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PERFORMANCE ANALYSIS OF A TUBULAR SOLAR STILL INCORPORATED WITH POROUS SOIL TO IMPROVE DISTILLATE OUTPUT

SHAH S.M.H.[1*], QAMAR N.[1], QURESHI H.U.[1], MUSTAFFA Z.[2], TEO F.Y.[3], SALEEM S.[1], QAMAR N.[1], AHMED F.[1], ALI Z.[1], HUSSAIN S.[1]

[1] Civil Engineering Department, Sir Syed University of Engineering and Technology, Karachi, Pakistan
[2] Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610, Seri Iskandar, Perak, Malaysia
[3] Faculty of Science and Engineering, University of Nottingham Malaysia, 43500 Semenyih, Selangor, Malaysia

(*) drmuzzamil@ssuet.edu.pk

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ABSTRACT

The scarcity of fresh water is one of the leading concerns for underprivileged remote communities due to their unaffordability to the conventional water supply. Bearing in mind the changing climatic conditions and annual increment in water demand, desalination has been stated as highly adequate since it utilizes natural sunlight and the simple concepts of evaporation and condensation to produce potable water. The productivity of conventional solar stills is reported to have been greatly influenced mainly due to design specifications and operating and ambient conditions. Herein, an experimental study was conducted focusing mainly on the output efficiency of a conventional rotatable tubular still and a conventional rotatable tubular still incorporated with native porous material to assure rapid condensation. Prior to conducting the runs, saline water samples were prepared at varying concentrations. Among several designs, the tubular was still selected due to its maximum exposure to solar radiation supported by an effective condensation collection zone. The design frame was modified by incorporating a few additional characteristics, i.e., (i) rotating the basin to 360° for smooth collection of vapors and (ii) bringing the native soil in contact to the basin cover to drop the vapor temperature, leading to better and timely yielding outputs. Initially, the potential hourly output of the conventional solar was still noticed alone; later, it was analyzed with the native soil to evaluate the yield productivity. The study outcome shows that the contact of basin cover with the soil leads to better yields under different ambient conditions. Thus, the proposed native method proved to have shown feasible improvements when compared to the conventional approach alone.

Keywords: Desalination, Condensation, Tubular still, Native soil, SDG 6.

INTRODUCTION

The availability of fresh water is limited since it has been rashly depleted (Zella and Smadhi, 2010; Remini, 2010; 2021). Thus, other available sources, namely, brackish water, seem to be an option to consider as an alternate drinkable source. Since saline water is not suitable for direct consumption, desalination has been widely considered either in the form of active or passive solar stills to fulfill water needs. The potable fresh water that is available to living entities in the world is limited, and it is predicted that the water demand by 2030 will drastically rise when compared to the water demands available by industry, agriculture and domestic use in 2010, as shown in Fig. 1. Drinking water is the basic necessity to everyone, and bearing in mind the acute water shortage as per changing climatic conditions together with a 4-5% annual increment in the water demand mainly due to population rise, it is evident that there is a strong need for alternate sources to mitigate the impact of this global problem. Water with salinity up to 500 ppm is considered harmless and drinkable. However, excess salt concentrations to this level together with other impurities could lead to several water-borne diseases, such as jaundice, cancer, cholera, etc. Sea water has a very high salinity of approximately 35000-40000, and it is therefore considered unsafe for drinking purposes. Attempts are being made by scientific researchers to transform impure water into potable use by means of renewable energy sources, i.e., solar energy. Producing fresh water from saline water by means of solar still follows the same criterion as that observed in the hydrological water cycle (Singh et al., 2021).

Solar stills are inexpensive, readily accessible, portable and environmentally friendly. Such stills have been considered appropriate to ensure the drinking water needs of small households (Kumar et al., 2020) and (Vaithilingam et al., 2021). Several factors, namely, operational parameters and design specifications, have affected the productivity of conventional solar stills. A variety of changes have been made in recent years while focusing on these parameters to enhance the yield of such stills. This involves maximizing the evaporation area, enhancing the solar still by introducing stepped solar distillers, rotating elements to maximize the utilization of solar energy, etc. (Singh et al., 2021).

Many systems have been reported whose functionality is totally dependent on solar energy, i.e., humidification-dehumidification (HDH), solar stills (SS), reverse osmosis powered by photovoltaic (PV) collectors, etc. However, for dry areas, SS has been recommended mainly for the given reasons, i.e., simple fabrication and operating system, negligible carbon emissions, cost effectiveness and availability of abundant solar energy (Xiao et al., 2013) and (Sharshir et al., 2021).

The stilling basins have been broadly categorized into two main parts, i.e., direct (passive) and indirect (active) systems. The direct system solely relies on solar radiation, whereas the indirect system comprises a PV collector and a distillation plant (Aybar et al., 2009). The working of passive solar still follows the conceptual framework of the natural hydrological cycle, i.e., the process of evaporation, condensation, and cloud formation, which then precipitates back to Earth in the form of snow and rainfall. In regard to evaporation from sea water, the liquid water evaporates into water vapor while keeping the salt content left behind. This mainly occurs due to the lower boiling point of water than salt. Similarly, the stilling basin, as shown in Fig. 2, follows the same criteria. For instance, the inclined glass cover herein allows sunlight to pass through it, which promotes evaporation and in turn leads to condensation. The top of the glass cover is usually painted black to receive the maximum solar flux, whereas the condensed water is collected in the distiller, placed outside (Singh et al., 2019). Herein, an experimental study was conducted focusing mainly on the design specifications to evaluate the performance of a rotatable tubular still incorporated with native porous soil to assure rapid condensation. Initially, the potential hourly output of the conventional solar was still noticed alone; later, it was analyzed with the native soil to evaluate the yield productivity.

