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Combined enhancement of evaporation and condensation rates in the solar still for augmenting the freshwater productivity using energy storage and natural fibres

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ABSTRACT

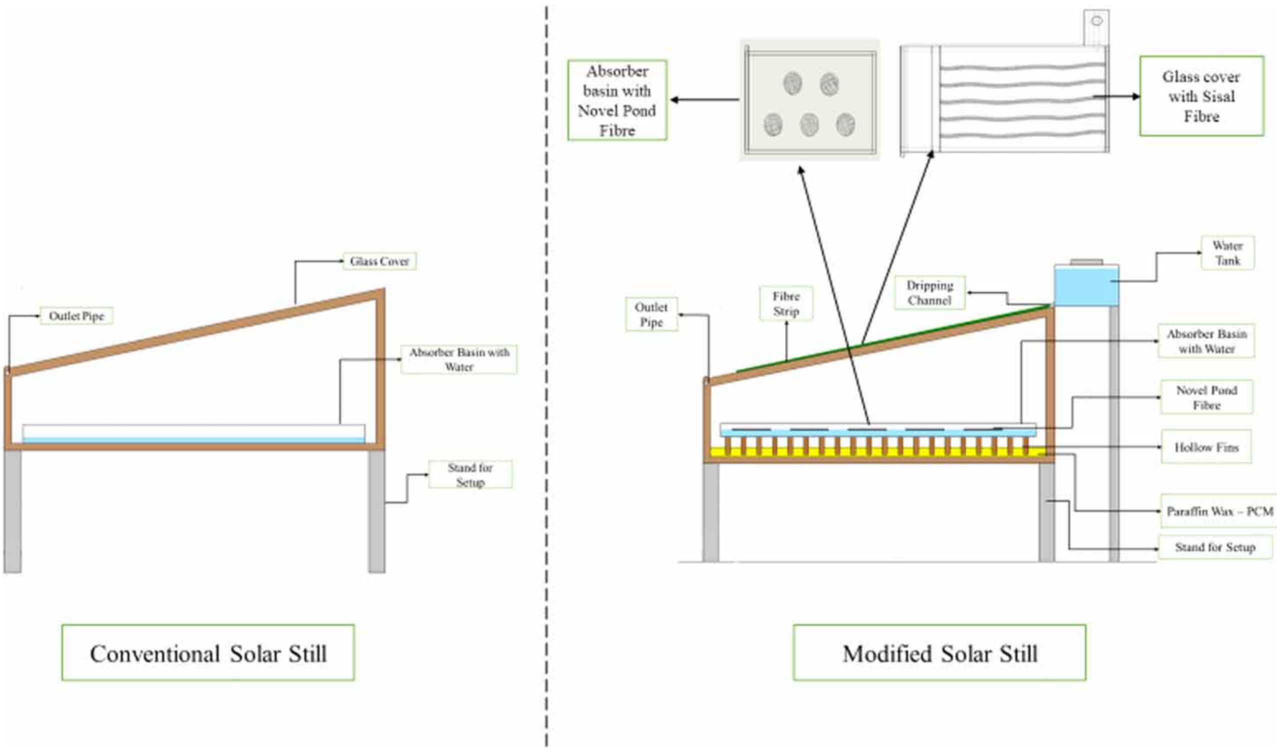
The freshwater production in a conventional solar still (CSS) is very less and it can be enhanced by either enhancing evaporation or condensation rates or both in the solar still. Therefore, the current investigation focused on enhancing both the evaporation rate in the absorber basin and the condensation rate over the top glass simultaneously. In this regard, the evaporation rate is enhanced by using a hollow-finned absorber basin with energy storage and novel pond fibres in the absorber basin. Likewise, the sisal fibre with a water dripping arrangement is utilized for enhancing the condensation over the top glass. The investigations on the CSS and the modified solar still (MSS) with hollow fins and energy storage, pond fibres, and sisal fibres are conducted to analyze the effect of energy storage and natural fibres on the distillate production. It is observed that the water temperatures of the MSS are increased by 12% and the glass temperatures of the MSS are reduced by 30% relative to the CSS. The outcomes reported that the productivity of the MSS is enhanced by 126%. Furthermore, the cost per litre (CPL) and the payback period (PP) of the MSS are 38.5 and 49.3% lesser than the CPL and the PP of the CSS, respectively.

