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Optimizing solar distillation to meet water demand for small and rural communities

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ABSTRACT

The demand of freshwater is constantly increasing due to population growth. Desalination, the process of converting salt water to freshwater, is a common technology. This study investigates the effect of different parameters on the potable water productivity of solar still under the climatic condition of Zagazig, Egypt in order to determine the numerical parameters and to be used for design of solar still for small and rural communities. The impact of varying water depths (2–12 cm), salinities (2,500–12,000 ppm) and angles of inclination (20°–40°) on the performance of the still were examined. The results showed that productivity of the solar still increases with decreasing water depth and salinity of water, while increasing the cover angle in winter enhances productivity and efficiency. The still produced water suitable for drinking and met World Health Organization standards with removal efficiency of 99.5% and 99.9% for total dissolved solids (TDS) and chloride for seawater. The study also includes a theoretical study that predicts the thermal behavior of the still and the predicted results were compared with the experimental results. Results show that there are slight differences between the experimental and predicted outputs within the acceptable range. Finally, seawater with total dissolved solids of 33,000 and 2,500 ppm was tested using the optimum conditions of the experimental work and the results showed a good agreement with synthetic water and also with the theoretical results. The maximum daily output was recorded as 850 mL/m^2 per 10 h for 2,500 ppm unfiltered seawater, 800 mL/m^2 per 10 h for 33,000 ppm unfiltered seawater, 790 mL/m^2 per 10 h for 2,500 ppm filtered seawater, 304 mL/m^2 per 10 h for 33,000 ppm filtered seawater. The maximum daily output was recorded as 710 mL/m^2 per 10 h for synthetic water of TDS of 2,500 ppm. The economic analysis revealed that solar still is cheaper than market water with a cost of 0.08142 $/L. The obtained results are of particular importance for small and rural communities, as they can be used to design simple solar still unit that does not require preliminary or post-treatment steps, with low operating and maintenance costs, and moreover does not require skilled labor.

Keywords: Desalination; Distillation; Solar still; Solar energy; Salinity

1. Introduction

Water is essential for life for all living things on the earth. Clean water is used for domestic, industrial and agricultural purposes. However, clean and safe drinking water is scarce in many regions around the world, especially in dry regions such as deserts and remote areas such as islands. These places often lack the means to purify or desalinate water and the cost of transportation is high [1]. More than a billion people around the world suffer from a scarcity

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of drinking water of acceptable quality [2]. Around 79% of water in the earth is saline water that require removal of salts. Desalination, the process of removing dissolved solids from seawater and brackish water, is a solution [3].

There are at least three main methods of desalination: thermal, pressure and electrical. The problem of these methods is they are expensive methods and also unfriendly to the environment. About 3.0 kg of CO_2 is produced to produce 1.0 m^3 of water by reverse osmosis (RO) plant using fossil fuel (oil) [2]. One potential solution is solar distillation, which uses solar energy to produce potable water. Solar still is a thermal desalination method that use solar energy to produce potable water. It is a practical solution for the production of potable water for locations where solar intensity is high and there is a lower availability in freshwater. This method is cost-effective for water distillation because it depends on solar energy which is clean and free. Moreover, solar stills are simple in design and simple in operation. In addition, there are no movable parts in solar stills which reduces maintenances and it can be transported easily to remote and poor locations [4].

There are many designs for solar stills, but the single slope solar still is the simplest in terms of design, construction, and modelling to compute the energy balance equation of components. The main drawback of solar still is its lower productivity and also the efficiency is very small. Akram et al. [5] designed and constructed a single slope solar still of 0.5 m^2 basin area and found that efficiency of the still was 26.32%. Several experiments have been carried out to improve the productivity and performance of solar stills. Omara and Kabeel [6] used sand beds as heat storage to increase the amount of distilled water, resulting in an improved output at a 0.01 m depth of sand bed. Also, Kabeel et al. [7] improved the performance of conventional solar stills using cement coated red bricks. They found that there is an increase in water temperature of about 34% which acts as driving force for water distillation. Attia et al. [8] enhanced the distilled freshwater production of traditional solar still using aluminium balls of 2.0 cm diameter and they found that distillation output increased by 27.16%. Attia [9] integrated a system that consists of solar collector (parabolic dish concentrator type with spherical tank (boiling bubble) in its focal point), pressure tank and RO module. The pressure resulting from the evaporation of fluid inside the boiling bubble led to push salt water into RO module. The productivity reached to 1.833 $m^3/m^2{\cdot}d$ for brackish water and 0.055 $m^3/m^2{\cdot}d$ for seawater. Mashaly et al. [10] assessed the efficiency of a solar desalination system (solar-still panel) to achieve nearly zero liquid discharge (ZLD) using three different types of feedwater. The ZLD process takes two important environmental problems for desalination plants into account: creating potable water and salt while reusing the concentrated brine effluent from desalination units, which eliminates the requirement for disposal (zero discharge). Shukla and Modi [11] examined a hybrid double basin solar still as both a co-generative and desalination system. The upper basin used a mixture of 40% concentrated calcium chloride and 33% concentrated magnesium chloride as a co-generative system, while the lower basin used saline water with a depth of 0.01 m and 0.10% concentration of zinc oxide nanoparticles as a co-generative system. In a desalination experiment, saline water depth of 0.01 m was used without nanoparticles. The daily average overall efficiency was 29.96% and 11.65% when used as both a co-generation and desalination system.

Solar stills are classified as direct (passive) and indirect (active). Direct solar stills collect solar energy directly where indirect solar stills use an additional heat source [12]. Direct solar stills are simple in design and construction, easy to operate, and usually small and cheap [13]. The main drawback of this type is its lower productivity. There are many examples of indirect solar stills such as solar still attached with flat plate or evacuated tube collectors (ETC), parabolic concentrator, heat pipe and hybrid systems such as: multistage active solar distillation system and multi-effect active solar distillation system [13]. One of the advantages of this type is its higher productivity. Solar stills consist of a shallow or deep basin and transparent glass cover. The sun's rays penetrate the inclined transparent glass cover and heat water inside basin. The vapor reaches to glass cover and condense on it then the condensed water flow down into collection through [1].

The performance of the solar stills is affected by various factors such as design, operational, and climatic conditions such as, water depth, basin materials, glass angle of cover, salinity of water, temperature difference between water and glass, and absorber area [14]. The effect of glass cover inclination on conventional solar still was studied by El-Maghlany et al. [15] and they found that the best glass cover inclination angle can improve still productivity by up to 22.3%. Tripathi and Tiwari [16] studied the effects of water depth in solar stills on the heat and mass transfer coefficients for passive and active system and found that distillate output decreased significantly with increasing water depth in the basin. Active solar distillation systems have been found to produce more output than passive solar stills due to the higher temperature difference between water and glass cover [17]. Arjunan et al. [14] conducted an experimental study to investigate the effect of water depth (10–60 mm) and found that 20 mm provides the optimum productivity. The effect of salinity of water on distillate productivity was studied by Akash et al. [18] who found that productivity decreases with increasing salt concentration. It is important to note that while it is impossible to control the salinity of seawater, appropriate still maintenance, such as cleaning the still on a regular basis, can significantly reduce the salinity. The performance of solar still can also be studied by numerical analysis by solving the energy balance equations of different elements of the system. Many studies have been carried out using computational fluid dynamics (CFD) simulations and MATLAB [13]. A numerical study of the performance of the solar still with film cooling parameters was introduced by Mousa and Abu-Hijleh [19] who reported that the efficiency of the still increased by 20% in the numerical study with the use of water film cooling. Abdenacer and Nafila [20] carried out a numerical analysis to study the effect of temperature difference between the basin water and the glass cover, and found that efficiency increases with the increase of temperature difference.

