.

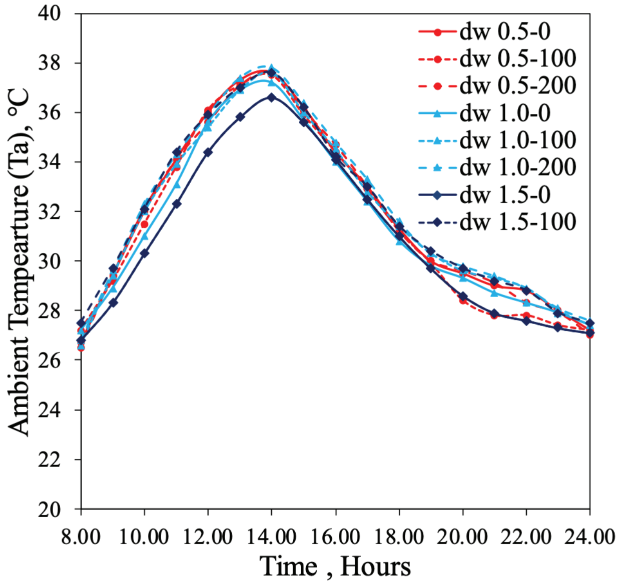


Figure 4. Variation of ambient temperature for different initial depth and feed water input.

The wind speed varied throughout the day and was measured hourly between 08.00 am and 12.00 midnight. The average velocity during the experimentation period varied between 4.88 m/sec and 9.66 m/sec. For any given day, the highest average wind velocity was during the period between 12.00 pm and 06.00 pm, followed by the nocturnal period between 06.00 pm and 12.00 am. Higher wind velocity during the noon period, improved the cooling of condensate cover, resulting in better condensation of vapors and augmented productivity. According to El-Sebaii [42], the productivity of conventional stills decreases as the wind velocity increases when the mass of water in the basin is below the critical mass of 45 kg. In our cases, an initial depth of water of 0.5 cm and 1.0 cm is the conditions attributed to the quantity of water in the still falls below the 45 kg. For every other case the level of water in the stills remained above 45 kg and hence the wind velocity does not have a negative effect on the yield.

Influence of depth of water on still productivity with no feed water addition

During these set of experiments, no feed water was added into the trays for compensating the quantity of water evaporated during each hour. Hence, the level of water in the tray descends as the day progresses. The rate of descend in the trays depend on the intensity of solar radiation received and the initial depth of water.

The trays have a projected area of 0.52 m^2 and with an initial water depth of 0.5 cm, the cumulative distillate output produced from 9.00 am to 1.00 pm was 14.2% and 31.6% higher than that of the initial water depth 1.0 cm and 1.5 cm respectively. By maintaining lower quantity of water in the tray, less energy is required to augment its temperature rise. As the depth of water increases more energy is required to raise the temperature of water. With low depth of water, the initial temperature rise is more, favoring the achievement of maximum temperature at noon, compared to higher depth of water in the trays. This resulted in higher productivity during the morning hours, as illustrated in Figure 5.

With a smaller volume of water in the trays, there is less thermal inertia, leading to a quicker increase in temperature at the beginning of the evaporation process. Lower depths of water had improved heat transfer coefficients resulting in increased productivity. Conversely, a low volume of water means reduced storage of specific heat energy, causing the water temperature to decrease at a faster rate as solar radiation intensity diminishes after 02.00 pm resulting in decreased productivity. From 02.00 pm to 06.00 pm the cumulative yields for $dw_{0.5}$, $dw_{1.0}$ and $dw_{1.5}$ are 475 ml, 585 ml and 585 ml. The depths $dw_{1.0}$ and $dw_{1.5}$ produced 23% more output compared to the depth of $dw_{0.5}$.

By collecting the nocturnal yield produced by the still, there has been an improvement in their productivity. When more water is in the trays, it stores more energy as sensible heat, allowing it to retain a higher temperature for an extended period, even as solar input diminishes. The temperature difference between water and glass for $dw_{0.5}$, $dw_{1.0}$ and $dw_{1.5}$ at 6.00 pm are 4.4°C, 6.3°C and 10°C respectively. This variation in temperature resulted in nocturnal yields of 15 ml, 40 ml, and 130 ml for trays with water depths $dw_{0.5}$, $dw_{1.0}$ and $dw_{1.5}$ respectively, each covering a projected area of 0.5 m^2.

The total daytime yield is the sum of the hourly yield collected from the still each hour starting from 09.00 am to 06.00 pm. Since the experiment is initiated at 08.00 am no hourly yield is produced at this hour. The total daytime