Key words: desalination, energy storage, natural fibres, productivity, solar still

HIGHLIGHTS

- The performance of the solar still is examined with energy storage and natural fibres.
- The water temperatures of the MSS are increased by 12% relative to the CSS.
- The glass temperatures of the MSS are reduced by 30% relative to the CSS.
- The productivity of the MSS is 126% higher than that of the CSS.
- Economic analysis depicted that the MSS is more economically viable than the CSS.

GRAPHICAL ABSTRACT



INTRODUCTION

A solar still is recognized as one of the sustainable and viable approaches to desalination. The solar still is an uncomplicated system in design and fabrication. Also, it is easy to operate and can be effectively adopted by less skilled operators for desalinating seawater (Sharon & Reddy 2015; Mohsenzadeh *et al.* 2021; Mu *et al.* 2021; Natarajan *et al.* 2022a; Suraparaju *et al.* 2022b; Thakur *et al.* 2022). However, the daily productivity of the solar still is relatively low and many kinds of research are currently being undergone to augment the overall yield through several modifications such as energy storage, natural fibres, and condensing units (Arunkumar *et al.* 2021; Chauhan *et al.* 2021). The various researches regarding enhancement of evaporation as well as condensation rates in the solar still are discussed. Mehta *et al.* (2021) studied the influence of integrating flat plate collectors (FPCs) to the solar still. It was observed that the solar still with FPC had better productivity at 3 and 4 cm water depths relative to the traditional solar still. Joe Patrick Gnanaraj & Ramachandran (2021) assessed the impact of various operational parameters on the performance of the solar still. It was found that the 16 kg energy storage, 2 cm water depth, and 4 mm glass cover thickness gave maximum productivity with a plain absorber basin. It was noted that the combination of all optimum parameters improved the productivity by 94% in the plain basin compared to the conventional solar still (CSS). Essa *et al.* (2021) examined the effect of porous steel fibres and shaded condensers on the freshwater production rate of the solar still. It was observed that the porous fibres and shaded condensers augmented the production rate by 5 and 12%, respectively, compared to the CSS. Shmroukh & Ookawara (2020) investigated the performance of the solar still with reflectors and energy storage for augmenting the distillate production. It was found that the productivity was augmented by 129% compared to the CSS. Suraparaju & Natarajan (2021a) studied the impact of porous luffa fibres on the productivity of the solar still. It was noted that the optimum number of fibres to be placed in the solar still was 15 and the productivity enhanced with 15 fibres was about 25.23% compared to the CSS. Dsilva Winfred Rufuss *et al.* (2022) studied the performance of the solar still with paraffin wax and graphite (nano) absorber plate. It was reported that the productivity of the solar still with modifications had attained a yield of 5.5 kg/m^2 whereas the CSS attained a yield of 35 kg/m^2. Mohammed *et al.* (2021) studied the performance of the solar still with phase change material (RT42PCM) for enhancing freshwater production. It was reported that the yield was enhanced by about 29.7% compared to the CSS. Nagaraju *et al.* (2022) assessed the significance of sand troughs as energy storage for enhancing the performance of the solar still. It was found that the productivity of the solar still with sand troughs was enhanced by 71.4% compared to the CSS. Tigrine *et al.* (2021) studied the performance of the solar still with energy storage and electric heater. It was observed that the solar-modified still had a better yield with 50% enhancement compared to the CSS. Attia *et al.* (2022) assessed the combined impact of glass cover cooling and copper oxide nanoparticles on the freshwater production rate of the solar still. It was observed that the solar still with glass cover cooling and nanoparticles augmented the production rate by 105.2%. Mohamed *et al.* (2021) investigated the impact of wick material and obtuse surface for better productivity of the solar still. It was observed that the solar still with porous media and the obtuse surface had 1.74 folds better production compared to the CSS. Mevada *et al.* (2021) studied the effect of combined enhancement of evaporation and condensation rate using fins, evacuated tube collectors, and air-cooled glass cover. It was found that the combined effect enhanced the productivity in modified still by almost 73.45% relative to the CSS. Also, the Enviroeconomic performance depicted that modified still was sustainable compared to the CSS. Adibi Toosi *et al.* (2021) assessed the combined impact of phase change material and external condenser on the daily potable water production from the solar still. It was noticed that the combination of PCM and condenser enhanced the daily potable water production by 104%.

