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ORIGINAL ARTICLE

Solar still for saline water desalination for low-income coastal areas

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Abstract

Solar still is a simple device that utilizes the evaporation–condensation technique to convert impure saline water into the distilled water by eliminating dissolved salts as well as other dissolved impurities and suspended solids. This study aims to produce fresh drinking water from saline water with solar still in the context of Bangladesh. For this study, a pilot-scale solar still with an effective surface area of 0.214 m^2 is fabricated with mild steel sheet. At first, solar still productivity is evaluated by varying basin water amount by 3 L, 3.5 L, 4 L and 4.5 L synthetic water. Experimental investigations show a decrease in water production with an increase in basin water amount. The optimum basin water amount is found to be 3.5 L at which distillate production is maximized. Then, the effect of salt concentration is assessed by synthetic solutions with 2000 ppm, 5000 ppm and 8000 ppm total dissolved solids (TDS). An inverse relation is found between salt concentration and freshwater production. Lastly, real seawater is fed to the basin and an average freshwater production of 2.38 L/m^2-day is obtained with a removal efficiency of 99.87%, 99.83%, 99.78% and 99.81% for turbidity, chloride, TDS and electrical conductivity respectively.

Keywords Saline water · Solar still · Solar desalination · Drinking water

Introduction

Water is the source of all forms of lives on earth which is equally important to the human as well as entire wildlife. It is estimated that about 3.6 billion people are faced with water crisis at present and by 2050, the number may increase to 4.8–5.7 billion (UN-Water 2018). In the coastal regions of Bangladesh, about 15 million people are compelled to drink saline water and 30 million people are deprived of drinking water for lack of safe water sources (Hoque 2009). In this context, desalination of water using solar still is a viable option to provide drinking water in remote and arid regions of Bangladesh, especially for smaller communities and domestic use.

Solar still is a device that harvests solar energy to produce fresh drinking water from saline water by utilizing the evaporation–condensation technique. The process is entirely dependent on solar radiation and does not involve any supply of external energy, which makes it an attractive choice for the regions that receive abundant solar energy throughout the year. A greater portion of coastal regions of Bangladesh is affected by the salinity of both groundwater and surface water. Many coastal regions around the world, especially in the Middle East and North Africa, are now dependent on treated saline water (Buros 2000). According to the International Desalination Association (IDA), 18,426 desalination plants around the world are in operation at present. The desalination plants use conventional desalination processes, namely reverse osmosis (RO), multi-stage flash (MSF), multi-effect distillation (MED), etc., which are both energy- and cost-intensive, require huge initial investment, skilled workforce, regular maintenance and expertise for smooth operation. Moreover, these plants are not favorable for small-scale water supply for their large capital cost of plant and coverage pipeline. In such cases, where the power supply is not available, water sources are saline and demand is less than 200 m^3/day. Solar still desalination remains the only process that can be utilized for freshwater production (Tiwari et al. 2003).

However, the main drawbacks of solar stills involve the requirement of large installation areas, lower productivity and higher land cost associated with the larger land requirement (Ayoub and Malaeb 2012). So, the studies mainly focus

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on enhancing the water production from solar still to negate the limitations as well as on keeping the unit cost of water as low as possible. According to Abujazar et al. (2016), the productivity of a solar still is influenced by ambient conditions (solar radiation, ambient temperature, wind velocity, etc.), operating conditions (brine water depth, saline concentration, etc.) and design conditions (cover angle, insulation, etc.). The behavior of solar stills with different configurations and different working conditions has been widely studied over the past few decades. Since the distribution of solar radiation around the world is non-uniform, the performance studies of solar still are required to be replicated under the climatic condition of Bangladesh. According to the meteorological data obtained from Bangladesh Meteorological Department (BMD), Bangladesh receives an average 3.125 kW h/m^2-day solar radiation during summer (March–June) with sunshine hour of 4.4–7 h while an average 2.31 kW h/m^2-day solar radiation during winter (October–March) with 6–9 sunshine hours. Thus, the condition of Bangladesh is in favor of the solar still application for drinking water production. In addition, solar still is easy to construct with local labor force using low-cost readily available materials and even illiterate people can operate solar still due to its very simple operations, which make it an excellent choice in the context of Bangladesh.