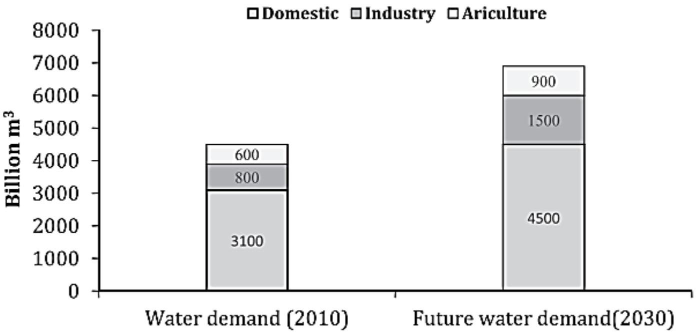


Figure 1: Global water demand gap between 2010 and 2030 (Singh et al., 2021)

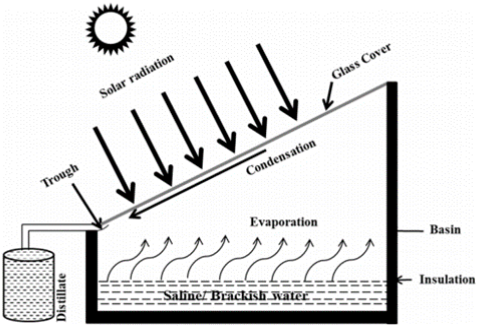


Figure 2: Schematic of a conventional basin-type solar still (Mohsenzadeh et al. 2021)

LITERATURE REVIEW

Yielding Maximum Output through Mushrooms

Due to the low productivity of passive stills, several researchers have modified different parameters by inserting different external and internal additives (Tiwari and Sahota, 2017; Tiwari and Tiwari, 2016). Among several designs, the tubular solar still (TSS) has been proven effective in yielding the maximum output mainly because of its maximum exposure to solar radiation from all sides supported by effective condensation collection, as shown in Fig. 3. In this study, a comparative analysis was performed between a conventional tubular solar still (CTSS) and a mushroom-developed tubular solar still (DTSS) to study the hourly productivity and insolation rate. It was observed that the presence of mushrooms ensured high solar absorption, which enhanced the process of evaporation (Sharshir et al., 2021). Fig. 4 shows the accumulated and hourly productivity obtained from both the CTSS and DTSS. It is evident that in terms of hourly productivity, the maximum output was witnessed at 13:00. For DTSS, it was found to be 0.63 kg/m^2, whereas for CTSS, it was found to be 0.52 kg/m^2. On the other hand, the accumulated productivity was found to be 4.37 kg/m^2 for the DTSS, whereas it was noticed to be 3.41 kg/m^2 for the CTSS. The tubular model incorporated with mushroom achieved improvement in the yields as well as enhancement in energy efficiencies.

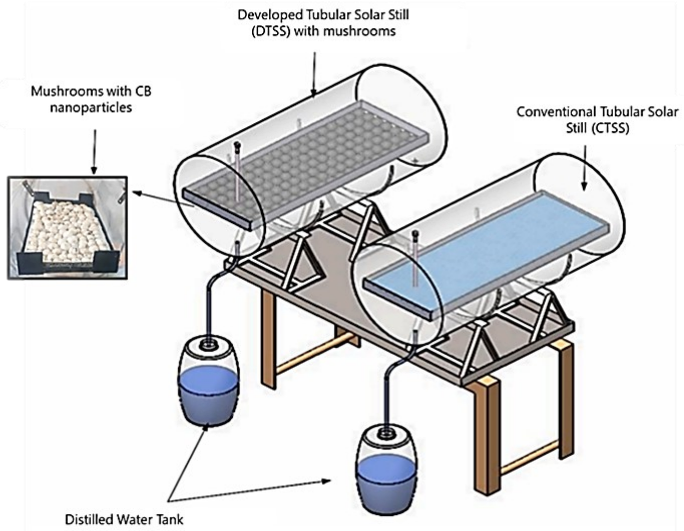


Figure 3: Schematic diagram of the tubular still (Sharshir et al., 2021)