It can be summarized from the above literature that many kinds of research have been conducted on the enhancement of evaporation and condensation rates thereby freshwater production is enhanced in the solar still. Nevertheless, the combined enhancement of evaporation and condensation rates improved the yield significantly compared to individual enhancement of either evaporation or condensation. However, there is very little research on the bottom-finned absorber basin with PCM and natural fibre utilization for performance improvement in the solar still. Thus, the current research is focused on improving freshwater production by augmenting the evaporation and condensation simultaneously in the solar still. The bottom-finned absorber basin with PCM (Suraparaju & Natarajan 2021b), novel pond fibres in the basin (Suraparaju *et al.* 2021), and sisal fibres are simultaneously used in the solar still for enhancing the water productivity. Furthermore, the cost assessment is analyzed for examining the viability of the considered solar stills.

METHODS

The current section gives a brief description of the overview of materials and methodology opted for experimentation.

Description of experimental setups

In the current investigation, the experiments are carried out for 2 days on two different solar stills. The solar stills considered for experimental investigation are:

- The conventional solar still (CSS) and
- The modified solar still (MSS) with hollow fins with PCM, novel pond fibre, and sisal fibre.

Materials and fabrication

The solar stills are primarily manufactured using plywood and the inner area is covered with an aluminium sheet of 2 mm thickness to restrict the direct contact of water/vapour with wood. Furthermore, the absorber basin of 0.6 m^2 area is fabricated using 1-mm thick copper sheets. In addition, the absorber basin is coated with selective coating and the aluminium sheet is coated with normal black paint for better absorption of solar radiation through a 3-mm transparent cover arranged at an angle of 11° over the solar still. Finally, the outer area of the solar still is covered with polystyrene sheets to arrest the heat losses to the ambient.

Methodology

In this investigation, the MSS with hollow fins with PCM (220 fins – Suraparaju & Natarajan 2021b), the novel pond fibre (Suraparaju *et al.* 2021), and the sisal fibre over the glass cover are analyzed for productivity improvement. The absorber basin is filled with seawater at a depth of 2 cm for better productivity (Suraparaju & Natarajan 2021c). The hollow-finned absorber basin and novel pond fibres in the basin are mainly utilized for enhancement of evaporation rate by augmenting the absorber and water temperatures in the solar still. Besides PCM and fins, the sisal fibre is utilized for enhancing the condensation rate in the solar still. The porosity, water absorption, and retention properties of natural fibre are the notable factors that affect the condensation rate of the glass cover. Also, the low cost, availability, and environmental aspects are the other factors considered for selecting fibres (Suraparaju & Natarajan 2022). The sisal fibre with good porosity (17%), water absorption

(104.5%), and retention (43 min) is selected in this research for cooling the glass cover (Teja *et al.* 2016). In this regard, five strips of sisal fibres (each strip: 65 cm × 5 cm = 0.0325 m^2 area) are placed over the top glass. The area covered by the five fibre strips is almost 20% (0.1625 m^2) of the glass cover area (0.8 m^2). The sisal fibres are attached to the holes of the dripping channel. Later, the dripping channel and sisal fibres are integrated into the water tank such that the water from the dripping channel flows through the fibres. The water is dripped over the glass cover every 30 min for cooling the glass cover. The sisal fibre absorbed the flowing water from the dripping channel and cooled the glass up to the next drip. Thus, the sisal fibre cooled the glass continuously such that the glass temperatures of the MSS are greatly reduced compared to the CSS. The experiments on the CSS and MSS are conducted in July 2021 to investigate the effect of the simultaneous enhancement of evaporation rate and condensation rate on freshwater production. Also, the experiments are repeated to ensure repeatability and it is observed that there was no major change in the productivity during the repetition of experiments. The methodology adopted and the schematic of the current investigation are represented in Figure 1(a) and (b). Also, the photograph experimental arrangement is shown in Figure 2. Besides experimentation, the incoming insolation is measured using a