This study aims to evaluate the effect of brine water depth and the effect of salt concentration on the productivity of a single slope passive solar still under the climatic condition of Chittagong, Bangladesh. It is an established fact that water production from solar still decreases with an increase in brine water depth (Khalifa and Hamood 2009). The effect of brine depth is studied to select an optimum water depth for the fabricated solar still. With the optimized water depth, the effect of basin water salt concentration on productivity is also studied using synthetic saline water. Later, the solar still is provided with real seawater to compare the productivity obtained from synthetic water. Finally, water parameters are tested to determine the removal efficiencies of dissolved impurities as well as suspended particles and to ensure the quality of distilled water upon comparing with WHO guideline.

Experimental procedure

Setup specification

For the experimental studies, a single slope solar still is fabricated with a mild steel sheet of 0.8 mm thickness. The solar still has an effective area of 0.214 m^2 with a basin dimension of 650 mm × 330 mm. The front wall is 100 mm high and rear wall is 240 mm high. Transparent glass of 5 mm thickness is used as cover at an inclination of 23° with the horizontal, which is nearly equal to the latitude of the experimental site (22.5°), as suggested by Singh and Tiwari (2004), to minimize radiation loss due to reflection. Moreover, this optimized angle ensures to receive solar radiations normal to the glass surface throughout the year (Srivastava and Agrawal 2013). A distillate collection trough is built integrally with the setup by bending of mild steel sheet with an inclination of 20 mm. Three steel nipples of 18.75 mm diameter are fitted in the rear wall and two side walls to connect PVC hose pipes with the setup for feeding and discharging water. Inner walls of the solar still are painted black to protect the still from corrosive brine as well as to absorb more heat from solar radiation. Since heat plays the vital role in the distillation process of solar still, proper insulation is necessary to avert heat loss from the inside to the environment in order to improve productivity. For the insulation of glass cover, all-purpose silicone sealant is used along the cover edge to prevent vapor escape from the still. Silicone is flexible when applied and can be easily removed when necessary for maintenance purpose. For the insulation of the walls, 30-mm-thick cotton pad is attached on the outer side of the walls. Additionally, 15-mm-thick expanded polystyrene sheet is attached over the cotton pad for further insulation as well as to protect the cotton from degradation. Figure 1 represents a schematic diagram of the designed solar still.

Working procedure

The experimental investigations are carried out at Chittagong University of Engineering and Technology, Chittagong, Bangladesh (22.46°N, 91.97°E). Both synthetic saline water and seawater are used for this study. The experiments involved in this study are the investigation of the

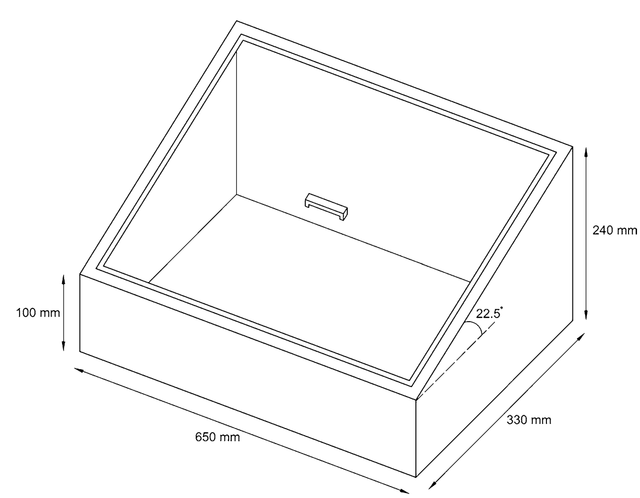

Fig. 1 Schematic diagram of solar still with dimensions

effect of water amount, effect of salt concentration and solar still performance with seawater.