This study aims to find a low-cost system that produce freshwater for small and remote regions and also serves as an alternative to the widely used RO systems. This study investigates the effect of water depth, salt concentration and angle of inclination on the productivity of a single slope passive solar still under the climatic condition of Zagazig, Egypt in order to determine the best operating technique for producing drinking water for the population of arid regions. Some parameters of produced water are measured for both seawater and synthetic water and compared to World Health Organization standards. The present results are validated against previous studies to check the accuracy of results. A numerical analysis is also conducted to compare the actual results with predicted results. Finally, a cost analysis is conducted to compare cost of the solar still with previous studies. Therefore, the main aim of this study was to determine the optimum operating conditions of the solar still unit and to determine the numerical parameters and to be used for design of solar still for small and rural communities.

2. Experimental set-up and measurements

2.1. Experimental program

The experiments were conducted using two identical conventional single slope solar still tanks (A and B) as shown in Fig. 1 Tank A served as a control unit while tank B was used to study the effect of various parameters on the still production. They were constructed and fabricated at the faculty of engineering, Zagazig university, located at a latitude angle of 30.5884° N and 31.4832° E. The still basin dimensions were 1.0 m in length and 0.5 m in width, with a net area of 0.5 m^2. Both solar stills were constructed using 1.4 mm thick galvanized steel sheets. The outside surface of the basin were coated with black paint to increase solar radiation absorption while the inner basin surfaces were coated with white paint to improve reflectivity. The lower vertical side of the still was 54 cm, and the higher vertical side was 100 cm. The tank was covered with 3.0 mm thick plexiglass, which was fixed on the top of the solar still with a wooden frame. Silicone sealant was used to prevent vapor leakage. Silicon sealant can be easily removed for maintenance purpose. The glass cover was oriented in an east–west direction to obtain the maximum energy as possible during all experiments. The distilled water was collected in a channel fixed at the lower end of the cover and taken out through a PVC pipe. A storage tank with a capacity 120 L was used for storing saline water. Three holes of 0.5 inches in diameter were provided to each tank. The first hole was used to allow raw water to enter the tank, the second hole was used to let the distilled water flow into the measurable bottle and the third one was for water drainage. The amount of distilled water was returned at the end of each day to the tank to maintain a constant water level inside the tank every day. The main advantages of the methodology are: no pretreatment before distillation, less maintenance, no post treatment after the distillation and easy in measuring results.

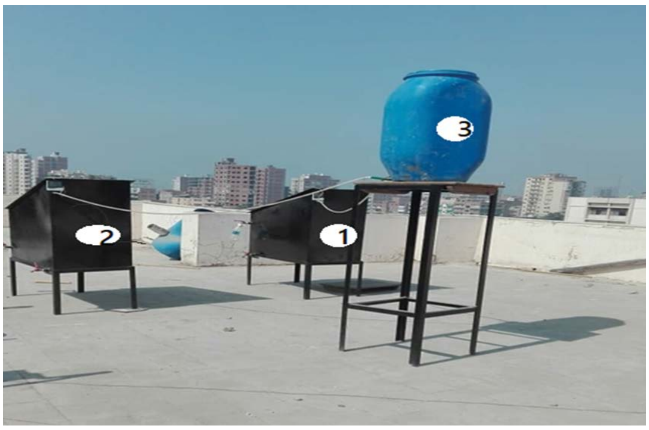

Fig. 1. Photograph of single slope solar still (1-tank(A), 2-tank(B), 3-storage tank).

To study the effect of water depth, brine water of 2–12 cm was used, which corresponds to 10 and 60 L of saline water. The experiments were carried out for 5 d using a synthetic saline solution made in the laboratory by adding sodium chloride, magnesium sulfate and potassium bicarbonate with an approximate total dissolved solids (TDS) of 5,000 ppm and an angle of inclination of 20° for tank B for each water amount. Tank A, which served as the control tank, had a constant water depth of 2 cm, a salt content of 5,000 ppm, and an angle of inclination of 20° throughout the study. The effects of salt concentration on freshwater production by a solar still were studied in this experiment. Synthetic solutions with a range of TDS between 2,500 to12,000 ppm were used. Experiments were conducted using the optimal water depth determined in experiment 1 and a cover tilt of 20°. For each TDS level, the setup was run for 5 d. TDS tests were performed before and after each trial to measure the efficiency of the solar still in purifying the water. The optimal TDS level was determined and used as a constant in further studies.

The angle of inclination of the inclined cover of a solar still can affect its productivity. In this study, the optimized water depth and salt concentration from previous experiments were used and the angle of the cover of tank B was varied from 20° to 40°. The experiment was performed for 5 d for each angle. The experiments were conducted from November 2021 to February 2022 and for 8 h from 8 AM to 4 PM of direct operation under solar radiation and then 16 h of indirect operation from 4 PM to 8 AM of the following day. Ambient temperature was recorded during direct operation and the accumulation of distilled water was recorded for both direct and indirect operation. The daily productivity was calculated as the sum of these two recordings. Energy balance equations were used to predict the performance of the solar still and the results were compared to the experimental results under optimal conditions. An experiment was conducted on March 2022 for 10 h (8 AM–6 PM) with a synthetic water of 2,500 ppm under the optimal conditions of the previous experiments and the results were compared to predicted results. To evaluate the effectiveness of the solar still using real conditions, seawater with a TDS of 33,000 ppm was collected from the Mediterranean Sea and used in four runs of experiments, with both filtered and unfiltered seawater and salt concentrations of 33,000 and 2,500 ppm. Dilution was used to achieve a salt content of 2,500 ppm by adding distilled water to the seawater. The experiments were run for 4 d in March 2022 from 8 AM to 6 PM using the optimum results from the previous experiments.

2.2. Measurements and instruments

The temperature and TDS were measured using calibrated ADWA instrument, which was integrated with an AD70030 with a range from 0 to 20,000 µS/cm. TDS ranges from 0 to 10 ppt and the temperature ranges from 0°C to 60°C. The volume of distilled water produced was measured using a 100 mL graduated flask with an accuracy of 1.0 mL. The accumulated production during 24 h was also measured in each experiment. The pH was measured using calibrated ADWA instrument, which ranges from –2 to 16 pH.

3. Theoretical analysis of solar still

Dunkle's 1961 study was the first to examine the relationship between heat and mass transfer in a solar still [21]. Fig. 2 illustrates the overall heat transfer process in a single-slope solar still. The theoretical model was developed based on ideal conditions of the experimental work. The input parameters used in the theoretical simulation are summarized in Table 1.

In order to calculate the daily productivity of condensed water, the energy balance method was applied under the following assumptions:

- The still is in quasi-steady state.
- No leakage of vapor- in solar still.
- Temperature gradients in water are neglected.
- Heat capacity of absorbing materials, glass cover and basin liner are neglected.
- Wind velocity is assumed to be constant.
- Temperatures are assumed constant in 1 h interval of time.
- Basin water depth is constant.