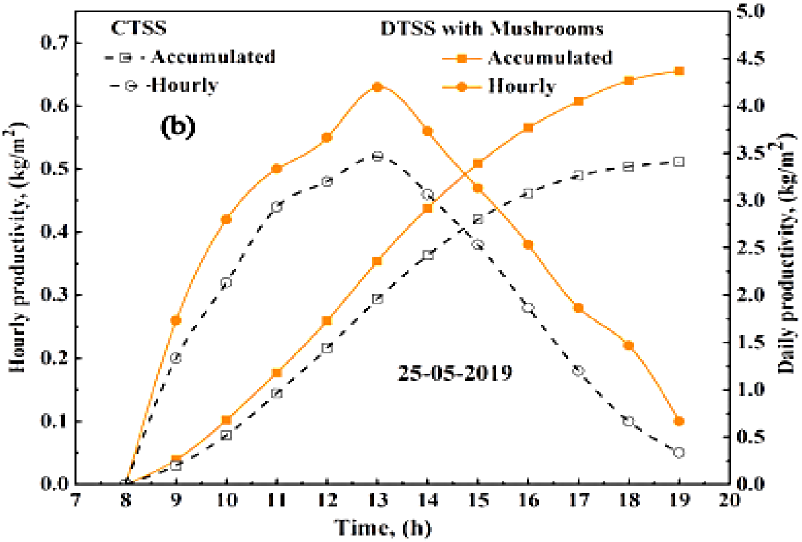


Figure 4: The variations in the hourly and accumulated productivity (Sharshir et al., 2021)

Enhancement in Efficiency through Energy Storage Materials

To increase fresh water productivity by means of solar stills, the use of rock stone beds has been proven effective when compared to the conventional approach. The reason is that stones are capable of conserving heat energy during the day and can release that energy to vaporize water after the day. When there is no solar radiation, the energy stored by the rocks is radiated, which ensures thermal equilibrium within the atmosphere, leading to the continuous process of evaporation and condensation. Thus, a comparative experimental investigation was performed between a plain conventional solar still and different energy storage materials (ESMs), namely, black color glass ball (BCGB), black granite (BG), and white marble stone (WMS), as shown in Fig. 5, to study the efficiency of the stilling basin in terms of yield, evaporation rate and energy efficiency. The ESMs were found to be effective, particularly at night, in terms of releasing heat; thus, higher distilled yields were observed. It has been stated that the energy efficiency was almost two times better than the conventional efficiency (Mevada et al., 2022). Fig. 6 shows that while performing the experimental runs, the hourly distillate remained almost the same in the morning hours, whereas during the peak hours, i.e., approximately 15:00, the distillate yields from the solar still with energy storage materials (SSWESM) were maximum mainly because of higher solar intensity. The placement of SSWESM ensured more heat inside of the basin area due to its capability to store heat. On the other hand, the conventional approach did not contribute much when compared.

Figure 5: Different energy storage materials: (a) black granite, (b) black glass balls and (c) marble stones (Mevada et al., 2022)

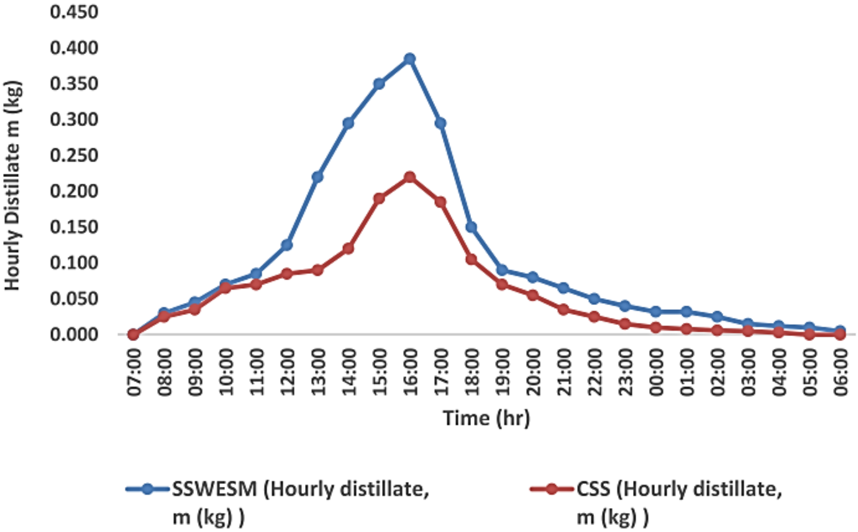
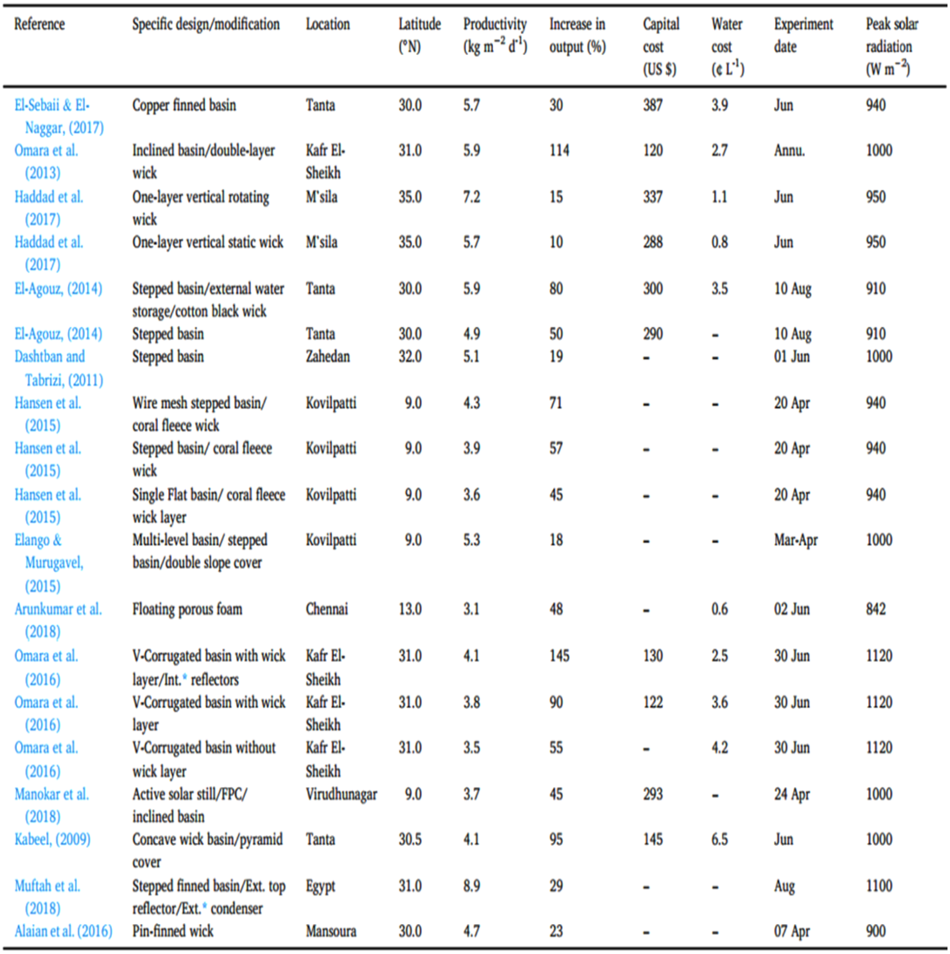