The experiments are performed on clear sunny days and are triplicated to have a clear understanding of the experimental findings. Before the commencement of the experiments, inside of the basin is washed by water flushing. The experiments are conducted for 8 h of direct operation under solar radiation from 9 a.m. to 5 p.m., and then 16 h of indirect operation from 5 p.m. to 9 a.m. of the following day. During 8 h of direct operation, ambient temperature, glass cover temperature, basin water temperature, relative humidity and distillate production are recorded in each hour. During 16 h of overnight operation, only accumulated distillate is recorded before 9 a.m. of the following day. The ambient temperature, basin water temperature and relative humidity are recorded with a digital thermometer, whereas glass cover temperature is recorded with a laser thermometer. The distillate is measured using a measuring cylinder with a resolution of 1 mL. The glass cover is oriented toward south–east direction up to 12 p.m., and then orientation is changed toward south–west direction. The distillate is collected in a PET bottle during each experiment.

Effect of basin water depth

Amount of basin water is the most important parameter that affects the solar still productivity. Since the operation of solar still is entirely dependent on solar radiation and no external energy is supplied, the amount of basin water plays a crucial role in the solar still productivity. The basin water amount is recommended to be within 2 cm to 6 cm (Al-Hinai et al. 2002). However, for this study, 1.4, 1.6, 1.8 and 2.1 cm brine water depths are considered initially which equal around 3 L, 3.5 L, 4 L and 4.5 L basin water for the fabricated setup. In case the distillate production shows an increasing trend, further experiments are to be conducted. For each water amount, experiments are performed for 3 days with the synthetic saline solution prepared in the laboratory with an approximate TDS of 5000 ppm. Based on the experimental results, an optimum water amount is to be fixed for further studies.

Effect of salt concentration

The concentration of salt in basin water also affects freshwater production from solar still. For this study, synthetic solutions are prepared with total dissolved solids of 2000, 5000 and 8000 ppm by adding sodium chloride. Experiments are carried out with optimized water amount found in Experiment 1. The setup is operated for 3 days for each amount of salt concentration. Water parameter tests, e.g., pH, total dissolved solids (TDS), electrical conductivity and chloride, are carried out both before and after the experiments to study the effectiveness in improving the water quality.

Performance evaluation with seawater

Seawater is collected and tested in the laboratory for selected parameters to assess the productivity of solar still with real seawater. Experiments are carried out with seawater for 3 days with the optimized basin water amount from Experiment 1. After the experiments, distillate samples are tested again for the selected parameters to compare removal efficiencies.

Results and discussion

Effect of basin water depth

The solar still productivity is evaluated with different basin water amount of 3.0 L, 3.5 L, 4.0 L and 4.5 L (Fig. 2).