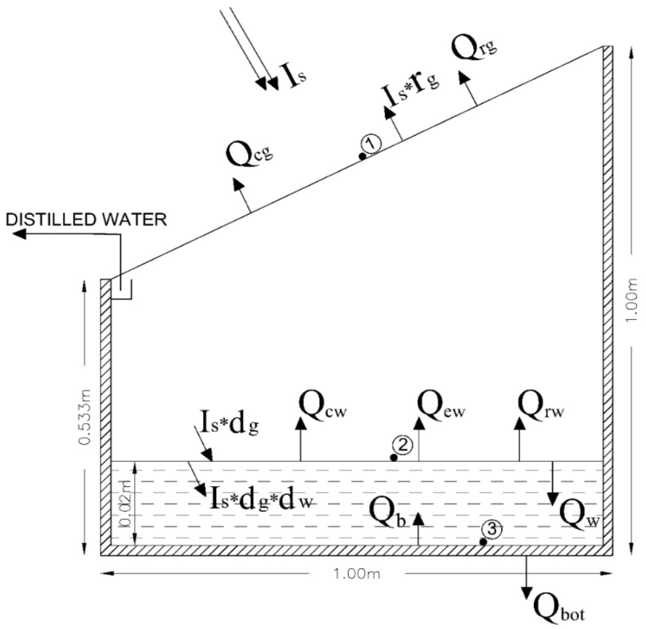

Fig. 2. Energy components of single slope solar still (1-incliclined cover, 2-water interface, 3-basin liner).

The sill balance equation of inclined cover is written as follows [3,14]:

$$I_s A_g + Q_{ew} + Q_{rw} + Q_{cw} = I_s r_g A_g + I_s d_g A_g + Q_{rg} + Q_{cg} \quad (1) \text{ [J/S]}$$

where I_s is solar radiation, A_g is area of glass cover, r_g is reflectivity of glass cover and d_g is transmissivity of glass cover.

$$A_g = A_b \cos\theta \quad (2)$$

θ is angle of inclination of cover.
where A_b is the basin area. The radiative heat transfer from inclined cover of the still to atmosphere can be expressed as [14]:

$$Q_{rg} = h_{rg} A_g \left[T_g - T_a\right] \quad (3)$$

where T_g is the glass temperature and T_a is the ambient temperature in K° and h_{rg} is radiative heat transfer coefficient from glass to atmosphere that given by the following formula [3,13,14,22]:

$$h_{rg} = \varepsilon_g \sigma \left(T_g^2 + T_a^2\right)\left(T_g + T_a\right) \quad (4)$$

where ε_g is emissivity of glass cover and σ is Boltzmann constant = 5.6697 × 10^{-8} W/m²·K⁴. The connective heat transfer from glass to atmosphere can described as [3,13,14]:

$$Q_{cg} = h_{cg} A_g \left(T_g - T_a\right) \quad (5)$$

where h_{c9} is connective heat transfer from glass to atmosphere that described as [1,3,12,13,23]:

$$h_{cg} = 5.7 + 3.8w \quad (6)$$

Table 1
Parameters employed in the theoretical simulation

Parameters	Value
Angle of inclination of cover θ	25°
Basin area, A_b, A_w	0.5 m²
Mass of water, M_w	10 kg
Heat capacity of water, C_w	4,184 J/kg·K
Boltzmann constant, σ	5.6697 × 10^{-8} W/m²·K⁴
Emissivity of cover, ε_g	0.89
Emissivity of water, ε_w	0.96
Transmissivity of glass, d_g	0.92
Reflectivity of basin, r_b	0.9
Reflectivity of glass, r_g	0.08
Reflectivity of water, r_w	0.1
Transmissivity of water, d_w	0.9
Thickness of plate, L_1	1.4 mm
Thermal conductivity of plate, k_1	0.7 W/m·K

where connective coefficient depend on wind speed, W (m/s). The evaporative heat transfer from water to glass is formulated as [14]:

$$Q_{ew} = A_w h_{ew} \left(T_w - T_g\right) \quad (7)$$

where A_w is surface water area, h_{ew} is evaporative heat transfer coefficient from water to glass. Radiative heat transfer from water to glass is defined as [14]:

$$Q_{rw} = A_w h_{rw} \left(T_w - T_g\right) \quad (8)$$

where h_{rw} is a radiative heat transfer coefficient from water to glass that given by following formula [14,23]:

$$h_{rw} = \varepsilon_{eff} \sigma \left(T_w^2 + T_g^2\right)\left(T_w + T_g\right) \quad (9)$$

where ε_{eff} is water emissivity. The connective heat transfer from water to glass is [14]:

$$Q_{cw} = h_{cw} A_w \left(T_w - T_g\right) \quad (10)$$

where h_{cw} is connective heat transfer coefficient from water to glass that given by [12,13,21,23]:

$$h_{cw} = 0.884\left[T_w - T_g + \frac{p_w - p_g}{268900 - p_w} T_w\right]^{\frac{1}{3}} \quad (11)$$

where p is the partial pressure of air inside the still in N/m^2. It is defined as [12]:

$$P = e^{25.317} - \frac{5144}{T} \quad (12)$$

By substituting in Eq. (1):

$$T_g = \frac{h_1 A_w T_w + h_2 A_g T_a}{h_1 A_w + h_2 A_g} \quad (13)$$

where h_1 is the overall heat transfer from water to glass and h_2 is the overall heat transfer from glass to atmosphere.

The still balance equation of basin is written as follows [3,14]:

$$I_s d_g d_w A_w + Q_w = I_s d_g d_w r_b A_b + Q_b + Q_{bot} \quad (14) \text{ [J/s]}$$

where r_b is reflectivity of plate and Q_w is connective heat transfer from water to plate and can be neglected as small depth of water. Q_{bot} is connective heat transfer from plate to atmosphere and can be defined as [5,13]:

$$Q_{bot} = U_{bot} A_b \left(T_b - T_a\right) \quad (15)$$

where U_{bot} is the overall heat transfer coefficient from plate to atmosphere and defined by [24]:

$$U_{bot} = \frac{1}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{1}{h_{c-I_0}}} \quad (16)$$

where L_1 is thickness of plate, L_2 is thickness of insulation, k_1 is thermal conductivity of plate, k_2 is thermal conductivity of insulation, h_{c-I_0} is connective heat transfer coefficient from insulation to atmosphere.

The still balance equation of water surface is written as follows [3,14]:

$$I_s d_g + Q_b + C_w \frac{\partial T_w}{\partial T} m_w = I_s d_g r_w + I_s d_g d_w + Q_{ew} + Q_{rw} + Q_{cw} \quad (17) \text{ [J/s]}$$

where C_w is heat capacity of water, r_w is reflectivity of water, d_w is transmissivity of water. The connective heat transfer from plate to water surface is defined as [14]:

$$Q_b = h_b A_b \left(T_b - T_w\right) \quad (18)$$

where T_b is basin temperature in K°, h_b is connective heat transfer coefficient from plate to water that given by [24]:

h_b = 200 W/m^2·K

By substituting in Eqs. (14) and (17):

$$\frac{dT_w}{dt} - T_w\left(\frac{h_b A_b + h_1 A_w}{C_w m_w}\right) = -\frac{1}{C_w m_w}\left[h_b A_b T_b + h_1 A_w T_g\right] \quad (19)$$

$$a_1 = \frac{h_b A_b + h_1 A_w}{C_w m_w} \quad (20)$$

$$f_1 = \frac{1}{C_w m_w}\left[h_b A_b T_b + h_1 A_w T_g\right] \quad (21)$$

By substituting from Eqs. (20) and (21) in Eq. (19), it become similar to differential equation format of $dT_w/dt - a_1 \times T_w = -f_1$.

So the solution is $T_{w(t)} = c_1 \times e^{a_1 t} + \frac{f_1}{a_1}$ (22)

for getting c_1, at $t = 0$ $T_w = T_{wi}$

so $c_1 = T_{wi} - \frac{f_1}{a_1}$ (23)

By substituting from Eq. (13) in Eq. (22), it is found that:

$$T_{w(t)} = \frac{f_1}{a_1}\left(1 - e^{-a_1 t}\right) + T_{wi} \times e^{a_1 t} \quad (24)$$

The theoretical hourly yield can be determined from equation [14]:

$$\dot{m} = \frac{h_{ew} A_w \left(T_w - T_g\right) \times 3{,}600}{h_{fg}} \quad (25)$$

where h_{fg} is latent heat of vaporization for water and equal to 2,400 kJ/kg [24].