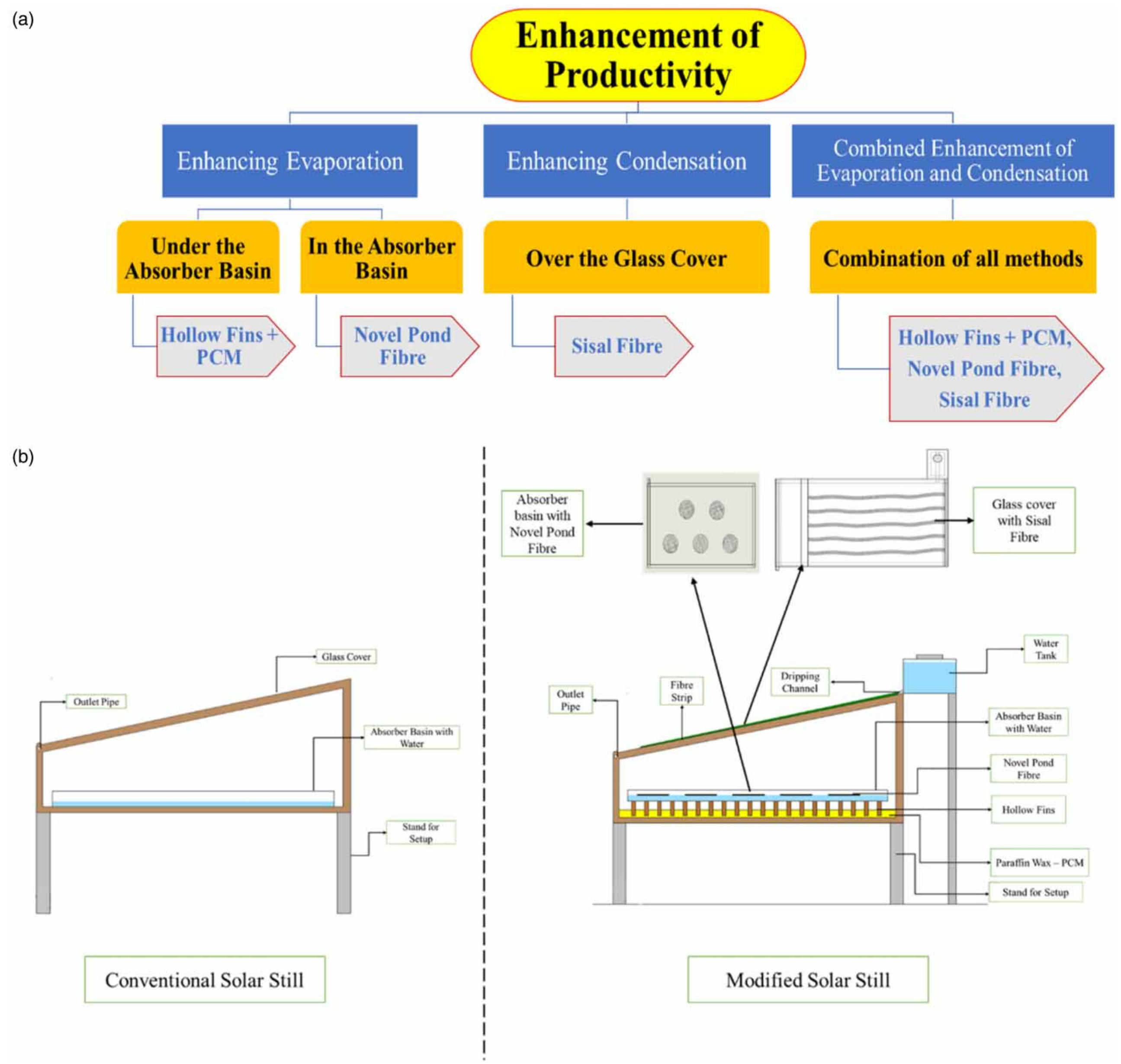


Figure 1 | (a) Methodology of current research and (b) schematic representation of the experimental setup.

Figure 2 | Photograph of the CSS and the MSS.

'Pyranometer'. The temperatures of the solar still and ambient temperature are measured using K-type thermocouples. The experiments are conducted during 08:30 and 21:30 (IST) and readings are noted for every half an hour. The standard uncertainty of the measuring instruments is shown in Table 1. The uncertainty in the efficacy is given by Equation (1). It was assessed that the uncertainty in instantaneous distillate output was 1% and the error in the efficiency of the solar still by taking all the above into account was about ±2%.

$$u_{\eta} = \left[\left(\frac{\partial \eta_d}{d_w} \times u_{d_w} \right)^2 + \left(\frac{\partial \eta_d}{I(t)} \times u_{I(t)} \right)^2 \right]^{\frac{1}{2}} \quad (1)$$

Thermal and economic analysis

This section gives an account of thermo-economic aspects of the single-slope solar still configurations considered for experimental investigation.

Thermal efficiency

The thermal efficacy of the solar still is assessed by using the following equation (Khallaf *et al.* 2021; Suraparaju *et al.* 2022a)

$$\text{Efficiency} = \frac{D \times L_{Water}}{A \times G} \quad (2)$$

$$L_{Water} = 10^3 \times [2501.9 - (2.40706 \times T_w) + 1.192217 \times 10^{-3} \times T_w^2 - 1.5863 \times 10^{-5} \times T_w] \quad (3)$$

Table 1 | Standard uncertainties (Suraparaju & Natarajan 2021b)

S. No.	Instrument	Range	Accuracy	Standard uncertainty
1	K-type thermocouple (°C)	−270 to 1,260	±0.1	0.058
2	Pyranometer (W/m^2)	0–1,600	±10	5.8
3	Measuring jar (ml)	0–1,000	10	5.8

where D is the cumulative distillate yield, L_{Water} is the latent heat of evaporation of water, T_w is the temperature of water in the absorber, A is the absorber area, and G is the overall solar radiation.