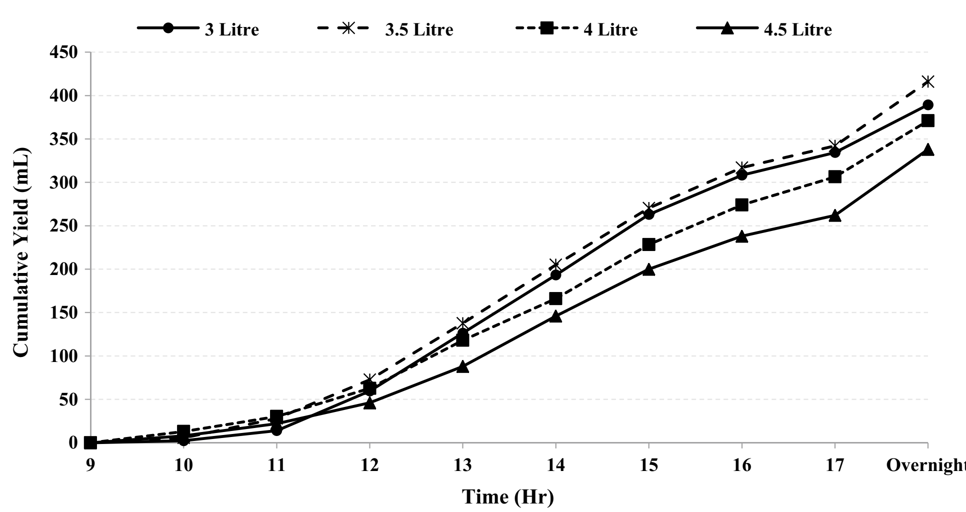

Fig. 2 Variation of daily yield with different basin water amount

Highest water productions from solar still fed with 3 L, 3.5 L, 4 L and 4.5 L are found to be 463 mL, 469 mL, 411 mL and 362 mL, respectively, whereas average water productions are 389 mL, 416 mL, 371 mL and 338 mL, respectively. With the increase in basin water amount from 3.5 to 4.0 L, average water production from solar still reduces by 10.82%. Average water production further reduces by 18.75% when basin water amount is increased from 3.5 to 4.5 L. From this study, 3.5 L, also analogous to 1.6 cm water depth, is selected as the optimum basin water since the highest average yield of 416 mL (1.94 L/m^2-day) is obtained from this configuration.

The experimental results from this study comply with findings reported by other researchers as shown in Table 1. According to the studies, freshwater production is inversely proportional to the basin water amount, i.e., lower basin water amount results in higher water production and vice versa (Khalifa and Hamood 2009). With the increase in basin water amount, the heat capacity of water increases that delays the evaporation process. As a result, freshwater production is also reduced. But too less basin water may develop dry spots in the basin that has a negative impact on the solar still productivity. The formation of dry spots may also cause outgassing of basin material which is not desirable (Kopperdal 2015).

Basin water temperature is directly related to the amount of water in the solar still basin that eventually affects solar still productivity (Fig. 3a–d). When basin water amount is increased, basin water temperature is lower in the early hours but is higher in the afternoon in case of greater water amount. Highest average basin water temperatures were recorded to be 64 (1 p.m.), 63 (1 p.m.), 60 (1 p.m.) and 61 °C (2 p.m.), while the highest hourly yield was recorded to be 70 mL (at 3 p.m.), 67 mL (at 2 p.m.), 62 mL (at 3 p.m.) and 58 mL (3 p.m.) for 3 L, 3.5 L, 4 L and 4.5 L basin water, respectively.

Water mass temperature decreases for the same solar radiation when the basin water amount is increased. As a result, shallow water depth gains temperature quickly from the incoming solar radiation due to its lower heat capacity, and evaporation is initiated quickly as compared to the solar still with higher basin water depth. This phenomenon also explains the decrease in solar still productivity with an increase in basin water depth. The 'time lag' between solar intensity and heat absorption by the basin water is pointed out by Dev et al. (2011) that explain the delay in the occurrence of the highest hourly yield at 2 p.m., while the highest basin water temperature is observed at 1 p.m.

Effect of salt concentration

The effect of salt concentration on the solar still productivity is studied with synthetic saline water consisting of the approximate TDS value of 2000 ppm, 5000 ppm and 8000 ppm with the optimized basin water amount of 3.5 L. From the experimental investigations, the average yield of solar still is found to be 508 mL, 488 mL and 471 mL for basin water TDS value of 2000, 5000 and 8000 ppm. With the increase in TDS from 2000 to 8000 ppm, water production drops by 7.28%.

The experimental results are also supported by the literature. With the increase in salt concentration up to saturation point, water production decreases at a linear rate. Akash et al. (2000) reported the adverse effect of basin water salt concentration on solar still productivity. In an experimental study, Kalbasi and Esfahani (2010) increased basin water salinity from 0 to 3.5% and observed a 20% reduction in water production. When salinity increases in basin water, vapor pressure reduces at water surface that slows down evaporation process (Al-Shammiri 2002). As a result, freshwater production decreases with an increase in salinity.