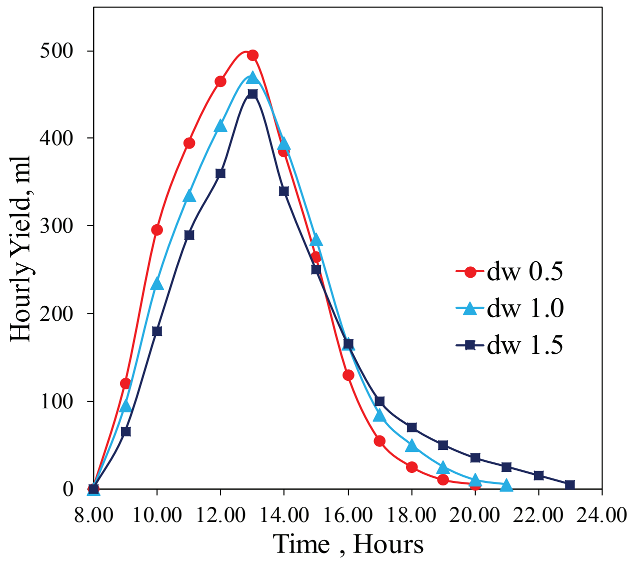


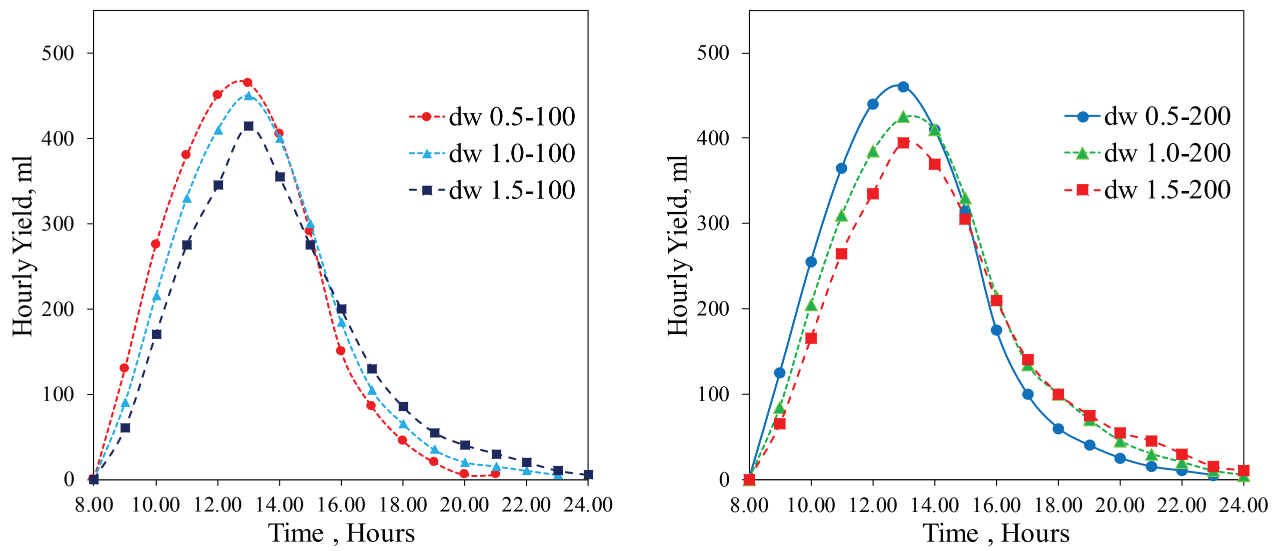
Figure 5. Hourly distillate yield from the solar still for different initial depths of water without any feed water input.

productivity for stills with $dw_{0.5}$, $dw_{1.0}$ and $dw_{1.5}$ conditions was 5260 ml, 5060 ml and 4540 ml respectively, for a projected area of one square meter. This clearly indicates that, as the depth of water increases, the productivity of the stepped solar still decreases. Incorporating nocturnal yield into the daytime productivity of the stepped still increased its output by 0.5%, 1.5%, and 5.7% for $dw_{0.5}$, $dw_{1.0}$ and $dw_{1.5}$ respectively, relative to the daytime yield. The overall yield increases for stills with low initial depths of water. For initial depth of water $dw_{0.5}$, $dw_{1.0}$ and $dw_{1.5}$ the daily distillate output is 5290 ml/m^2, 5140 ml/m^2 and 4800 ml/m^2 respectively.

Influence of depth of water on still productivity with input feed water

During this experimental phase, 100 ml and 200 ml of water were introduced into each tray of the stepped still at 9:00 am, 10:00 am, and 11:00 am, respectively. The addition of feed water causes a slight drop in the temperature of the water in the trays, which is affected by the quantity and temperature of the feed water introduced. As solar radiation intensity decreases, the water temperature in the trays follows a corresponding decline. To mitigate the temperature drop caused by feed water addition, its introduction is restricted until 11:00 am. The strategy of adding water aims to harness excess heat received by the still in the form of sensible heat, leveraging the increasing solar radiation intensity during the morning hours. Experiments were conducted with 100 ml and 200 ml of feed water addition for the three different depth of water viz. 0.5 cm, 1.0 cm and 1.5 cm.

Experimental studies by [13] clearly indicate that, low initial depth of water in the trays reduces the thermal inertia of water mass resulting in an improvement in the yield. The tray with minimum initial depth of water produced the highest yield in the first hour of the experimental study. At 09.00 am, with the addition of 100 ml feed water, the yields produced by initial depths 0.5 cm, 1.0 cm and 1.5 cm were 130 ml, 90 ml and 60 ml respectively. From 09.00 am to 01.00 pm, the cumulative productivity for $dw_{0.5\text{-}100}$ and $dw_{0.5\text{-}200}$ slightly declined by 3.9% and 7.0% respectively compared with the scenario where no feed water was added



(a) (b)

Figure 6. Hourly distillate yield, with (a) 100 ml of feed water added to each tray, (b) 200 ml of feed water added to each tray

as shown in Figure 6(a) and 6(b). This decline in productivity is due to the increased volume of water in the trays due to feed water addition.

Beyond 1.00 pm, with the declining solar radiation intensity the temperature drastically drops for trays with lesser volume of water. Addition of feed water during the forenoon session augments the quantity of water in the trays enhancing the specific heat storage capacity. The specific heat energy stored in the water is released to compensate the temperature decline due to reduced radiation intensity received by the still. Maintaining higher water temperature in the afternoon session helped to prolong the yield in the nocturnal hours. Hence in the afternoon session the trays with higher quantity of water produced more distillate output. Compared to the trays without feed water addition, by adding 100 ml feed water in each tray, the productivity improved by 2.3%, 2.5% and 2.9% for $dw_{0.5\text{-}100}$, $dw_{1.0\text{-}100}$ and $dw_{1.5\text{-}100}$ respectively as shown in Figure 6(a) and 6(b). Similarly, for 200 ml water addition, the productivity of the stepped still improved by 5.9%, 8.2% and 7.5% respectively. Hence as the initial depth of water increased, the productivity also reduced.

Effect of varying the quantity of feed water added

Conventional practice among researchers involves feeding water into solar stills at hourly intervals to sustain a constant water level in the trays or basin. When no compensating feed water is supplied, the level of water declines, and thus results in lower quantity of water in the trays. Consequently, a smaller amount of sensible heat can be stored by the tray water, rendering it incapable of generating nocturnal yield. Notably, this investigation deviates from established research protocols by incorporating a feed water addition strategy that exceeds the quantity of evaporated water.

From Figure 7, it can be noted that, level of water in the tray rises on an hourly basis till 11.00 pm as the feed water is added to the trays. After 11.00 pm, no feed water is added and the depth of water in the tray descends as evaporation continues. The augmented quantity of water facilitated the storage of more energy in the form of sensible heat. This ultimately helps to improve the yield during the afternoon hours and the nocturnal period. Whereas in the case of $dw_{0.5}$, as the evaporation continues the depth of water in the trays descends when no feed water is added.

The hourly productivity of the stepped still with 0.5 cm initial depth, with feed water quantity ranging from 0 ml to 400 ml is depicted in Figure 8. For low initial quantity of water in the trays, the evaporation commenced early and the temperature rise of water was at a faster pace. Upon introducing the feed water, the mixing of hot and cold fluids, along with the increased quantity in the tray, reduced the rate of temperature rise. Augmentation in the volume of water in the trays, led to a minor decrease in the overall distillate generated from 9:00 am to 1:00 pm. This decline is due to the decrease in temperature of tray water due to feed water addition. The accumulated distillate yield from 9.00 am to 1.00 pm for the stepped still with initial depth of 0.5 cm with hourly feed water quantity of 0, 100, 200 and 400 ml are 3540, 3400, 3290 and 3240 ml/m^2 respectively.