Figure 6: Variation in the hourly distillate between the conventional solar still (CSS) and solar still with energy storage materials (SSWESM) (Mevada et al., 2022)

A detailed description of the major studies that focused on various basin design improvements has been taken from (Mohsenzadeh et al. 2021), as shown in Table 1. The table focuses mainly on the specific design, location, latitude, productivity, percentage increase in the output, capital cost, water cost, experiment date and peak solar radiation. The table shows that the enhancements within the basin in terms of design, geometry, inclination, sensible heat storage material, insulation layers of wall, condenser design, use of multilayers, etc., lead to better yielding outputs.

Table 1: An overview of studies on different geometries of basins and materials that were incorporated for heat absorption improvement (Mohsenzadeh et al. 2021)



Reference	Specific design/modification	Location	Latitude (°N)	Productivity (kg m^{-2} d^{-1})	Increase in output (%)	Capital cost (US $)	Water cost (¢ L^{-1})	Experiment date	Peak solar radiation (W m^{-2})
El-Sebaii & El-Naggar, (2017)	Copper finned basin	Tanta	30.0	5.7	30	387	3.9	Jun	940
Omara et al. (2013)	Inclined basin/double-layer wick	Kafr El-Sheikh	31.0	5.9	114	120	2.7	Annu.	1000
Haddad et al. (2017)	One-layer vertical rotating wick	M'sila	35.0	7.2	15	337	1.1	Jun	950
Haddad et al. (2017)	One-layer vertical static wick	M'sila	35.0	5.7	10	288	0.8	Jun	950
El-Agouz, (2014)	Stepped basin/external water storage/cotton black wick	Tanta	30.0	5.9	80	300	3.5	10 Aug	910
El-Agouz, (2014)	Stepped basin	Tanta	30.0	4.9	50	290	-	10 Aug	910
Dashtban and Tabrizi, (2011)	Stepped basin	Zahedan	32.0	5.1	19	-	-	01 Jun	1000
Hansen et al. (2015)	Wire mesh stepped basin/ coral fleece wick	Kovilpatti	9.0	4.3	71	-	-	20 Apr	940
Hansen et al. (2015)	Stepped basin/ coral fleece wick	Kovilpatti	9.0	3.9	57	-	-	20 Apr	940
Hansen et al. (2015)	Single Flat basin/ coral fleece wick layer	Kovilpatti	9.0	3.6	45	-	-	20 Apr	940
Elango & Murugavel, (2015)	Multi-level basin/ stepped basin/double slope cover	Kovilpatti	9.0	5.3	18	-	-	Mar-Apr	1000
Arunkumar et al. (2018)	Floating porous foam	Chennai	13.0	3.1	48	-	0.6	02 Jun	842
Omara et al. (2016)	V-Corrugated basin with wick layer/Int.* reflectors	Kafr El-Sheikh	31.0	4.1	145	130	2.5	30 Jun	1120
Omara et al. (2016)	V-Corrugated basin with wick layer	Kafr El-Sheikh	31.0	3.8	90	122	3.6	30 Jun	1120
Omara et al. (2016)	V-Corrugated basin without wick layer	Kafr El-Sheikh	31.0	3.5	55	-	4.2	30 Jun	1120
Manokar et al. (2018)	Active solar still/FPC/ inclined basin	Virudhunagar	9.0	3.7	45	293	-	24 Apr	1000
Kabeel, (2009)	Concave wick basin/pyramid cover	Tanta	30.5	4.1	95	145	6.5	Jun	1000
Muftah et al. (2018)	Stepped finned basin/Ext. top reflector/Ext.* condenser	Egypt	31.0	8.9	29	-	-	Aug	1100
Alaian et al. (2016)	Pin-finned wick	Mansoura	30.0	4.7	23	-	-	07 Apr	900