Table 1 Study of basin water depth from the literatures

Feature of the still	Basin water depth	Obtained results	References
Basin area: 1 m^2 Cover angle: 23°	10 cm to 0.5 cm	19.6% increase in yield	Al-Hinai et al. (2002)
Basin area: 1 m^2 Cover angle: 23°	1, 2, 3 cm	Yield: 2.152, 1.931 and 0.826 kg/m^2-day	Dev et al. (2011)
Basin material: aluminum sheet (3 mm) Basin area: 1 m^2 Cover angle: 40°	0.5, 2, 3, 4 cm	Yield: 5.40, 4.99, 4.82, 4.73 L/m^2-day	Tarawneh (2007)
Basin Material: Iron sheet (1.4 mm) Basin area: 1 m^2 Cover angle: 32°	3.5 cm to 2 cm	26% increase in yield	Badran (2007)
Basin area: 1 m^2 Cover angle: 35°	1, 4, 6, 8, 10 cm	48% decrease in yield	Khalifa and Hamood (2009)
Basin material: Galvanized iron sheet (2 mm) Basin area: 1.19 m^2 Cover angle: 25°	3 cm to 1 cm	Thermal efficiency increased from 15.3 to 57.1%	Morad et al. (2015)

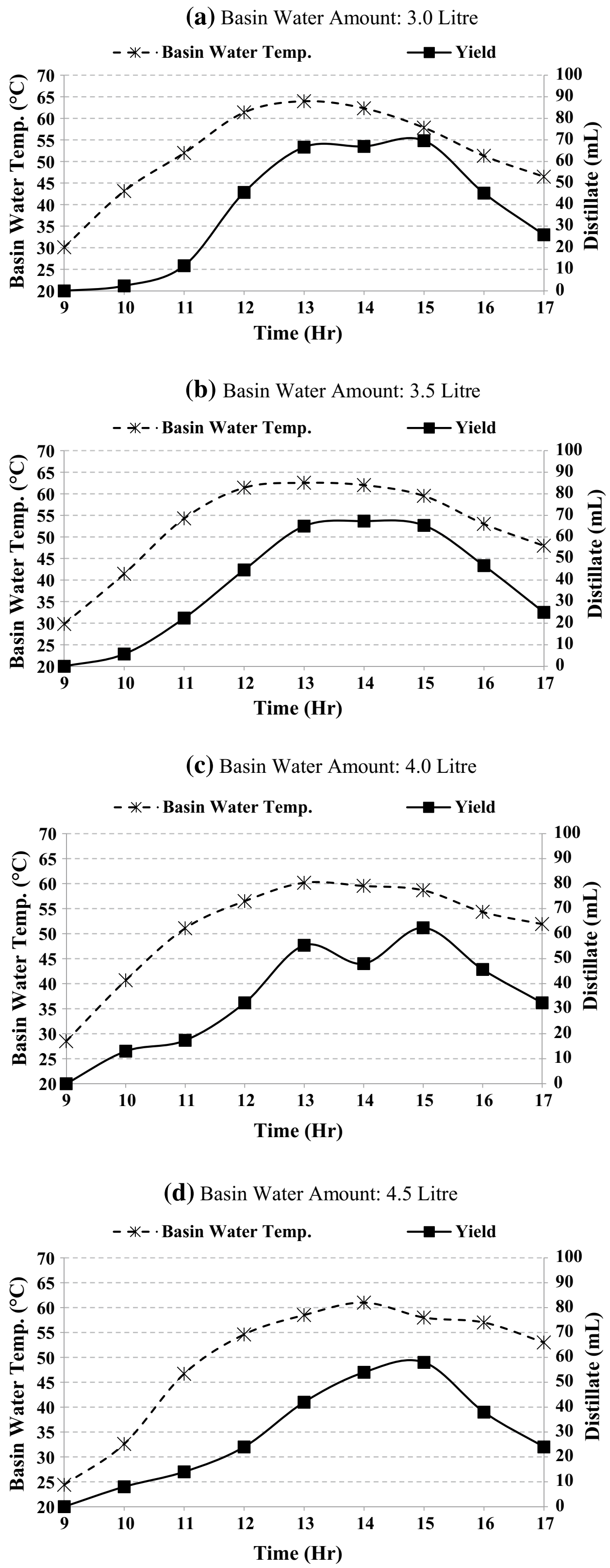

Fig. 3 Effect on basin water temperature and yield for basin water amount of **a** 3.0 L; **b** 3.5 L; **c** 4.0 L; **d** 4.5 L

From Fig. 4a, basin water temperature decreases with an increase in basin water saline concentration. Gnanadason et al. (2015) opined that a fraction of solar radiation absorbed by basin water is spent in heating the dissolved salt in water which might be the reason for lower basin water temperature for higher salt concentration. Samuel et al. (2016) echoed similar behavior in their experiments. They identified salt as 'latent heat storage material' that has higher heat capacity. These explanations satisfy lower basin water temperature as well as lower freshwater production with an increase in salt concentration in basin water as shown in Fig. 4a, b.