In contrast, there was an enhancement in the cumulative yield observed between 2:00 pm and 6:00 pm, as well as during the nocturnal hours. This improvement can be attributed to the release of energy stored as sensible heat energy from the water in the trays. The accumulated yield between 02.00 pm and 06.00 pm for $dw_{0.5\text{-}100}$, $dw_{0.5\text{-}200}$ and $dw_{0.5\text{-}400}$, were 975 ml, 1060 ml and 1220 ml respectively. Compared to no feed water addition, the improvement in

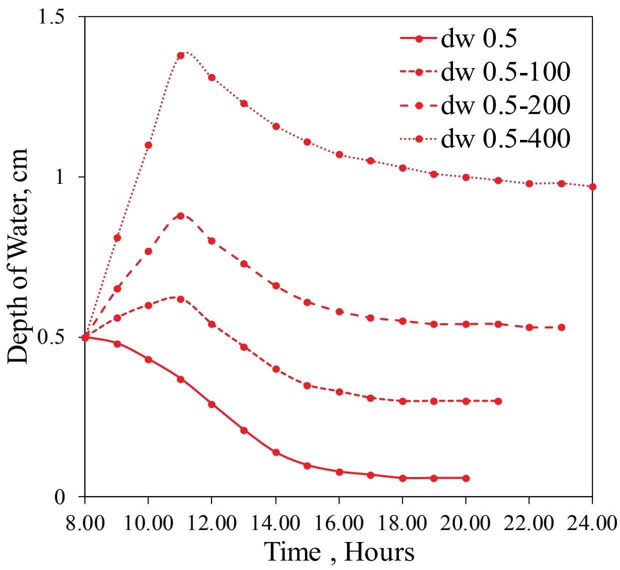


Figure 7. Hourly variation in water level for diverse feed water inflows at initial water depth 0.5 cm.

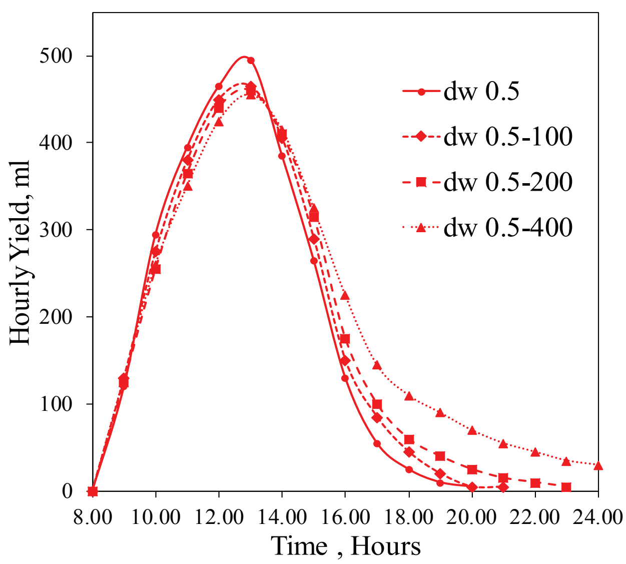


Figure 8. Hourly distillate yield for 0.5 cm initial depth and at different combinations of feed water input to each tray.

afternoon yield for $dw_{0.5\text{-}100}$, $dw_{0.5\text{-}200}$ and $dw_{0.5\text{-}400}$, were 13.3%, 23.2% and 41.8% respectively.

At 06.00 pm, the temperature of water for $dw_{0.5\text{-}100}$, $dw_{0.5\text{-}200}$ and $dw_{0.5\text{-}400}$, were 35.7°C, 38.2°C, 39.1°C and 41.4°C respectively. Correspondingly the nocturnal output obtained were 15 ml, 30 ml, 95 ml and 325 ml respectively. The distillate output for $dw_{0.5}$, $dw_{0.5\text{-}100}$, $dw_{0.5\text{-}200}$ and $dw_{0.5\text{-}400}$, are 5290 ml/m^2, 5410 ml/m^2, 5600 ml/m^2 and 6330 ml/m^2 respectively. The daily output improved by 19.7% as the quantity of water added was increased from 0 ml to 400 ml for an initial depth of 0.5 cm.

Temperature of water in the stepped still

The specific heat storage capacity is dependent on the water temperature and quantity of water in the trays. The sensible energy stored in the water is released when the radiation intensity declines. This released energy partly compensates for the reduction of energy received from the sun, hence contributing to the evaporative heat transfer coefficient.

The energy received by $dw_{0.5}$, $dw_{0.5\text{-}100}$, $dw_{0.5\text{-}200}$ and $dw_{0.5\text{-}400}$ are 21.6, 21.7, 21.7 and 22 MJ/m^2 respectively. The temperature rise from 08.00 am to 9.00 am was almost the same for all the combinations, since they all started with the same initial depths of water and with similar energy received. The temperature difference of water between 08.00 am and 01.00 pm for $dw_{0.5}$ and $dw_{0.5\text{-}400}$ were 42.2 °C and 37.6°C respectively. Thus the rate of increase of temperature was more with trays with lesser quantity of water. Again from Figure 9, it can be seen that as the quantity of feed water increased, the peak temperature also decreased. For $dw_{0.5}$ and $dw_{0.5\text{-}400}$, the peak temperatures obtained were 69.1°C and 65.3°C respectively. At 01:00 pm, the water volumes in trays $dw_{0.5}$ and $dw_{0.5\text{-}400}$ were 1230 ml and 7380 ml, respectively. The stepped still $dw_{0.5\text{-}400}$ carries at least five times the quantity of water than that of $dw_{0.5}$. Consequently, it is evident that more energy is needed to elevate the temperature of water as the water mass increases, hence resulting in lower peak temperature for $dw_{0.5\text{-}400}$ compared to $dw_{0.5}$.

At 06.00 pm with minimal solar radiation intensity, the temperature of water for $dw_{0.5}$ and $dw_{0.5\text{-}400}$ is 35.7°C and 41.4°C. The volume of water in $dw_{0.5}$ and $dw_{0.5\text{-}400}$ at 06.00 pm are 370 ml and 6160 ml respectively. Ultimately, a higher water temperature is observed with a larger quantity of water, indicating the influence of sensible heat. Since $dw_{0.5\text{-}400}$ possesses higher mass of water than that of $dw_{0.5}$ at 06.00 pm, the temperature of water is 16% higher due to the energy storage in the form of specific heat. It augmented the hourly yields during the nocturnal hours due to the higher stored sensible heat energy and temperature of water at 06.00 pm.