METHODOLOGY

The study was performed at the Environmental Engineering Lab, Civil Engineering Department, Sir Syed University of Engineering and Technology, Pakistan. Prior to conducting the runs, the saline water samples were prepared with varying concentrations, namely, 07, 15 and 35 grams per liter, to ensure slightly saline, moderately saline and highly saline water samples. Among several designs, the tubular was still selected mainly because of its effectiveness in yielding the maximum output due to its maximum exposure to solar radiation supported by effective condensation collection. Herein, the design frame was modified by incorporating a few additional characteristics, i.e., rotating the basin to 360° for smooth collection of vapors and by bringing the native soil in contact to the basin cover to enhance the process of condensation, leading to better and timely yielding outputs. A detailed description of the model and the dimensions of the tray can be found in Fig. 7 and Fig. 8, respectively. For the conventional approach, droplets on top of the rotatable surface region were formed once the process of evaporation started. These droplets were collected by rotating the basin at different RPSs (rotation per second). On the other hand, for the native approach, once sufficient droplets at the top surface were formed, a porous material at the bottom of the platform was used to drop the temperature and enhance the condensation process. Once the vapors were converted to liquid and accumulated at the bottom of the basin, the rotatable basin was slightly tilted by using the iron angle to collect the desalinated water in the storage tank.

Figure 7: Description of the experimental model

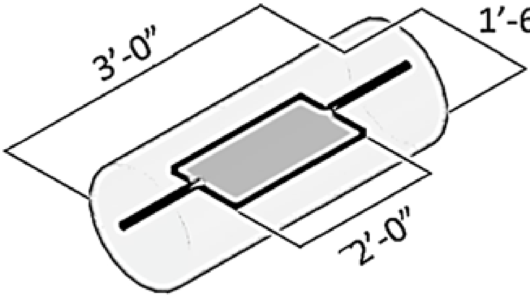


Figure 8: Dimensions of the tray and tubular still

RESULTS AND DISCUSSION

The study was performed during the winter season, i.e., November and December 2022, when the average temperature remained low compared to the average annual temperature of Karachi, Pakistan. A comparative performance analysis was conducted between the conventional and native approaches. The study outcomes included assessing the rate of evaporation at different concentrations of salts with respect to temperature and humidity after every hour, whereas the impact of wind velocity was not taken into consideration. The amount of saline water in the tray was also noticed so that the salt content left after evaporation could also be noticed. Later, the output in terms of potable water was also measured.

Rate of Evaporation at Various Temperatures and Humidity-Conventional Approach

In recent studies, it has been noticed that solar stills are usually connected with extra solar collectors to raise heat energy, which then leads to greater water productivity. Herein, the aim of the study was to enhance the condensation process of the solar still alone by interacting native porous material with the cover section, also called the condensation structure.

Initially, the tests were performed following the criteria of the conventional approach, as shown in Fig. 9, i.e., by allowing the saline water to evaporate based on the varying temperatures and humidity under sunlight and normal weather conditions. Since the tests were performed on different days, the temperature varied accordingly. For instance, the sample with a salt concentration of 15 grams gave maximum evaporation rates when compared to other salt concentrations, namely, 07 and 35 grams, respectively. Due to higher temperatures, the water molecules are believed to be moving faster, which provided enough energy to break away from the liquid to gas. On the other hand, the evaporation rates remained low for the sample with the maximum salt concentration, i.e., 35 grams, as shown in Fig. 10. This occurred mainly for two reasons: first, low temperatures were noticed throughout the entire day, and second, the water molecules are believed to have created a strong bond with the dissolved salt ions for which a strong heat energy source was needed to break apart those water molecules.

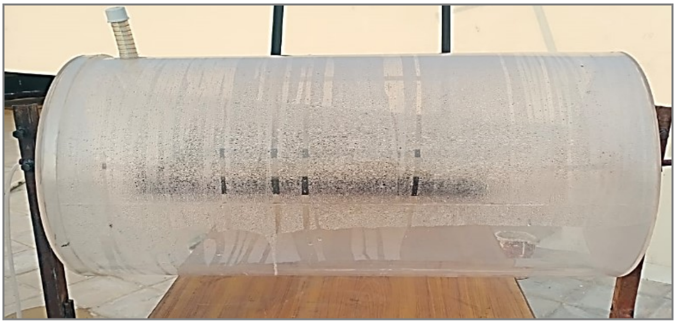


Figure 9: Condensation phase-conventional approach.

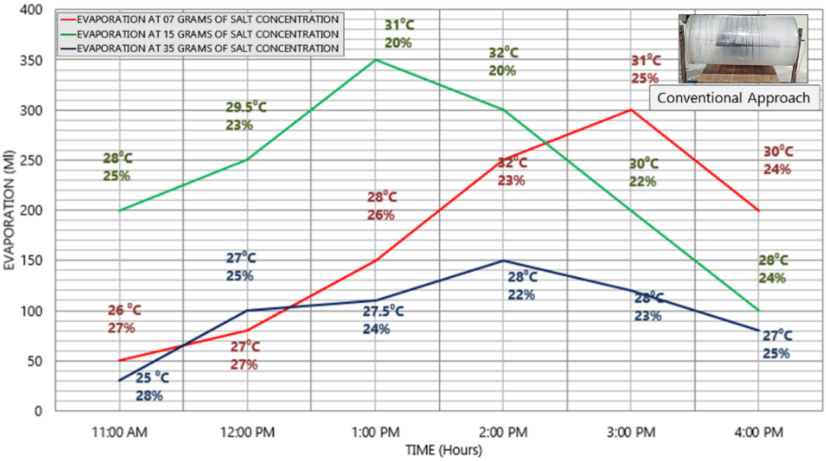


Figure 10: Rate of evaporation at varying temperatures and humidity-conventional approach.