Performance evaluation with seawater

Seawater is provided in the solar still with initial turbidity of 303 NTU, TDS value of 20,000 ppm and chloride concentration of 8309 ppm. Through experimental work, highest production is recorded to be 596 mL (2.79 L/m^2-day), while average production is 509 mL (2.38 L/m^2-day). Samee et al. (2007) did similar experiments on raw water and found average water production to be 3.15 L/m^2-day.

Daily yield of seawater and synthetic water is compared in Fig. 5a. Recalling the experimental results of the effects of salt concentration, water production decreases with an increase in TDS. Since seawater has higher TDS (20,000 ppm) as compared to synthetic water (5000 ppm), synthetic water is supposed to produce a greater amount of distillate. But the opposite result is observed in this case. According to the findings of Paaijmans et al. (2008), suspended particles in water absorb and scatter sunlight. As a result, water temperature increases with an increase in water turbidity. Since synthetic water is prepared from tap water, turbidity is negligible for synthetic water. On the other hand, seawater has a turbidity of 303 NTU, which enables higher basin water temperature (Fig. 5b). Higher basin water temperature is associated with higher freshwater production from a solar still.

Quality of produced water

The main function of solar still is not to produce saline-free water only, but to produce water that confirms other drinking parameters as well. Solar still is supposed to eliminate a wide range of dissolved solids and also suspended solids responsible for turbidity. When basin water is heated by incoming solar radiation, water starts to evaporate from water surface leaving all the dissolves as well as suspended impurities behind. As a result, the distillate is expected to be of superior quality close to boiled water.

To assess the improvement in water quality after the experiments, both basin water samples and distillate samples have been tested. Five parameters are tested in this