Validation of the experimental results with the theoretical model

The heat balance matrix of the solar still, represented by Equation 1, was resolved to predict the temperatures of the basin, water, and glass. The predicted temperatures were compared with experimental results as shown in Figure 10, for an initial water depth of 0.5 cm and a feed water addition of 100 ml. Generally, the theoretical predictions were found to be slightly higher than the actual values. The maximum percentage deviations between predicted and actual temperatures for the basin, water, and glass were 3.9%, 3.8%, and 4.3%, respectively.

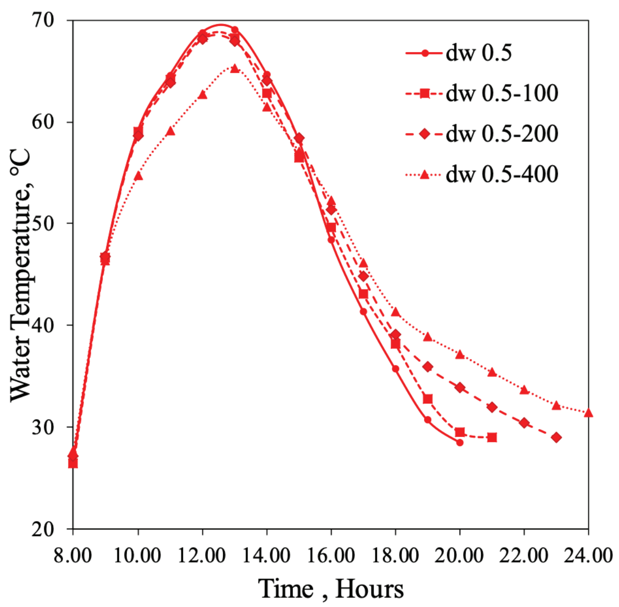


Figure 9. Temperature variation of water in the tray stepped solar still on an hourly basis.

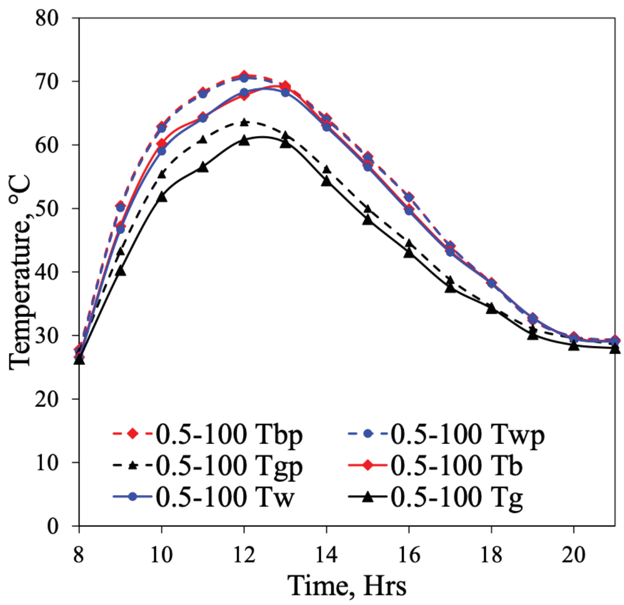


Figure 10. Comparison of predicted temperature of basin, water and glass with experimental results for $dw_{0.5\text{-}100}$.

Daily efficiency

The theoretical hourly distillate output from the stepped solar still is computed using the relation [33],

$$m_w = \frac{h_{evp} \times (T_w - T_g) \times \Delta t}{L_{ev}} \quad (8)$$

Where the evaporative (h_{evp}) and convective (h_{cnv}) heat transfer coefficients are directly dependent on the temperature difference between the water and the condensate cover, which are given as [33],

$$h_{evp} = 16.28 \times 10^{-3} \times h_{cnv} \times \frac{(P_w - P_g)}{(T_w - T_g)} \quad (9)$$

$$h_{cnv} = 0.884 \left[(T_w - T_g) + \frac{(P_w - P_g) \times (T_w + 273.16)}{((268.9 \times 10^3) - P_w)} \right]^{1/3} \quad (10)$$

The hourly efficiency of the still is determined by taking into account the average solar energy input during the hour, the latent heat of vaporization, and the hourly distillate output [40]. Similarly, the daily thermal efficiency of the still is a function of solar radiation intensity, distillate production, and the amount of water in the still, as formulated in [33].

$$\eta = \frac{\sum m_w \times L_{ev}}{A_t \times \sum I(t) \times \Delta t} \quad (11)$$

The theoretical thermal efficiency can be computed by substituting the theoretical value of distillate quantity calculated using Equation 8 in Equation 11. While the actual daily efficiency can be calculated using the measured hourly distillate quantities.

The hourly efficiency can be calculated by substituting the quantity of distillate produced during an hour into Equation 11. As depicted in Figure 11, the maximum hourly efficiencies obtained without feed water replenishment were 76.4% at 0.5 cm, 72.8% at 1.0 cm, and 70.4% at 1.5 cm initial water depths. These peak efficiencies occurred at 01:00 pm, corresponding to the maximum hourly yields. The efficiency of the $dw_{0.5\text{-}400}$ still arrangement, which received 400 ml of feed water, was found to be 13.5% higher than that of the $dw_{0.5}$ arrangement without feed water addition. The enhancement in efficiency can be attributed to the improved heat storage capacity, primarily in the form of sensible heat.

In Figure 12, for each initial depth of water, the daily efficiency improved with the augmented feed water input. The daily efficiency includes both the daytime and nocturnal yield, while the daytime yield only includes the cumulative yield during the sunshine hours. The daily efficiency consistently surpassed the daytime efficiency as seen in Figure 13, due to the inclusion of the nocturnal yield. For initial water depths of 0.5 cm, 1.0 cm, and 1.5 cm, the improvement in daily yield compared to daytime yield continued to increase as the amount of added feed water increased.