Output obtained at each hour based on evaporation rates-Conventional Approach

Fig. 11 describes more about the output obtained at each hour for all samples with different salt concentrations. Since evaporation is directly proportional to the output, higher water volumes were witnessed when the temperature remained high. Due to the capability of the tube to rotate at 360°, the vapors collected at the cover section accumulated and were collected by slightly tilting the basin toward the outlet. It was noticed that to gather the water in the vaporized form, the basin was rotated at 360°, and it took nearly 3.0 seconds for the basin to complete one rotation cycle. Thus, to gather the maximum output, the basin was rotated at least 12 times. The basin was designed in such a way that the water carrying tray remained intact and no saline water was dropped into the collection zone. The minimum output was found to be 15 ml for 07 grams of salt concentrated sample at 11:00 am in the morning, where the amount of water evaporated was almost 50 ml at 26°C and 27% humidity. Similarly, the maximum output of almost 180 ml for 35 grams of salt concentrated sample was collected at 3:00 pm, where the amount of water evaporated was approximately 200 ml at 30°C and 22% humidity. This ensures that the rate of evaporation efficiently increases at higher temperatures.

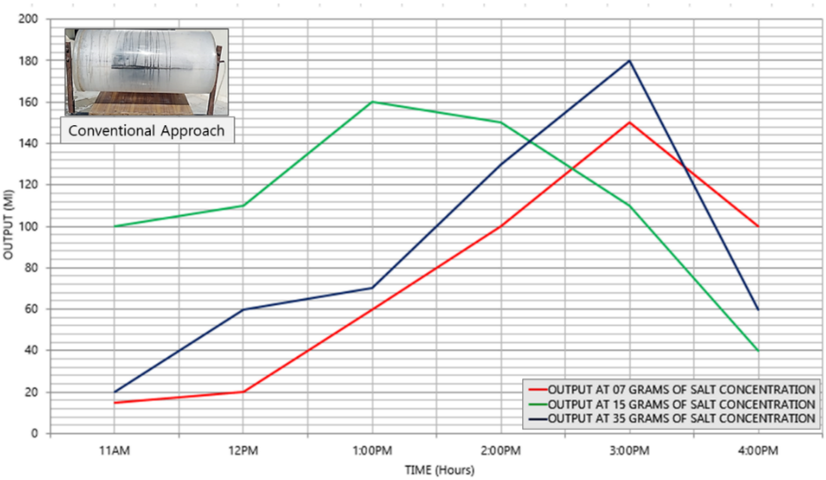


Figure 11: Output attained at different intervals (hours)-conventional approach.

Salt concentrations with respect to time-Conventional Approach

Desalination is a process that separates water molecules from saline water. Herein, the overall salinity at different intervals remained high for high salt concentrations, which is obvious. However, for every passing interval, the salinity was found to increase, as shown in Fig. 12. This occurred because the amount of water kept in the tray remained constant, i.e., 2000 ml, while initiating the test runs. After every hour, a portion of the saline water evaporated, and the salt minerals were left behind in the tray. Thus, with every passing interval, the leftover salt remained in the tray, which increased the salinity of the water in the tray.

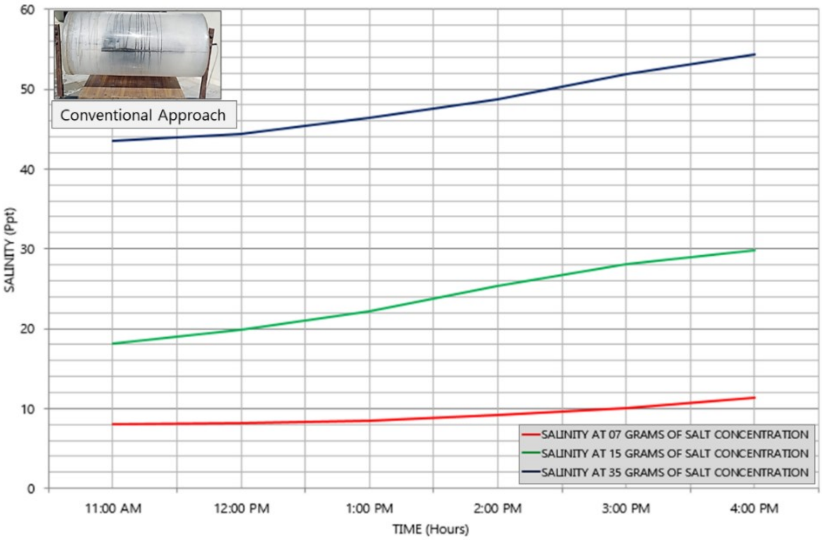


Figure 12: The amount of salinity in the tray after every interval (hour)-conventional approach.