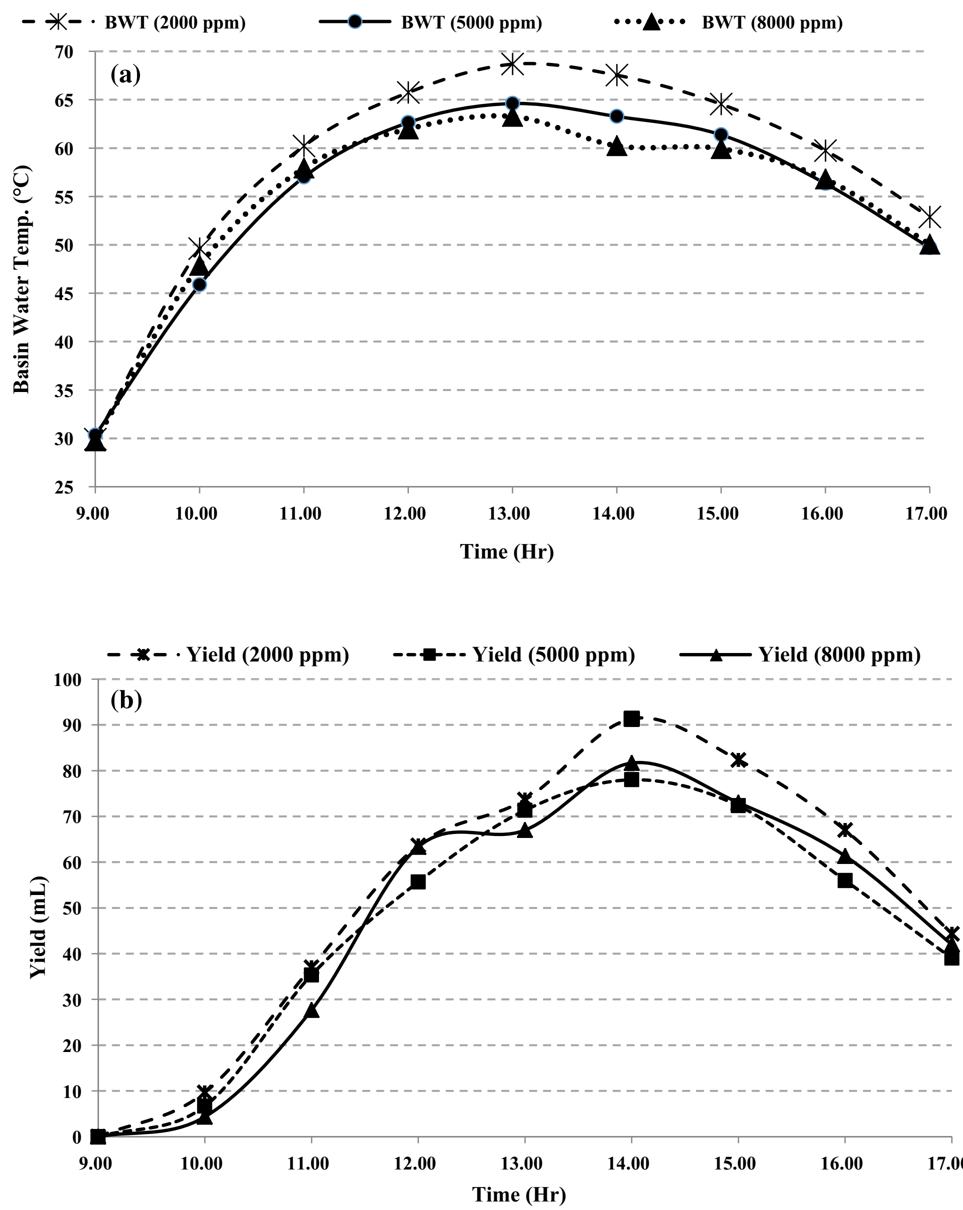

Fig. 4 Effect of basin water salt concentration on **a** Basin water temperature and **b** yield

regard: pH, turbidity, chloride, total dissolved solids and electrical conductivity.

Table 2 represents water parameter test results of both synthetic and saline water before and after the experiment.

After the desalination of water with the solar still, water parameters are improved significantly with more than 99% elimination of impurities as well as dissolved salt. All the parameters tested are within WHO guideline that ensures drinking quality of water produced from the solar still. The test results are in fair agreement with the experimental findings of other researchers. Dev et al. (2011) reported to produce distillate of similar property after the experiments (EC < 100 µS/cm and TDS < 50 ppm), while Samee et al. (2007) also obtained distillate conforming WHO guideline.

Conclusion

The following outcomes of the study can be addressed:

- The productivity of a solar still is inversely proportional to the basin water amount; lower basin water yields higher freshwater and vice versa. With the increase in brine depth from 1.6 cm (3.5 L) to 1.8 cm (4 L), average freshwater production reduces by 10.82%. Water production reduces by 18.75% when brine depth is increased from 1.6 cm (3.5 L) to 2.1 cm (4.5 L). Optimum basin water depth is found to be 1.6 cm for this study, which in terms of water amount is 16.34 L/m^2.