The climatic conditions of Zagazig city in January–February 2022 during the experiments are shown in Table 2.

4. Economic analysis

Cost estimation is conducted for solar still of the present work of 0.5 m². Table 3 shows the actual cost of the used conventional solar still (CSS) in the current study.

The annual cost (AC) of the studied system can be defined as [25]:

$$AC = CC \times CRF \quad (26)$$

where CC is the first capital cost of the studied system and CRF is the capital recovery factor that can be given as [25]:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \quad (27)$$

where r is the interest rate that can be considered to be 12% and n is the lifetime of the still that assumed to be 10 y.

Total annual cost (TAC) and the annual cost per liter (CPL) are assessed as follows [4]:

$$TAC = AC + AMC \quad (28)$$

where maintenance cost (AMC) is assumed as 15% of the AC as follows [4]:

$$AMC = 15\%Ac \quad (29)$$

Cost per liter (CPL) is calculated as follows [4]:

$$CPL = \frac{TAC}{L} \quad (30)$$

where L is the best annual productivity of the studied work.

5. Results and discussion

Conventional solar still is a type of passive solar still that uses direct sunlight to operate. Its performance is affected by a various factors, which are studied in this research to determine their effect on production and performance. Also, the results of using synthetic water and genuine seawater are compared.

5.1. Effect of water depth

The effect of water depth on solar still productivity was tested at 2, 4, 6, 8, and 12 cm. Fig. 3 shows the relationship between the water productivity and the water depth over 5 d using synthetic water with 5,000 ppm TDS and 20° angle of inclination. The average water yields were 74.8, 50.6, 28.2, 24, and 25.5 mL/d for depths of at 2, 4, 6, 8 and 12 cm, respectively. Fig. 3 demonstrates that water depth affects solar distillation, with the optimal outputs of 87, 58, 35, 30, and 30 mL/d observed on the second day. A 68% decrease in average water production was observed when water depth increased from 2 to 8 cm.

The maximum production on the second day was due to heat storage from first day, while productivity decreased over the next 3 d as the result of water loss in the basin during distilled water return. Distilled output is inversely proportional to the water depth and the lower water depth results in higher water production and vice versa. Sharma et al. [26] reported that distilled output is inversely proportional to the basin water depth, with lower depths resulting in higher water productivity. This can be attributed to differences in water-glass temperature. For smaller water depths, productivity is high in the morning due to a large difference between glass and water temperature. However, productivity decreases after sunset as water and glass temperature decrease, leading to a smaller difference in water-glass temperature. Raj

Table 3
Cost analysis of studied single basin solar still

Item	Cost, $
Basin liner with area of 0.5 m² and 4 vertical walls	50
Glass cover (plexiglass)	50
Saline water storage tank (120 L)	5
Water taps (3-items)	2.5
Silicon sealant	7.5
Metal stands	5
Total capital cost	120

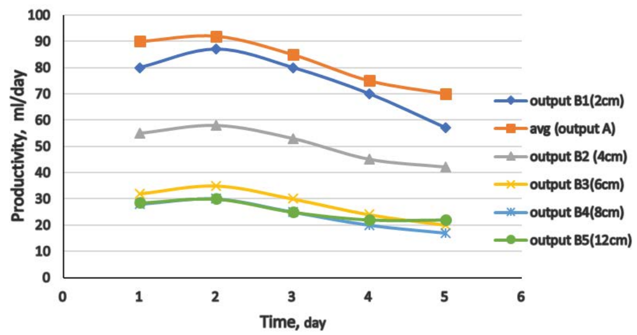

Fig. 3. Variation of daily productivity for different water depth, date from 21-11-2021 to 15-12-2021.

Table 2
Summary of average climatic conditions

Specification	Average solar radiation intensity, W/m²	Average ambient temperature, °C	Average wind speed velocity, m/s
January	3,500	15	3.6
February	4,300	16	3.8

and Manokar [27] noted that water capacity affects internal heat transfer inside the still. For smaller capacities, internal heat transfer from water to glass increases. Sharma et al. [26] also reported that increased natural circulation of air inside the still enhances convective and evaporative heat transfer between the basin water and cover. On the other hand, after sunset, increased basin water depth leads to increased productivity as stored heat is released, raising water temperature and creating a larger difference with falling air temperature. In contrast, in the morning, low water temperature due to its high heat capacity combined with low air temperature results in smaller temperature difference and lower productivity. According to Badran [28], the night production in the absence of solar radiation contributed to 16% of the daily production, so small depths give higher outputs than high depths. As a result of the present study, shallow water depth accumulates temperature faster from incoming solar radiation compared to deeper water depth, leading to earlier evaporation. This was confirmed by Hoque et al. [22] who also found that lower water depth results in higher productivity.

Studies on the impact of water depth on solar still productivity have shown consistent results. Raj and Manokar [27] studied the effect of water depth on a single slope solar still made of galvanized iron and found that lower water depths result in higher productivity from 9.00 AM to 1.00 PM, then decrease until evening. Meanwhile, higher water depths show slow productivity growth from 9.00 AM to 1.00 PM, then steadily increase until the end of the day's experiment. A 12% increase in productivity was observed as the water depth decreased from 60 to 10 mm. Hoque et al. [22] developed a solar still and found that varying the amount of synthetic water in the basin (3, 3.5, 4, and 4.5 L) had an impact on productivity, with the optimum amount found to be 3.5 L.

It can be noted from Fig. 3 that an increase in water depth from 8.0 to 12.0 cm led to approximately equal values of productivity. Al-Hinai et al. [29] recommended that brine water depth should be in the range of 2.0 to 6.0 cm, while Tiwari and Tiwari [30] found that the yield becomes almost constant for depths greater than 10 cm. The maximum output in the present study was 87 mL/d for 0.5 m^2 basin area, lower compared to previous studies (Ahmed and Ibrahim [31] found 2.5–5 L/m^2·d, Cheng et al. [25] found 2.4 L/m^2·d). The lower output in the present study was due to the experiments being conducted in winter and the angle of inclination being less than the latitude of the place. A proportional comparison between the production of tank B and tank A at different water depths was conducted to easily compare the tanks' productivity under different conditions, with the results adjusted to account for atmospheric changes such as rain, clouds, or winds. The results, as shown in Fig. 4, indicate that 2.0 cm water depth is optimal.

5.2. Effect of salts concentration

The effect of water salinity on the still productivity was studied at TDS values of 2,500; 5,000; 7,500; 10,000 and 12,000 ppm. Fig. 5 shows the relationship between the water salinity and the water productivity over 5 d, with 2.0 cm water depth and 20° angle of inclination. The average water yields were 54, 33.6, 28.2, 22.8 and 5.1 mL/d for TDS values of 2,500; 5,000; 7,500; 10,000 and 12,000 ppm, respectively. Fig. 5 reveals that salt concentration influences solar distillation, with highest outputs of 75, 26.5, 26, 21, 9 mL/d for TDS values of 2,500; 5,000; 7,500; 10,000 and 12,000 ppm observed on the second day. The average water production decreases by 90% with an increase in TDS from 2,500 to 12,000 ppm. This occurs because the vapor pressure of saline water is lower than that of pure water and the still's productivity depends on the condensation of water vapor. Thus, an increase in water salinity results in a decrease in vapor pressure and a decrease in still productivity.