Utilization of received energy and improvement of daily efficiency can be enhanced with the addition of feed water to a given initial depth of water. Considering nocturnal yield, the daily efficiency at an initial water depth of 0.5 cm showed improvements of 0.32%, 0.64%, and 2.02% for feed water additions of 0 ml, 100 ml, and 200 ml, respectively. Similarly as the initial depth of water was increased, there was an improvement in the nocturnal yield produced. For no feed water condition, the daily efficiency improvements

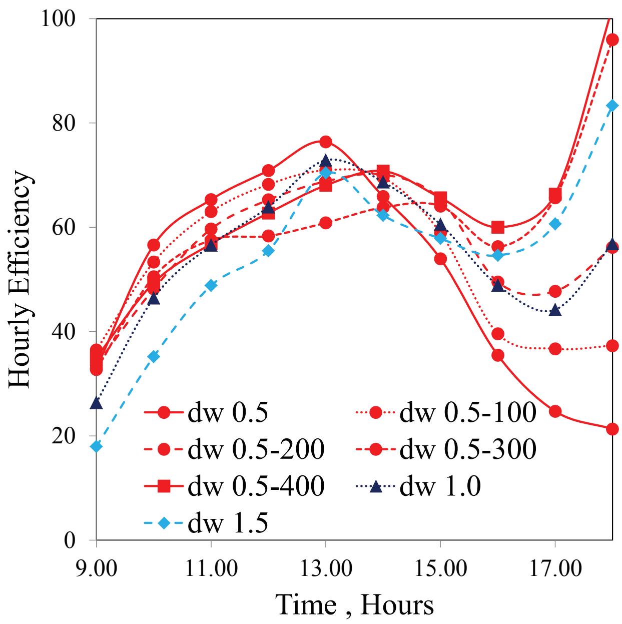


Figure 11. Hourly efficiency of stepped still for different water depth combinations.

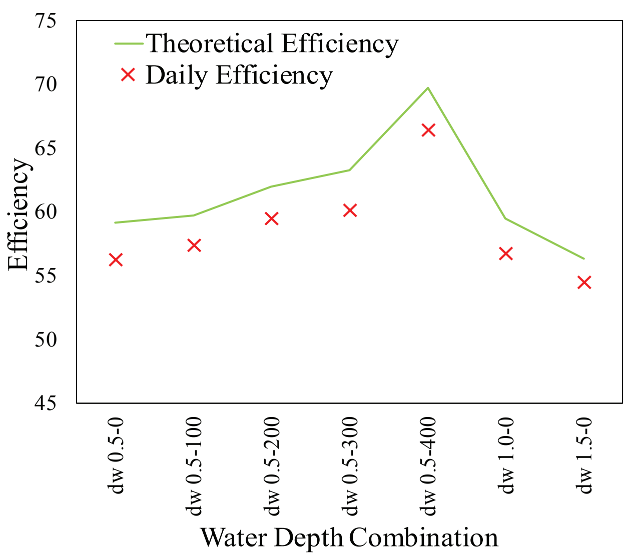


Figure 12. Stepped still efficiency –validation of experimental values.

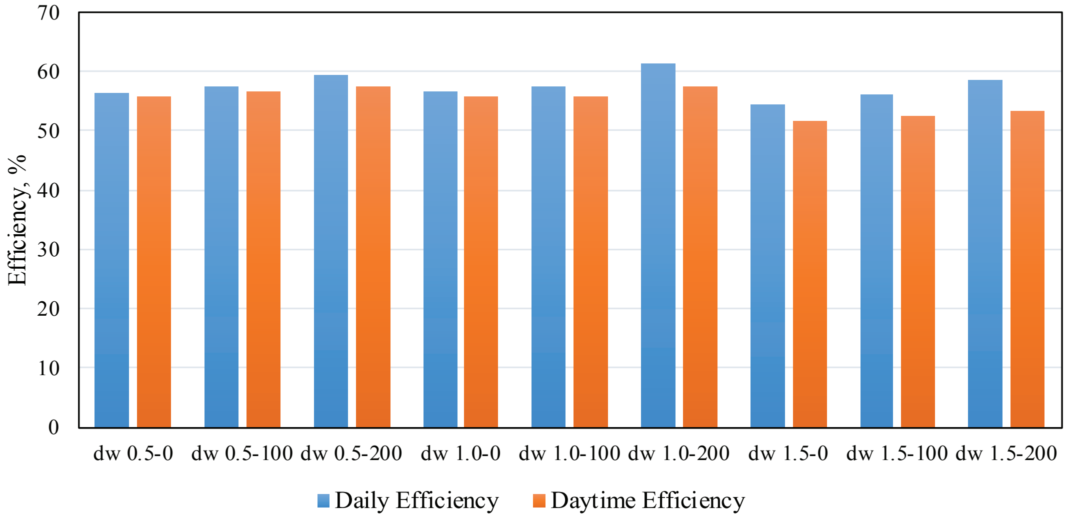


Figure 13. Daily efficiency of the stepped solar still for different quantities of feed water.

were 0.32%, 0.88%, and 2.95% for initial water depths of 0.5 cm, 1.0 cm, and 1.5 cm, respectively. With the addition of 200 ml of feed water, the improvements in daily efficiency over daytime efficiency were 2.02%, 3.97%, and 5.21% for $dw_{0.5\text{-}200}$, $dw_{1.0\text{-}200}$ and $dw_{1.5\text{-}200}$ respectively. While for the initial depth of water at 0.5 cm with 200 ml and 400 ml feed water addition, the improvement in daily efficiency over daytime efficiency was 2.02% and 6.82% respectively.

The highest daily efficiency of 66.45% was obtained for $dw_{0.5\text{-}400}$ (Figure 12). With $dw_{0.5\text{-}100}$ and $dw_{0.5\text{-}400}$, the efficiency of the stepped still improved by 1.12% and 10.22% respectively. With no feed water addition, as the initial depth increased from 0.5 cm to 1.5 cm, the daily efficiency declined from 55.91% to 51.56%. At lower initial depths, the thermal heat capacity is low which facilitates better rate of temperature rise, hence improves the daily productivity.

The validation of experimental values were performed by comparing the efficiencies with the theoretical energy balance equations. The energy balance equations from the literature [33] were utilized to predict the temperatures of both tray and condensate cover. The thermal efficiency of the still is the ratio of the energy required to evaporate the daily distillate output to the energy received from the sun for a given period of time. These predicted temperatures were then used to calculate the evaporative heat transfer coefficient and hence the theoretical efficiency. Likewise, the daily efficiency of the still was calculated using the experimental temperature values. Theoretical efficiency of the stepped still was compared with the actual efficiency as shown in Figure 12. Both the theoretical and daily efficiencies followed similar trends. The theoretical efficiency values of the stepped still support the experimental findings explained in this work. The percentage change between the theoretical and actual efficiency is less than 6%. The daily efficiency improved with the addition of feed water quantity, whereas daytime efficiency declined with the increase in initial depth of water. From Figure 13, it can be recorded that the addition of nocturnal yield improved the efficiency of the stepped still.