Rate of Evaporation at Various Temperatures and Humidity-Native Approach

A similar approach was followed while assessing the evaporation rates when compared to the conventional approach. From the native approach, it can be seen that the maximum evaporation output was approximately 220 ml, whereas in comparison to the conventional approach, the maximum evaporation output was 350 ml. It should be emphasized that the porous material introduced herein has no relevance in regard to evaporation rates, as the aim of the porous material was to enhance the process of condensation once the water is evaporated from the tray. The main reason for higher evaporation rates herein is due to low relative humidity and high temperature. For instance, at the time interval of 2:00 pm, the evaporation rates were higher at 32° and 19% relative humidity, as shown in Fig. 13.

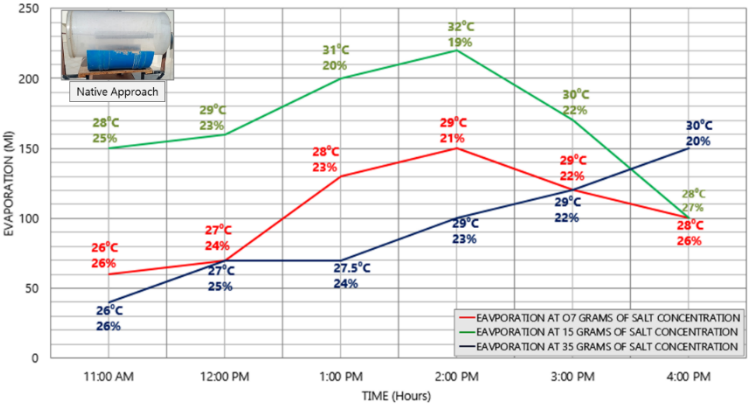


Figure 13: Rate of evaporation at varying temperatures and humidity-native approach

Output obtained at each hour based on evaporation rates-Native Approach

Referring to the conventional approach, the tube was rotated at least 12 times to ensure sufficient vapor collection by slightly tilting the basin toward the outlet. The purpose of rotation was to ensure sufficient collection of vapors. Similarly, for the native approach, it was noticed that after evaporation when the contact of native material was made to the cover section, the rotations were significantly decreased to almost 04 times at the same time. The use of clay as a native material, as shown in Fig. 14, ensured that the tiny pores on its surface allowed the water to evaporate quickly. The heat energy accumulated in the basin was transferred to this porous material, which lowered the inside temperature to some extent. This low temperature enhanced the condensation process, which in turn allowed the accumulated vapors to quickly change their state and gather at the designed outlet. The maximum output obtained by using the native material reached up to 220 ml for 15 grams of salt concentration at 2:00 pm, as shown in Fig. 15, whereas for the conventional approach, the maximum output was found to be approximately 180 ml for 35 grams of salt concentration at 3:00 pm. A better justification regarding overall outlet collection from both approaches is discussed later in this paper.

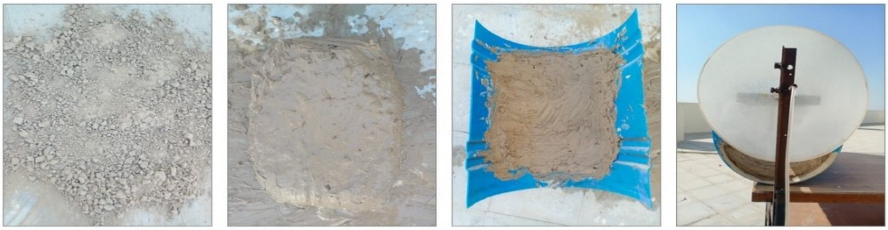


Figure 14: Use of porous material to enhance the condensation-native approach

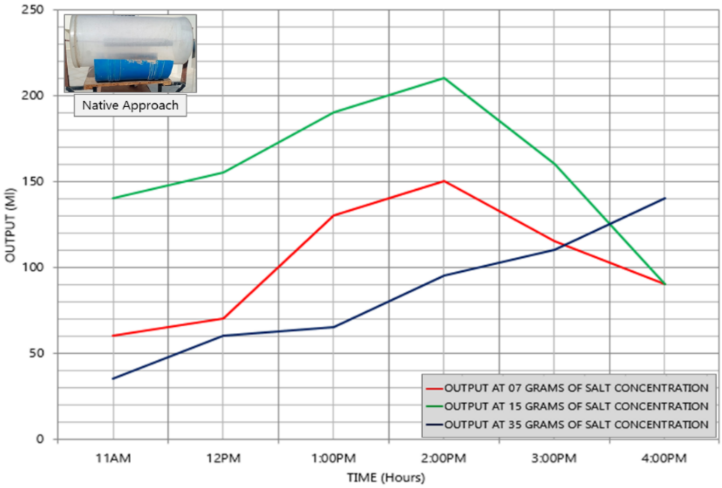


Figure 15: Output attained at different intervals (hours)-native approach.

Salt concentrations with respect to the time-Native Approach

A very similar trend of salt concentration was noticed for both the conventional and native approaches. For instance, the overall salinity at different intervals remained high for high salt concentrations, whereas for every passing interval, the salinity was found to be increasing. The maximum salinity was found to be 10, 26 and 52 ppt for salt concentrations of 07, 15 and 35 grams, respectively, at the end of the test runs, i.e., at 04:00 pm, as shown in Fig. 16.