The current study confirms that solar distillation efficiency decreases with an increase in water salinity, in agreement with previous studies. Hoque et al. [22] found that water production decreases by 7.28% when TDS increases from 2,000 to 8,000 ppm, due to absorption of solar radiation by the salt in the water, causing the basin water temperature to lower. Samuel et al. [32] found that salts function as "latent heat storage material" with higher heat capacity, leading to lower water temperature and so decreased water productivity. Morad et al. [33] conducted an experiment to investigate the effect of water salinity on productivity of solar still, using ground water, Mediterranean seawater, and Red seawater with varying salinity levels, which resulted in daily productivity values of 5.54, 5.07, and 4.45 L/d, respectively. The experiment showed that the salt concentration in water raises its boiling point due to the clustering of salt molecules and increased water density, reducing the effectiveness of capillary forces in bringing water to the inclined cover. Kalbasi and Esfahani [34] similarly found that daily production

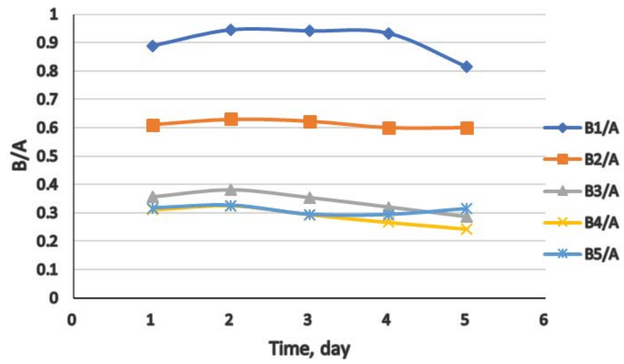

Fig. 4. Comparison in productivity of tanks B and A.

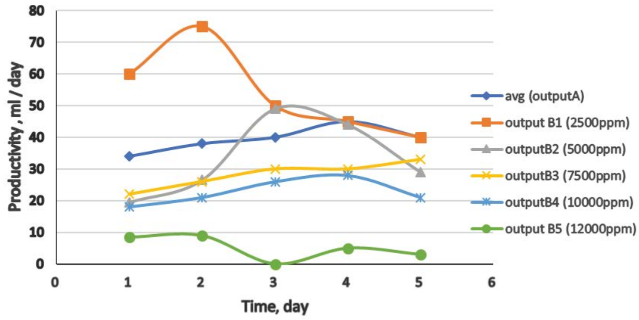

Fig. 5. Variation of water productivity for different water salinity, date from 21-12-2021 to 14-1-2021.

decreases as salinity increases, observing a 20% when the salinity of the water rises from 0% to 3.5%. As shown in Fig. 5, the production of tank B at various salinity concentrations displays a similar pattern, with production increasing on the second day due to stored heat from the first day and then gradually decreasing over the next 3 d. However, there are exceptions to this trend caused by fluctuations in weather conditions such as an increase in temperature, more intense sunshine, and stronger winds, which boost production. On the other hand, precipitation, temperature drops, and clouds coverage result in decreased productivity. The maximum output observed this study was 75 mL/d for 0.5 m^2 basin area, which is lower than previous studies due to the experiments being carried out during winter and the angle of inclination being less than the latitude of the place.

A proportional comparison between the production of tank B and tank A at different salt concentrations was conducted to easily compare the tanks' productivity under different conditions. The results were adjusted to take into account atmospheric changes such as rain, clouds, or winds. As demonstrated in Fig. 6, the results indicate that an optimal salt concentration of 2,500 ppm.

5.3. Effect inclination angle

Effect of inclination angle on the still productivity was studied at 20°, 25°, 30°, 35° and 40°. Fig. 7 displays the relationship between water productivity and inclination angle over 5 d for each angle at 2,500 ppm TDS and 2.0 cm water depth. The average yields of a solar still were 33.6, 316, 278.3, 142, and 176 mL/d at slopes of 20°, 25°, 30°, 35°, and 40°, respectively. The highest yields were 58, 410, 364, 250 and 364 mL/d at 20°, 25°, 30°, 35° and 40° slopes, respectively. The results shown in Fig. 7 indicate that the solar distillation is dependent on the angle of inclination, with optimal productivity observed at 25° on the second day.

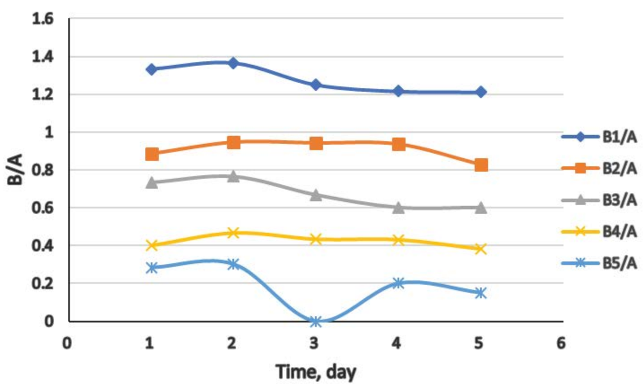

Fig. 6. Comparison in productivity of tanks B and A.

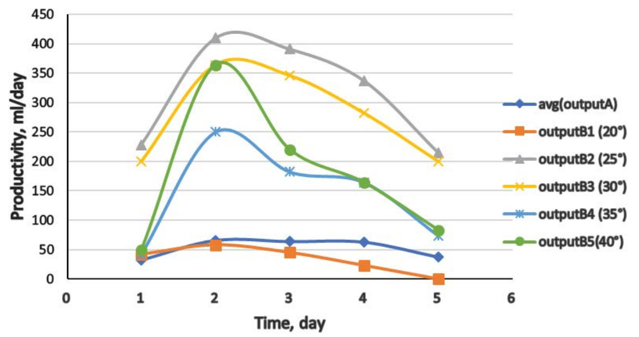

Fig. 7. Variation of water productivity for different inclination angles, date from 24-1-2022 to 17-2-2022.

Increasing the cover angle from 20° to 25° led to an increase in average water production by nine times the value of average water production at 20° as the cover angle approaches the location's latitude (30.5884°). The amount of sun radiation plays a significant role in distillation productivity. Thus, the solar tilt angle is still an important factor to consider, it should be equal to the location's latitude to ensure that maximum solar radiation is received by the inclined cover. This allowing the maximum amount of solar radiation falling on the basin surface [35,36]. The results showed that the second day had the highest water production of 410 mL/d at 25° and the lowest production of 58 mL/d at 20°. The low production at 20° was due the low intensity because the angle is not closer to the latitude angle, and the large gap distance between the glass cover and basin liner, causing condensed water droplets fall into the basin [36].

As the angle of inclination increases from 35° to 40°, the average water productivity increased by 24%. This is in accordance with previous studies that demonstrated that the output of a solar still increases with an increasing in angle of inclination in winter and increases with a decreasing in angle of inclination in summer [17,35,37–39]. This is due to the fact that in winter, the sun's declination angle is negative, while in summer, it is positive. When the angle of inclination decreases in summer, the positive declination angle results in an increase in reflected cover radiation to the basin liner, causing an increase in water temperature and thus water yield. Conversely, when the angle of inclination decreases in winter, the negative declination angle results in a decrease in reflected cover radiation to the basin liner. As a result, increasing the angle of inclination in winter leads to more reflected radiation to the basin liner and an increase in water temperature [29].