Daily Cumulative Yield

The daily cumulative yield without feed water addition for $dw_{0.5}$, $dw_{1.0}$ and $dw_{1.5}$ are 5290 ml, 5140 ml and 4800 ml respectively. The daily cumulative yield is the sum of daytime cumulative yield and nocturnal cumulative yield. The daily cumulative yield without feed water addition for an initial depth of 0.5 cm is 3% and 10.2% greater than that of initial depth of 1.0 cm and 1.5 cm respectively as shown in Figure 14. The nocturnal yield produced for $dw_{0.5}$, $dw_{1.0}$ and $dw_{1.5}$ were 30 ml, 80 ml and 260 ml respectively. Despite

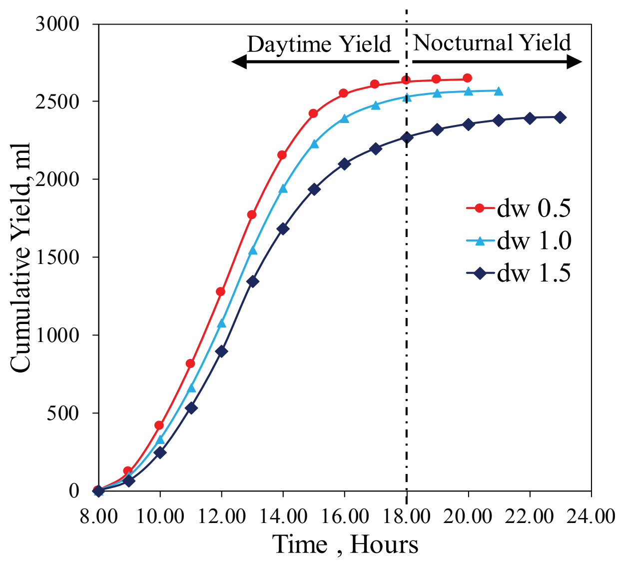


Figure 14. Daily cumulative yield for initial water depth of 0.5 cm, 1.0 cm and 1.5 cm without feed water inlet.

the prolonged nocturnal yields observed with deeper water depths, the cumulative daily yield for $dw_{0.5}$ was 3% and 10.2% higher than $dw_{1.0}$ and $dw_{1.5}$, respectively.

With the addition of feed water into the trays, there was an improvement in the daytime and nocturnal productivity of the stepped still as shown in Figure 15(a-c). Three different depths of water exhibited a uniform trend, wherein the nocturnal productivity increased in correlation with the augmentation of feed water quantity. With the feed water addition of 100 ml and 200 ml for a depth of 0.5 cm, the daytime yield improved by 1.7% and 2.8% respectively, when compared to no feed water addition. Similarly the nocturnal yield also improved from 30 ml to 60 ml and 190 ml with the addition of 100 ml and 200 ml feed water respectively. With the addition of feed water, the daily yield improved in comparison to no feed water addition.

For each initial water depth, the maximum cumulative yield has achieved when 200 ml of feed water was added, followed by 100 ml and 0 ml. Adding 100 ml per tray to 0.5 cm, 1.0 cm and 1.5 cm water depth improved the day time yield by 1.7%, 0.8% and 1.7% respectively, compared to no feed water addition. Similarly for 200 ml feed water addition per tray to an initial depth of 0.5 cm, 1.0 cm and 1.5 cm improved the day time yield by 2.8%, 2.7% and 3.5% respectively. The nocturnal productivity for $dw_{0.5\text{-}100}$, $dw_{1.0\text{-}100}$, and $dw_{1.5\text{-}100}$ with 100 ml water addition improved by 60 ml/m²/day, 170

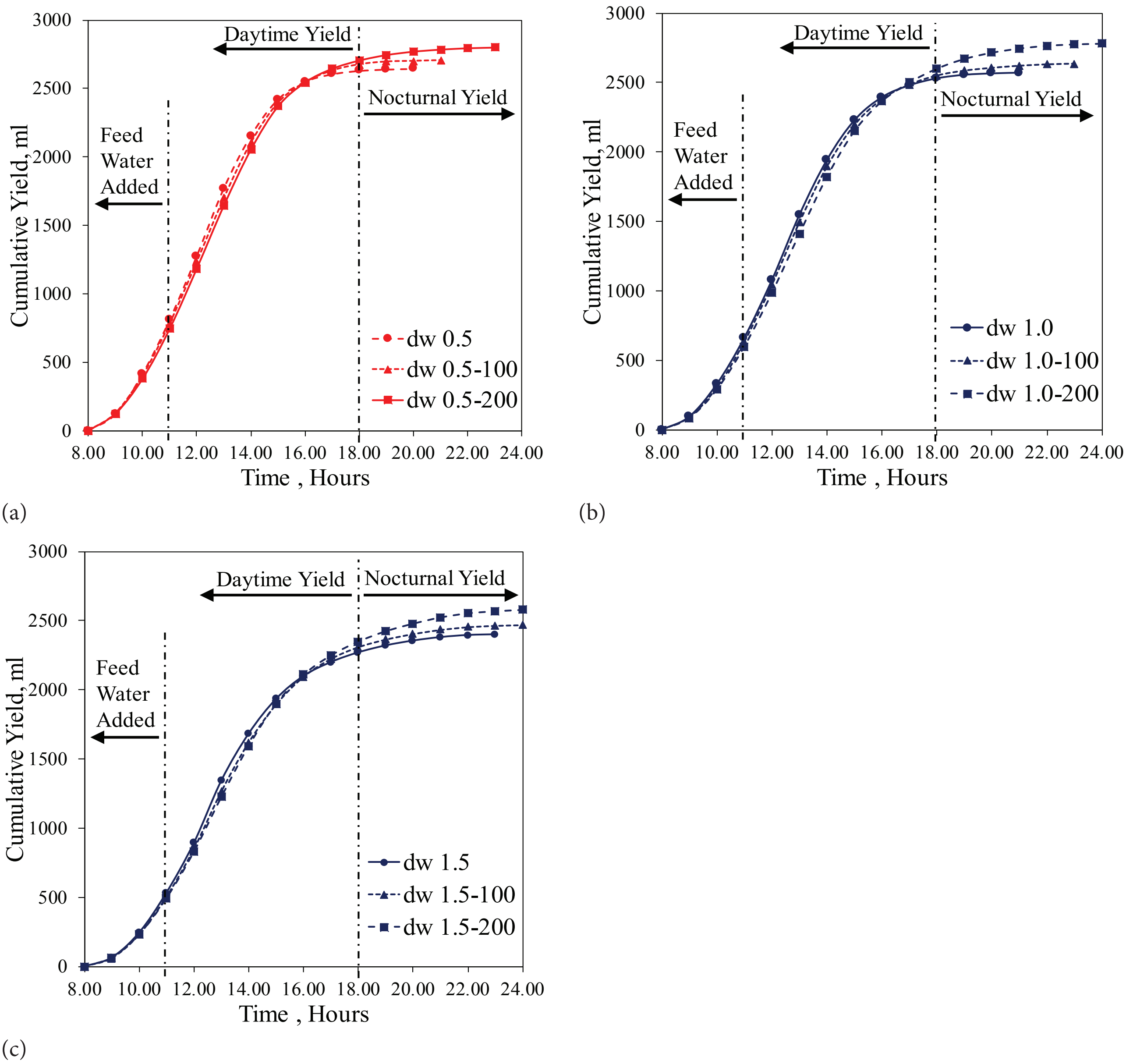


Figure 15. Daily cumulative yield for initial water depth of (a) 0.5 cm, (b) 1.0 cm and (c) 1.5 cm with an input feed water of 100 and 200 ml.