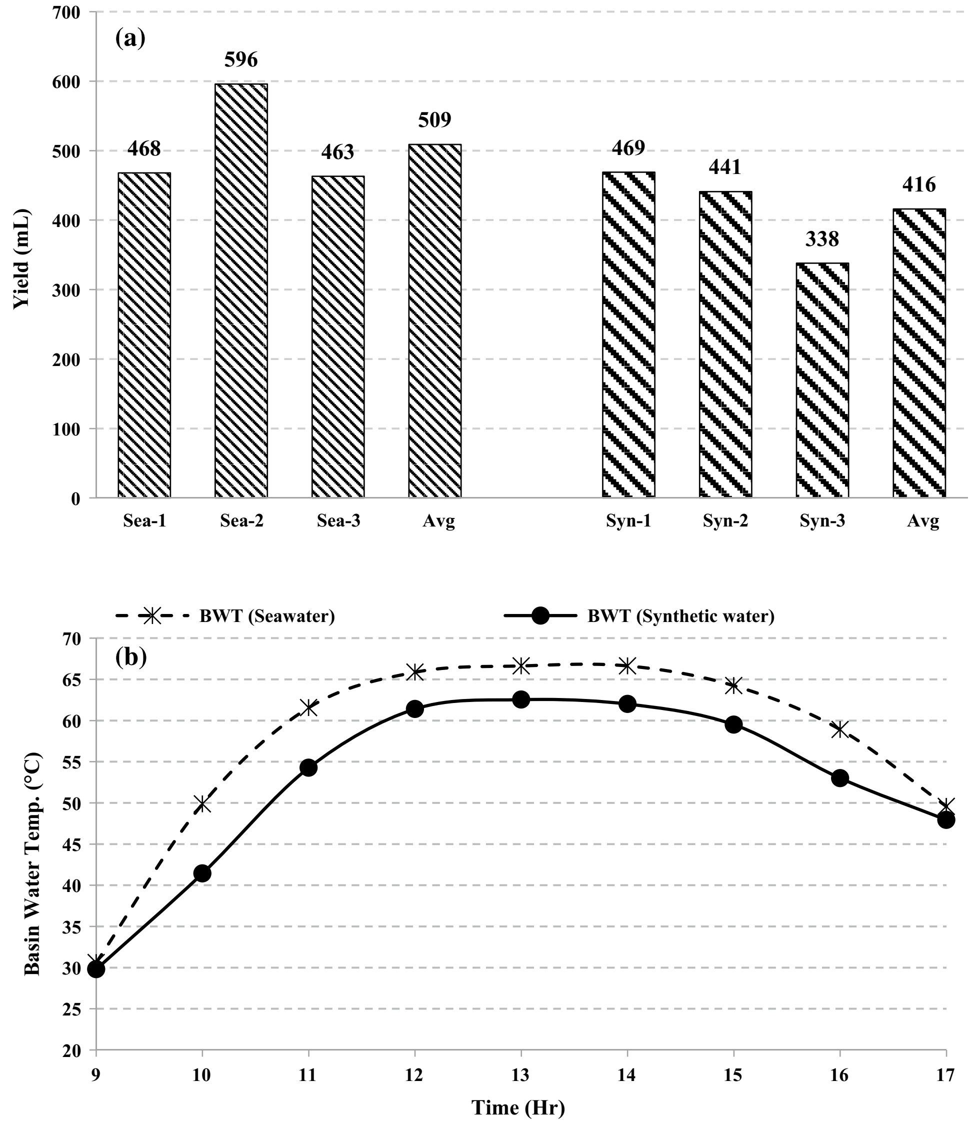

Fig. 5 **a** Daily yield comparison of seawater and synthetic water; **b** Basin water temperature of seawater and synthetic water

Table 2 Water parameter test results

Parameter	Unit	Synthetic water			Seawater			WHO guideline
		Before	After	%Removal	Before	After	%Removal	
pH	–	6.95	7.12	–	7.87	6.92	–	7–8
Turbidity	NTU	< 5	< 5	–	303	0.39	99.87	05
Chloride	ppm	4505	10	99.78	8309	14	99.83	200
TDS	ppm	9200	26	99.72	20,000	45	99.78	500
EC	µS/cm	13.1×10^3	32.2	99.75	28.5×10^3	55	99.81	–

- Freshwater production decreases by 7.28% when basin water salt concentration is increased from 2000 to 8000 ppm.
- When supplied with seawater without any treatment, an average 2.38 L/m^2-day yield is obtained from the solar still.
- The quality of produced water is confirmed by test results (pH, turbidity, electrical conductivity, chloride and TDS) and the results are found to be within standard limits. Test results show 99.83% chloride removal and 99.78% TDS removal.

Hence, it can be concluded that solar still can be a good and effective solution for producing fresh water from saline water in coastal areas of low-income countries, where modern desalination techniques are not suitable due to high initial investment and higher maintenance cost.

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