Since the current experiments were conducted in winter, so increasing the angle of inclination led to an increase in water productivity. Another reason for this increase could be attributed to the reduction of the, gap distance between the glass cover and basin liner, which allows for a sufficient tilt angle to prevent water droplets from falling into the basin. The inclination angle of 30° gave an output close to maximum output as it equal to latitude of the place. According to Thakur et al. [36], when the sun is higher than the latitude during the summer, the lower angle of solar still will provide the most solar radiation, whereas when the sun is lower than the latitude during the winter, the higher angle will be suitable. Various studies have examined the effect of inclination angle on solar still productivity and reported similar findings. In the month of May, the experiments carried out by Akash et al. [18] at a latitude 31.57°N showed that the angle of inclination of 35° resulted in the highest yield. Singh and Tiwari [40] conducted a numerical analysis and found that the highest yearly distillation occurs when the glass tilt angle is equal to the latitude of the location. As a result, it is suggested that the still should have a glass tilt angle equivalent to the latitude of the location and also it was found that angle of inclination similar to latitude angle of ±10° providing the higher productivity.

The productivity of both tanks (A and B) has the same trend, with productivity around 1.0 L/m²·d which is in line with previous studies. As shown in Fig. 8, the results of tank B were compared to those of tank A, revealing that the optimum angle of inclination was 25°.

5.4. Theoretical model estimation

A theoretical analysis was carried out to predict the output of the still based on temperatures of its components (water, inclined cover and basin) were also predicted. The temperature values shown in Fig. 9 revealed that maximum temperature difference between glass and water basin occurred at 3 PM. Production of solar stills depend on temperature difference between the inclined cover and water basin, so the predicted water production would be at its optimum value around 3 PM. The applied model of solar still was validated using experimental measurements. The experiment was conducted using the optimal conditions from run 1, 2 and 3 for synthetic water with a concentration of 2,500 ppm, over 1 d (8 AM to 6 PM) with a measured ambient temperature of 23°C. Predicted results of outputs were conducted during the hours of the day by substitution in Eq. (23).

Using temperature results from Fig. 9, Fig. 10 shows the relation between experimental output results, predicted output results, and time during the hours of the day. The results showed a close match between the predicted and the actual results with deviation ±15%. The value of hew was 28.5 W/m²·K [14], however, in this study, a value of 5.2565 W/m²·K was used via least square analysis to achieve a closer match between actual results and predicted results within ±15% deviation.

The productivity was found to be lowest in the morning and evening due to low solar intensity and highest in the afternoon, leading to maximum vapor and productivity before declining. The highest water productivity for experimental and predicted results was achieved around 3 PM, when the maximum temperature difference between inclined cover and water was recorded. Fig. 10 suggests that the tank productivity was zero at the start and rising from 8 AM and peaking at 3 PM with productivity of 60 mL. In the morning, the temperature of the basin water and the inclined cover was almost equal to the ambient temperature, resulting in a negligible temperature difference between water and inclined cover, thus no productivity. The accumulation of the produced water from the experimental work and predicted work was 710 and 800 mL/m²·d.

5.5. Performance evaluation with seawater

Seawater was collected from Mediterranean Sea with TDS value of 33,000 ppm. During this run, filtered and unfiltered seawater with a concentration of 33,000 and 2,500 ppm were tested. Fig. 11 represents the relationship between accumulative water production from the still over

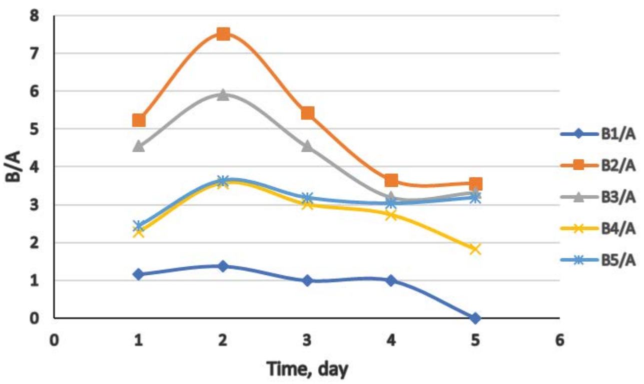

Fig. 8. Comparison in productivity of tanks B and A.

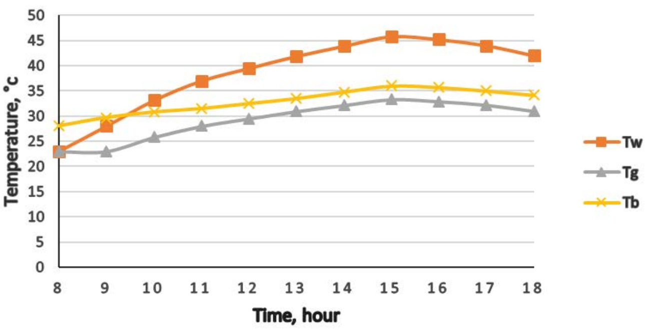

Fig. 9. Theoretical temperatures of water, glass and basin liner.

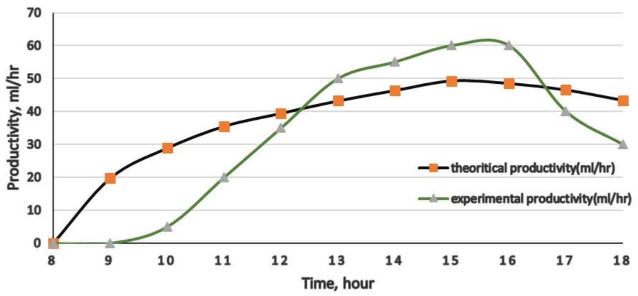

Fig. 10. Comparison of daily experimental and theoretical results, date on 15-3-2022.

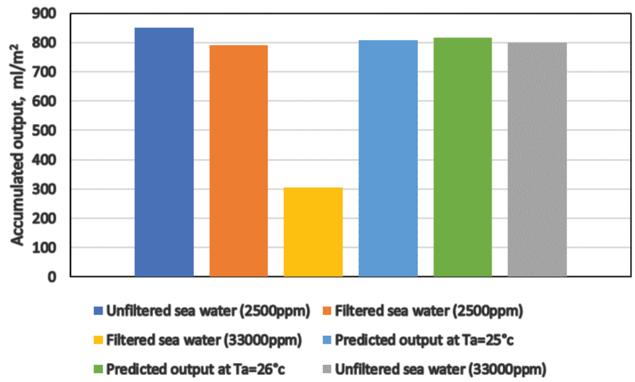

Fig. 11. Experimental results of filtered and unfiltered seawater on 26, 27, 28 and 29 March 2022, respectively.

10 h of the whole day and the type of seawater used. The experiments were conducted over-days, from 8 AM to 6 PM, using unfiltered seawater of 2,500 ppm, unfiltered seawater of 33,000 ppm, filtered seawater of 2,500 ppm, and filtered seawater of 33,000 ppm. The measured ambient temperature (T_a) was 25°C on the first 2 d and 26°C on the next 2 d.

The results shown in Fig. 11 indicated that the maximum outputs were 850 mL/m^2 for 2,500 ppm unfiltered seawater, 800 mL/m^2 for 33,000 ppm unfiltered seawater, 790 mL/m^2 for 2,500 ppm filtered seawater, 304 mL/m^2 for 33,000 ppm filtered seawater. The results showed that unfiltered seawater with a TDS of 33,000 ppm had a higher productivity than filtered seawater with a TDS of 2,500 ppm, which is the opposite of what was observed in this study and previous studies, where water productivity increased with decreasing salinity.

The temperature of the water has a direct impact on the productivity of the still. seawater contains high levels of turbidity, which works as a heat storage material, but synthetic water made from tap water does not have turbidity. This results in an increase in seawater temperature and production. It is therefore recommended to use unfiltered seawater for optimal performance. Paaijmans et al. [41] found that suspended particles in water absorb and store sunlight, which results in increased water temperature with increased of water turbidity. Suspended particles act as storage material in water.