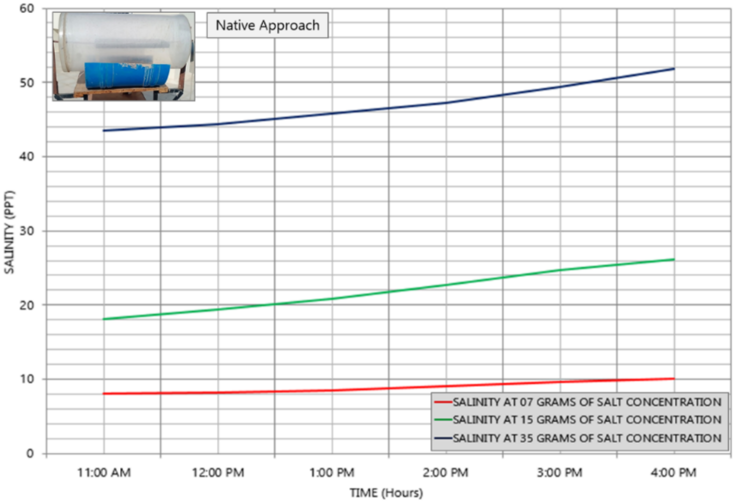


Figure 16: The amount of salinity in the tray after every interval (hour)-native approach.

RESEARCH CONTRIBUTION

From the study outcomes, it can be seen that incorporating porous soil into the stilling basin assisted in quickly changing the state of the vapors to liquid since it lowered the inner temperature of the basin. Additionally, the rotation mechanism of the basin helped collect the accumulated water quickly. Thus, the output efficiency was found to be greatly enhanced. The use of native soil assured quick formation of vapors back to the liquid state, whereas the rotation mechanism further enhanced the collection phase with only a few rotations. Therefore, this research is believed to have contributed well to obtaining effective yields. The overall amount of water collected at the end of each day for both the conventional and native approaches is shown in Fig. 17. The maximum output for both approaches was obtained for a 15 gram/liter salt concentration sample. This occurred mainly because of two factors, i.e., low relative humidity and higher temperatures, while conducting the test runs. However, it was perceived that for both the conventional and native approaches, the rate of evaporation would be higher for the 07 grams/liter salt concentration sample since it contained a lower salt content. However, from the study outcomes, it was found that the rate of evaporation is more contingent on heat energy and relative humidity than on the salt concentration. On the other hand, the outcomes obtained from the native approach, i.e., 945 ml of water at 15 grams/liter salt concentration, seem to have been dominant when compared to the conventional approach, i.e., 670 ml of water at 15 grams/liter salt concentration. This ensured that the use of porous material had the capability to lower the temperature of the evaporated droplets. This not only reduced the number of rotations needed for collecting the droplets but also helped accumulate the droplets at a faster pace. Thus, it can be stated that the yielding capability of the still is enhanced if such native material is used.

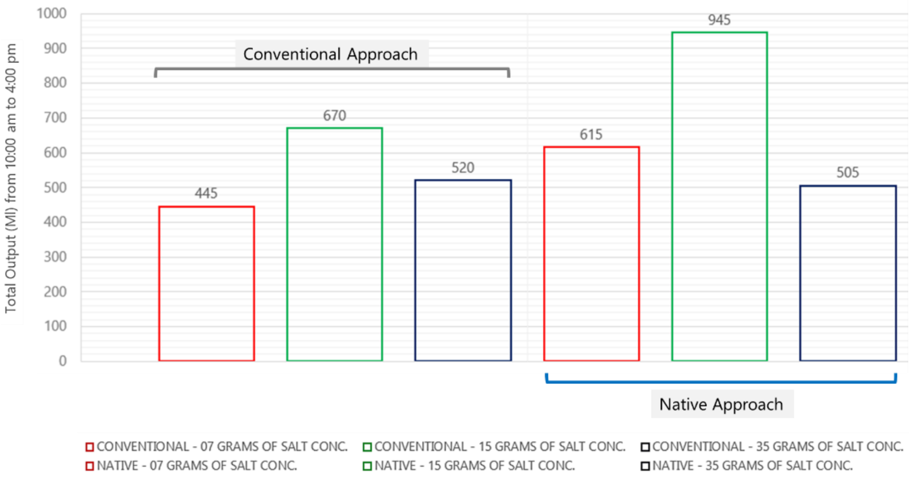


Figure 17: The cumulative output for the entire day (10:00 am to 6:00 pm) observed for both the conventional and native approaches

CONCLUSIONS

In this study, conventional and native solar stills were modeled to investigate the yield efficiency at different salt concentrations. The study outcomes were found to be proportional to parameters such as the intensity of solar radiation, ambient temperature, relative humidity and wind pressure. Tubular designs have been previously used; however, the concept of rotating it to 360° drastically enhanced the yields. Moreover, the induction of porous material to enhance the condensation process also worked well. The tiny pores on the porous surface allowed the water to evaporate quickly. The heat energy accumulated in the basin was transferred to this porous material, which lowered the inside temperature to some extent. This low temperature enhanced the condensation process, which in turn allowed the accumulated vapors to quickly change their state and gather at the designed outlet. The maximum output was obtained for a salt concentration sample of 15 grams/liter. This occurred mainly because of two factors, i.e., low relative humidity and higher temperatures. Thus, it can be concluded that the rate of evaporation is more contingent on heat energy and relative humidity than on the salt concentration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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