ml/m²/day, 320 ml/m²/day respectively. Similarly for $dw_{0.5-200}$, $dw_{1.0-200}$, and $dw_{1.5-200}$ with 200 ml feed water addition the nocturnal yield improved by 190 ml/m²/day, 360 ml/m²/day and 460 ml/m²/day respectively. Compared to the condition of no feed water addition, the nocturnal yield improved by 100%, 112.5% and 23% for $dw_{0.5-100}$, $dw_{1.0-100}$, and $dw_{1.5-100}$ respectively. While for 200 ml feed water addition, the nocturnal yield improved by 530%, 350% and 77% respectively for $dw_{0.5-200}$, $dw_{1.0-200}$, and $dw_{1.5-200}$.

The stepped still with minimum initial depth of 0.5 cm and maximum feed water inlet of 200 ml per tray produced the highest distillate output of 5600 ml/m²/day. Lowest productivity of 4800 ml/m²/day was produced by the still having the maximum initial depth of water 1.5 cm and when no feed water was added. Low initial depth of water during the commencement of experiment improved the temperature rise due to the low volume of water in the trays. Gradual addition of feed water into the trays in an hourly manner augmented the water in the trays without compromising much on the temperature rise of water. The increased volume of water in the trays aggravated the energy stored in the form of sensible heat, which again improved the

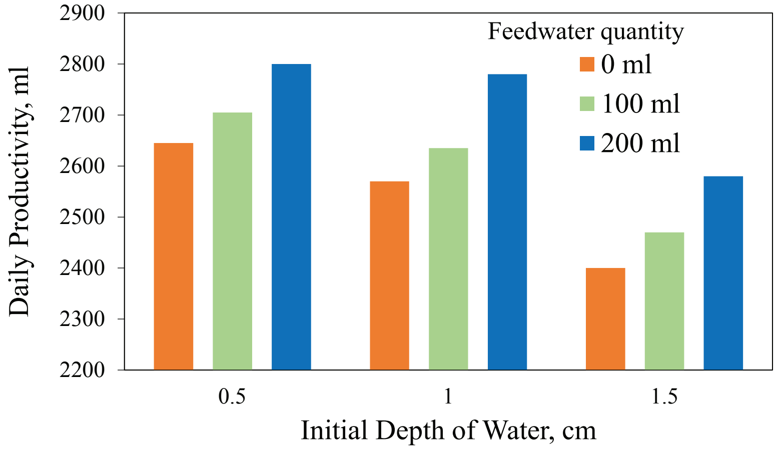


Figure16. Daily distillate output for water depth of 0.5 cm, 1.0 cm and 1.5 cm with different feed water inlets of 0, 100 and 200 ml.

Table 5. Comparison of cumulative daily yield of various solar stills with different heat storage elements reported in literature

Sl. No.	Still Type	Energy Storage Material	Specific Heat Capacity (J/Kg°C)	Yield (ml/m²/day)
1	Inclined stepped still [10]	Copper scraps	398	4890
2	Stepped still [11]	Aluminum fillings	900 [52]	5400
3	Stepped still [13]	Fins	460	8900
4	Pyramid solar still [43]	Palmately leaf -Natural fibers	-	5160
5	Stepped double slope [44]	Linen wicks	-	3260
6	Conventional still with V-shaped floating wicks[41]	Black jute cloth	-	6200
7	Stepped concave trays [7]	Sand	830	3780
8	Stepped still [6]	Black sand	830	5750
9	Trays solar still [45]	Black sand	830	5650
10	Conventional still [46]	Fine basalt stones	1230	1075
11	Conventional still [47]	Pumice stones	870	2000
12	Conventional still with preheating [39]	Coarse aggregate	860	4210
13	Stepped concave trays [7]	Concrete pieces	1000	4060
14	Stepped concave trays [7]	Brick	800	3650
15	Proposed work-stepped extended type trays	Water	4179	6330
16	Stepped Still – 120 mm wide tray (extended type) [25]	Water	4179.6	5630
17	Stepped Still – 120 mm wide tray (extended type) [26]	Saline Water	4190	5840
18	Stepped Still – 120 mm wide tray (extended type) with mirrors [26]	Saline Water	4190	6350
19	Inclined stepped Copper Trays [40]	Water	4179.6	4383

nocturnal output. This implies that with the minimum initial depth of 0.5 cm and maximum feed water input of 200 ml improved both the daytime and nocturnal productivity as seen in Figure 16.

As seen from Table 5, different types of heat sensible materials were used in designs of still to improve its productivity. The daily productivity of the stepped still with initial depth of water 0.5 cm and 400 ml feed water addition was 6330 ml.

Economic analysis of freshwater

The projected area of the stepped still is 0.5 m^2, and the cost parameters considered for the economic analysis is provided in Table 6. The capital recovery factor of the solar still depends on the initial investment made and its changing value of money during its lifetime. Considering the monsoons of Kerala, it is forecasted to receive 300 sunlight days, and the average productivity of the still to be 3000 ml.

It is speculated that, aside from the scrap value of the GI trays, no other material used have some value at the end of 6 years. The Salvage value of the still is considered as the scrap value of the trays used, and is taken as 30% of its initial value. The annual maintenance cost shall include the purchase of paint, sawdust and sealing material and shall be accounted for 15% of the initial annual cost. The total annual cost is given by [48],

$$TAC = IIF + AMC - ASV \tag{12}$$

Cost analysis and comparison studies by [48], indicated that the cost per liter of water produced using still desalination techniques is between 0.0066$ and 0.2696$. The market rate of drinking water in India is expected between 0.12$ and 0.24$, considering the dollar exchange rate to be 0.012$/INR.