Hoque et al. [22] studied real seawater with a TDS of 20,000 ppm and synthetic water with a TDS value of 2,000 ppm. and found that raw seawater yielded the maximum output. From Fig. 11 unfiltered seawater with a TDS of 2,500 ppm produced the maximum output because of its turbidity, which acted as heat storage, and its lower salinity, which increased productivity. Filtered seawater with a TDS value of 33,000 ppm had the lowest productivity because it had no turbidity and a higher salt concentration, which resulted in a lower vapor pressure and thus lower productivity. The experimental results were compared to theoretical results under the same ambient temperature condition and had a good agreement, with a predicted total output of 808 and 816 mL/m^2 over 10 h for ambient temperature of 25°C and 26°C, respectively. The maximum output that obtained was about 2 L/m^2·d which is in line with previous studies.

6. Validation

The accuracy of theoretical results of present work is verified with available data by Afrand et al. [12]. Table 4 displays results that closely match Afrand et al. [12] results. Afrand et al.'s [12] findings from their single slope solar still experiment conducted at 30°C and 25° angle of inclination. The present study, conducted at 33°C and 25°, shows a lower in water temperature and a higher in glass temperature than Afrand et al. [12]. This discrepancy is attributed to the use of a 3 mm plexiglass cover instead of a 4 mm glass cover, as the higher heat capacity of the glass results in lower external heat transfer losses and the thermal energy of glass cover is higher than thermal energy of plexiglass cover [24]. The average deviation in water temperature and glass temperature of present work and Afrand et al. [12] is –13.85% and +34%.

7. Improved quality of produced water

Solar stills are believed to effectively remove dissolved and suspended solids that cause turbidity. When exposed to solar radiation, water in a basin evaporates, leaving contaminants behind. Tests were conducted on basin and distillate samples to assess water quality improvement. Results in Table 5 indicate that both seawater and synthetic water samples meet the World Health Organization (WHO) drinking water standards after being processed through solar stills. Studies by Arunkumar et al. [42] have also found that distilled water from various solar stills meets WHO standards.

8. Cost estimation

The current solar still design is intended for using in remote areas where freshwater is scarce. Cost analysis is presented in Table 6, while Table 7 shows a comparison

Table 4
Hourly variation of theoretical temperatures values between present work and Afrand et al. [12]

Time	Present work		Afrand et al. [12]		% error	% error
	T_w	T_g	T_w	T_g	T_w	T_g
9–10 am	49.4	41.14	40.53	21.51	17.95	47.7
10–11 am	55.4	44.74	54.45	26.34	1.71	41.1
11–12 pm	61	48.1	64.61	28.97	–5.91	40.14
12–1 pm	63.6	49.66	80.12	36.35	–25.9	26.8
1–2 pm	65.1	50.56	85.88	38.42	–31.9	24
2–3 pm	65.6	50.86	82.67	35.8	–26	29.6
3–4 pm	65	50.5	79.45	34.62	–22	27.4
4–5 pm	63.8	49.8	75.82	30.09	–18.8	39.6

Table 5
Water parameters test results

Parameter	Seawater		Synthetic water		WHO guidelines
	before	after	before	after	
Chloride (mg/L)	27,050	6.8	4,800	11.4	250
Electrical conductivity (μS/cm)	46,959	183	7,115	85	250
Total dissolved solids (mg/L)	33,000	150	5,000	70	500
pH	6.6	7.4	6.7	7.3	6.5–8.5

Table 6
Product water unit cost for conventional solar still

Item	Value for conventional solar still
Lifetime, *n* (y)	10
Interest rate, *r* %	12
Capital cost $	120
Capital recovery factor	0.177
Annual cost	21.24
Annual maintenance cost	3.186
Total annual cost $	24.426
Distilled water productivity L (liter)	1
Cost per liter $/L	0.08142

Table 7
Comparison for cost of current study s and previous studies

References	Cost per liter (U$/L)
Current work	0.08142
Shalaby et al. [43]	0.07182
Morad et al. [33]	0.03

with previous studies. The estimated cost in Table 6 was calculated per year, assuming a working period of 300 d due to rainy days. Results in Table 6 suggest that the cost of the current solar still is in line with previous studies.

Conventional desalination systems, such as RO have a cost ranging from 0.4 to 3 $/m^3$. The cost increases when renewable energy sources are used, reaching up to 15 $/m^3$ [33]. The cost of the present study is the most cost-effective among solar desalination technologies, but is still higher than RO due to lower productivity However, this cost is counterbalanced by the environmental benefits of using solar energy instead of fossil fuels. Using a modification on the solar still may increase the productivity. Kabeel et al. [7] made a modification on a conventional solar still using a cement-coated red bricks in the absorber. The cost per liter found to be 0.0045 $/L. In conclusion, the environmental benefits of using solar energy make it a worthwhile investment for remote areas with limited access to freshwater.

9. Conclusion

This study explored desalination through a solar still. A single slope solar still was used as a standard unit and another single slope solar still was used to study the effects of water depth, salt concentration, and angle of inclination. The experimental results showed that the production of water was inversely proportional to water depth up to 8.0 cm. Salinity of water was also inversely proportional to productivity of the still. It was concluded from the current study that the latitude of the location should determine the angle of the inclined cover in solar stills to optimize the solar radiation incident. The numerical model was quite accurate and produced acceptable results compared to the experimental results. The theoretical results were validated with previous results of a single slope solar still and showed a good agreement. The properties of produced water met WHO standards for drinking water. The maximum production from the study was 1 L/d with a basin area of 0.5 m^2. For a family of five members, a passive solar still with basin area of 5 m^2 is required. The cost per liter was 0.08142 $/L, making it cheaper than market water. Using cheaper materials or making a modification on the solar still increases the productivity and also decreases the cost. So, it is recommended to make a modification such as external heater, external fan or using a cement-coated red bricks. RO has a lower cost per liter 0.003 $/L. The lower cost of solar still after the modification is still higher than RO cost but the environmental benefits of solar energy may be counter balanced with the difference in cost. The obtained results are of particular importance for small and rural communities, as they can be used to design simple solar still unit that does not require preliminary or post-treatment steps, with low operating and maintenance costs, and moreover does not require skilled labor.

References

[1] A.A.F. Al-Hamadani, S.K. Shukla, Modelling of solar distillation system with phase change material (PCM) storage medium, Varanasi, India, Therm. Sci., 18 (2015), doi: 10.2298/TSCI120102110A.

[2] G.R. Gamea, A.T. Taha, Y.A. Qaid, Simulation model for seawater distillation by solar energy, Misr J. Agric. Eng., 28 (2011) 1053–1072.

[3] P.İ. Ayav, G. Atagündüz, Theoretical and experimental investigations on solar distillation of IZTECH campus area seawater, Desalination, 208 (2006) 169–180.

[4] M.R. Salem, M.R. Salem, M.G. Higazy, M.F. Abdrabbo, Performance enhancement of a solar still distillation unit: a field investigation, Sol. Energy, 202 (2020) 326–341.

[5] Md. W. Akram, S.M. Abdul Motin, M.A. Hoque, N.N. Mustafi, Design, construction and performance test of a solar still for water desalination in Bangladesh perspective, AIP Conf. Proc., 2121 (2019) 130001, doi: 10.1063/1.5115947.

[6] Z.M. Omara, A.E. Kabeel, The performance of different sand beds solar stills, Int. J. Green Energy, 11 (2014) 240–254.

[7] A.E. Kabeel, E. El-Agouz, M.M. Athikesavan, R.D. Ramalingam, R. Sathyamurthy, N. Prakash, C. Prasad, Comparative analysis on freshwater yield from conventional basin-type single slope solar still with cement-coated red bricks: an experimental approach, Environ. Sci. Pollut. Res., 27 (2020) 32218–32228.