An economic comparative study was performed to analyze the cost of water produced from different types of stills and is presented in Table 7. From Table 7, the stills having longer salvage period and lower investment costs produced water at a lower price. The CPL for stills using sand as energy storage material is 0.016$ [6] and 0.015$ [45], while in this study the CPL is 0.013$. When no heat storage materials were used the CPL stood slightly higher at 0.021$ [23] and 0.047$ [40]. Even with the addition of fins and pebbles to a stepped tray for treating effluent water with a CPL of $0.32 [49], there was no decrease observed in the CPL. Even though [22] had lesser daily yield compared to this work, the CPL is only 0.01$/L, due to higher absorber area of the trays, higher solar radiation intensity, higher ambient temperatures, more days of working and longer salvage period.

Considering the hot and wet climates of Kerala, and the material used for the construction of the still box, the salvage period was fixed at 6 year. The low salvage period of the still box had an impact on the price of water produced. Despite of this, the cost of water produced is less than 10% of the market price prevailing in the region. The current market price of bottled water is Rs.20, while the distilled water produced in this study is only Rs 1.08.

CONCLUSION

An extended type stepped solar still was tested with different initial depths of water and various feed water inputs to identify the influence of sensible heat storage capacity

Table 6. Cost Analysis Parameters [50,51] [There is no table legends comprise of referrals to other articles. So the written permission is not required in this case.]

1	**Input Parameters considered**		
1.1	Asset Cost	P	Rs. 8837.5
1.2	Salvage Cost (30 % of tray material cost)	S	281.25
1.3	Period of operation	n	6 years
1.4	Bank Interest Rate	i	8%
1.5	Production Days Annually	d	300 days
1.6	Mean Annual Distillate Productivity	M	900 litres
2	**Parameters Calculated**		
2.1	Capital Recovery Factor	CRF	0.22
2.2	Sinking Fund Factor	SFF	0.14
2.3	Initial investment for first year	IIF	1944.25
2.4	Annual Maintenance Cost	AMC	Rs. 291.64
2.5	First Annual Salvage Value	ASV	Rs. 1237.25
2.6	Total Annual Cost	TAC	Rs. 998.64
2.7	Cost of Water per litre	CPL	Rs. 1.11/ Litre

Table 7. Economic analysis of different designs of stills

Sl. No.	Still Type	Energy Storage Material	Total Fixed Cost ($)	Salvage Period (years)	Days of productivity per year	Yield ($ml/m^2/day$)	Cost of water per liter ($/L)
1	Stepped Still [Present work]	Water	106.05	6	300	6330	0.013
2	Stepped Still [6]	Black Sand	187	20	340	5750	0.016
3	Inclined Stepped Solar Still [40]	Nil	1200	10	340	4383	0.047
4	Tray Solar Still [45]	Black Sand	157	20	340	5650	0.015
5	Tray Solar Still [23]	Nil	154	10	340	4800	0.021
6	Multi-tray evaporator still [22]	Nil	85.47	10	340	5820	0.01
7	Stepped Double Slope [44]	Linen Wicks	89	10	270	3260	0.0221
8	Stepped Still with Fins [49]	Pebbles	160	-	-	1370	0.32
9	Pyramid Solar Still [43]	Palmately leaf -Natural Fibers	865	10	-	5160	0.081
10	Conventional Still [46]	Fine Basalt stones	275	10	340	1075	0.017
11	Conventional still with V-shaped floating wicks [41]	Black Jute Cloth	129.41	10	250	6200	0.022
12	Conventional Still with preheating [39]	Coarse aggregate	147.12	10	-	4210	0.0618

of water in the trays. These following conclusions were derived from the experiments conducted:

1. In the stepped stills, with no feed water addition an increase in the initial depth of water results in the decrease of distillate output. As the initial depth of water increased from 0.5cm to 1.0cm and 1.0cm to 1.5cm, the productivity decreased by 3% and 7% respectively.
2. The addition of feed water led to a significant improvement in daily distillate production. Notably, adding 400 ml of feed water to an initial water depth of 0.5 cm resulted in a 19.7% increase in yield.
3. Increasing the quantity of feed water added resulted in a nearly twofold increase in nocturnal yield.
4. The highest distillate yield of 6330 $ml/m^2/day$, was produced for 0.5 cm initial depth of water and 400 ml feed water addition per tray for the stepped solar still.
5. The daily efficiency of the still improved with the addition of feed water, reaching a maximum efficiency of 66.45%.

NOMENCLATURE

A_t	Total area of the tray, m^2
B	Average number of observations
C_{pb}	Specific heat of basin in solar still (J/kg °C)
C_{pg}	Specific heat of glass in solar still (J/kg °C)
C_{pw}	Specific heat of water in solar still (J/kg °C)
dw	Initial depth of water, cm
$dw_{x\text{-}y}$	x gives the initial depth of water (cm) and y the quantity of feed water added per tray, ml
h_{cnv}	Convective heat transfer coefficient between water and glass, $W/m^2{}^\circ C$
h_{evp}	Evaporative heat transfer coefficient, $W/m^2{}^\circ C$
h_{tbw}	Total heat transfer coefficient between basin and water, $W/m^2{}^\circ C$
h_{tga}	Total heat transfer coefficient between glass and ambient, $W/m^2{}^\circ C$
h_{twg}	Total heat transfer coefficient between water and glass, $W/m^2{}^\circ C$
I(t)	Solar radiation intensity, W/m^2
$I_b(t)$	Fraction of solar radiation intensity absorbed by basin, W/m^2
$I_g(t)$	Fraction of solar radiation intensity absorbed by glass, W/m^2
$I_w(t)$	Fraction of solar radiation intensity absorbed by water, W/m^2
IIF	Initial investment for first year
L_{ev}	Latent Heat of Vaporization of water, kJ/Kg
m_b	mass of trays (kg)
m_g	mass of glass (kg)
m_s	mass of stored water in the trays (kg)
m_w	Hourly yield, kg
M_w	Cumulative yield, kg
n	Total number of observations
n_o	Number of observations in one set
P_g	Partial saturated vapor pressures at glass cover temperature (N/m^2)
P_w	Partial saturated vapor pressure at a basin water temperature (N/m^2)
t	Time interval, seconds
T_a	Ambient Temperature, °C

T_g Temperature of glass cover, °C
T_{sky} Ambient Sky Temperature, °C
T_w Temperature of Water in the trays, °C
U_{ba} Total heat transfer coefficient between basin and ambient, W/m²°C
V_w Wind velocity, m/sec

Greek symbols
η Hourly thermal efficiency of the still
ε_{eff} Effective emissivity between water surface and glass cover
ε_g Emissivity of glass cover

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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