[8] M. El Hadi Attia, Z. Driss, A.M. Manokar, R. Sathyamurthy, Effect of aluminum balls on the productivity of solar distillate, J. Energy Storage, 30 (2020) 101466, doi: 10.1016/j.est.2020.101466.

[9] A.A.A. Attia, Thermal analysis for system uses solar energy as a pressure source for reverse osmosis (RO) water desalination, Sol. Energy, 86 (2012) 2486–2493.

[10] A.F. Mashaly, A.A. Alazba, A.M. Al-Awaadh, Assessing the performance of solar desalination system to approach near-ZLD under hyper arid environment, Desal. Water Treat., 57 (2016) 12019–12036.

[11] D. Shukla, K. Modi, Hybrid solar still as a co-generative system and desalination system - an experimental performance evaluation, Cleaner Eng. Technol., 2 (2021) 100063, doi: 10.1016/j.clet.2021.100063.

[12] M. Afrand, A. Behzadmehr, A. Karimipour, A numerical simulation of solar distillation for installation in Chabahar-Iran, Int. J. Mech. Sci., 4 (2010), doi: 10.5281/zenodo.1327810.

[13] N. The Bao, Chapter 3 – The Mathematical Model of Basin-Type Solar Distillation Systems, V. Steffen, Ed., Distillation - Modelling, Simulation and Optimization, InTechOpen, 2019. doi: 10.5772/intechopen.83228.

[14] T.V. Arjunan, H.S. Aybar, J. Orfi, S. Vijayan, Performance Analysis of Solar Desalination Systems, A. Kumar, O. Prakash, Eds., Solar Desalination Technology. Green Energy and Technology, Springer, Singapore, 2019. Available at: https://doi.org/10.1007/978-981-13-6887-5_4
[15] W.M. El-Maghlany, Y. El-Samadony, A. Kabeel, Glass cover inclination angle effect on the radiation shape factor within conventional solar still, Desal. Water Treat., 57 (2016) 17722–17730.
[16] R. Tripathi, G.N. Tiwari, Effect of water depth on internal heat and mass transfer for active solar distillation, Desalination, 173 (2005) 187–200.
[17] A.F. Muftah, M.A. Alghoul, A. Fudholi, M.M.A. Majeed, K. Sopian, Factors affecting basin type solar still productivity: a detailed review, Renewable Sustainable Energy Rev., 32 (2014) 430–447.
[18] B.A. Akash, M.S. Mohsen, W. Nayfeh, Experimental study of the basin type solar still under local climate conditions, Energy Convers. Manage., 41 (2000) 883–890.
[19] H.A. Mousa, B. Abu-Hijleh, Water film cooling over the glass cover of a solar still including evaporation effects, Energy, 22 (1997) 43–48.
[20] Pr. K. Abdenacer, S. Nafila, Impact of temperature difference (water-solar collector) on solar-still global efficiency, Desalination, 209 (2007) 298–305.
[21] R.V. Dunkel, Solar water distillation: the roof type still and the multiple effect diffusor, Int. Dev. Heat Transfer, 4 (1961) 895.
[22] A. Hoque, A.H. Abir, K.P. Shourov, Solar still for saline water desalination for low-income coastal areas, Appl. Water Sci., 9 (2019) 104, doi: 10.1007/s13201-019-0986-9.
[23] A.Z. Al-Garni, Productivity enhancement of single slope solar still using immersion-type water heater and external cooling fan during summer, Desal. Water Treat., 52 (2014) 34–36.
[24] J.A. Jones, L.W. Lackey, K.E. Lindsay, Effects of wind and choice of cover material on the yield of a passive solar still, Desal. Water Treat., 52 (2014) 1–3.
[25] W.L. Cheng, Y.K. Huo, Y. Le Nian, Performance of solar still using shape-stabilized PCM: experimental and theoretical investigation, Desalination, 455 (2019) 89–99.
[26] M. Sharma, A. Kr. Tiwari, D.R. Mishra, A review on desalination of water using single slope passive solar still, Int. J. Dev. Res., 6 (2016) 10002–10012.
[27] S.V. Raj, A.M. Manokar, Design and analysis of solar still, Mater. Today Proc., 4 (2017) 9179–9185.
[28] O.O. Badran, Experimental study of the enhancement parameters on a single slope solar still productivity, Desalination, 209 (2007) 136–143.
[29] H. Al-Hinai, M.S. Al-Nassri, B.A. Jubran, Effect of climatic, design and operational parameters on the yield of a simple solar still, Energy Convers. Manage., 13 (2002) 1639–1650.
[30] A. Kr. Tiwari, G.N. Tiwari, Thermal modeling based on solar fraction and experimental study of the annual and seasonal performance of a single slope passive solar still: the effect of water depths, Desalination, 207 (2007) 184–204.
[31] H.M. Ahmed, G.A. Ibrahim, Performance evaluation of a conventional solar still with different types and layouts of wick materials, Int. J. Energy Technol. Policy, 6 (2016) 5–14.
[32] D.G.H. Samuel, P.K. Nagarajan, R. Sathyamurthy, S.A. El-Agouz, E. Kannan, Improving the yield of freshwater in conventional solar still using low-cost energy storage material, Energy Convers. Manage., 112 (2016) 125–134.
[33] M.M. Morad, H.A.M. El-Maghawry, K.I. Wasfy, A developed solar-powered desalination system for enhancing freshwater productivity, Sol. Energy, 146 (2017) 20–29.
[34] R. Kalbasi, M.N. Esfahani, Multi-effect passive desalination system, an experimental approach, World Appl. Sci. J., 10 (2010) 1264–1271.
[35] M.N.I. Sarkar, A.I. Sifat, S.M.S. Reza, M.S. Sadique, A review of optimum parameter values of a passive solar still and a design for southern Bangladesh, Renewables Wind Water Solar, 4 (2017) 1–13.
[36] V.K. Thakur, M.K. Gaur, M.K. Sagar, Performance Analysis of Different Tilt Angles-Based Solar Still, H.M. Dubey, M. Pandit, L. Srivastava, B.K. Panigrahi, Eds., Artificial Intelligence and Sustainable Computing. Algorithms for Intelligent Systems, Springer, Singapore, 2022. Available at: https://doi.org/10.1007/978-981-16-1220-6_17
[37] V. Sivakumar, E.G. Sundaram, Improvement techniques of solar still efficiency: a review, Renewable Sustainable Energy Rev., 28 (2013) 246–264.
[38] S.A. El-Agouz, Experimental investigation of stepped solar still with continuous water circulation, Energy Convers. Manage., 86 (2014) 186–193.
[39] H. Fadhel, Q.A. Abed, D.M. Al-Shamkhee, A review on improvement techniques of freshwater productivity for solar distillation systems, Al-Furat J. Innovations Mech. Sustainable Energy Eng., 1 (2021) 1–15.
[40] H.N. Singh, G.N. Tiwari, Monthly performance of passive and active solar stills for different Indian climatic conditions, Desalination, 168 (2004) 145–150.
[41] K.P. Paaijmans, W. Takken, A.K. Githeko, A.F.G. Jacob, The effect of water turbidity on the near-surface water temperature of larval habitats of the malaria mosquito *Anopheles gambiae*, Int. J. Biometeorol., 52 (2008) 747–753.
[42] T. Arunkumar, K. Raj, M. Chaturvedi, A. Thenmozhi, D. Denkenberger, G. Tingting, A review on distillate water quality parameter analysis in solar still, Int. J. Ambient Energy, 42 (2021) 1335–1342.
[43] S.M. Shalaby, E. El-Bialy, A.A. El-Sebaii, An experimental investigation of a v-corrugated absorber single-basin solar still using PCM, Desalination, 398 (2016) 247–255.