Economic analysis

The primary intention of the economic assessment is to find out the cost per litre (CPL)/1 m^2 absorber area of the solar still. The approach for evaluating CPL and the PP for a solar still is determined in the previous studies (Tiwari & Sahota 2017; Suraparaju & Natarajan 2021d, 2022).

$$\text{Cost per liter/m}^2\ \ (\text{CPL}) = \frac{A_c}{Y_{li}} \tag{4}$$

where Y_{li} is the average distillate yield per year and A_c is the annual cost. The PP is assessed by the following equation

$$\text{Payback period (PP)} = \frac{\text{Capital investment}}{\text{Total revenue per day}} \tag{5}$$

RESULTS AND DISCUSSION

The experiments are conducted with the CSS and MSS to assess the combined performance of solar stills with energy storage and natural fibres.

Global solar radiation and ambient temperature

The variation of global solar radiation and ambient temperature during the experiment (08:30–21:30 IST) on all the testing days is graphically plotted and represented in Figure 3. From Figure 3, the maximum and average global solar radiation on all days of testing are in the range of 1,030 and 704–512 W/m^2, respectively. It is also revealed that the ambient temperature is ranging from 23 to 41 °C during the experimentation. The average ambient temperature reported on all testing days is about 32 °C. The part of incoming solar radiation is hindered by the sisal fibre strips over the glass cover and the remaining solar radiation is transmitted through the transparent glass to the absorber basin. However, the effect of solar radiation on the corresponding temperatures of the solar still is discussed in the next sections.

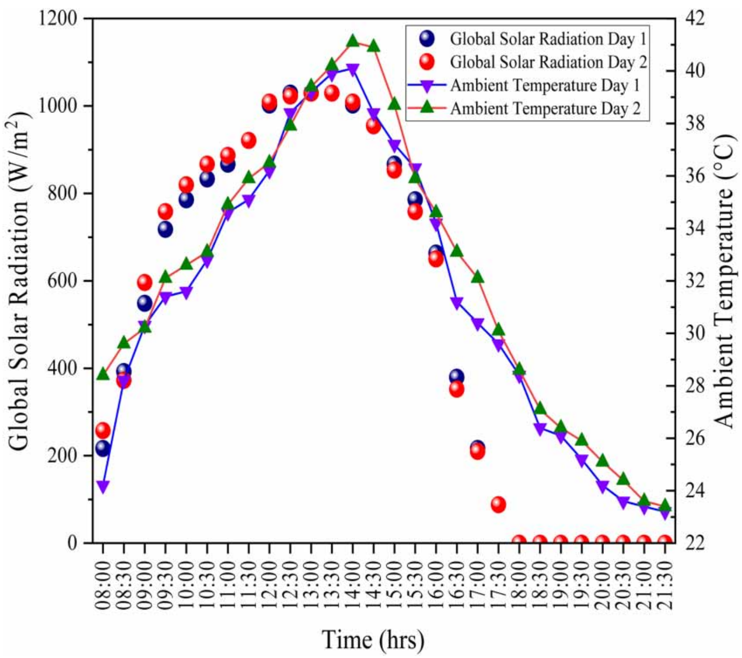


Figure 3 | Variation of solar radiation and ambient temperature.

Solar still temperatures

The system temperatures of the CSS and MSS on the first day and second day are graphically plotted and represented in Figure 4(a) and (b), respectively. From Figure 4(a), the highest glass cover temperatures on the first day are observed as 47.1 and 36.2 °C, respectively, for the CSS and MSS during peak sunshine hours of the day. It is observed that the maximum temperature of the sisal fibre is about 35.6 °C, which reduced the glass cover temperatures significantly by about 30.1%. It is also noticed that the highest temperatures of PCM, fins, and novel pond fibres are about 57.5, 61.2, and 62.3 °C, respectively, which augmented the water and absorber temperatures of the MSS compared to the CSS. On the other hand, the highest absorber temperatures of the CSS and MSS are reported as 62.4 and 70.3 °C, respectively. The absorber temperature of

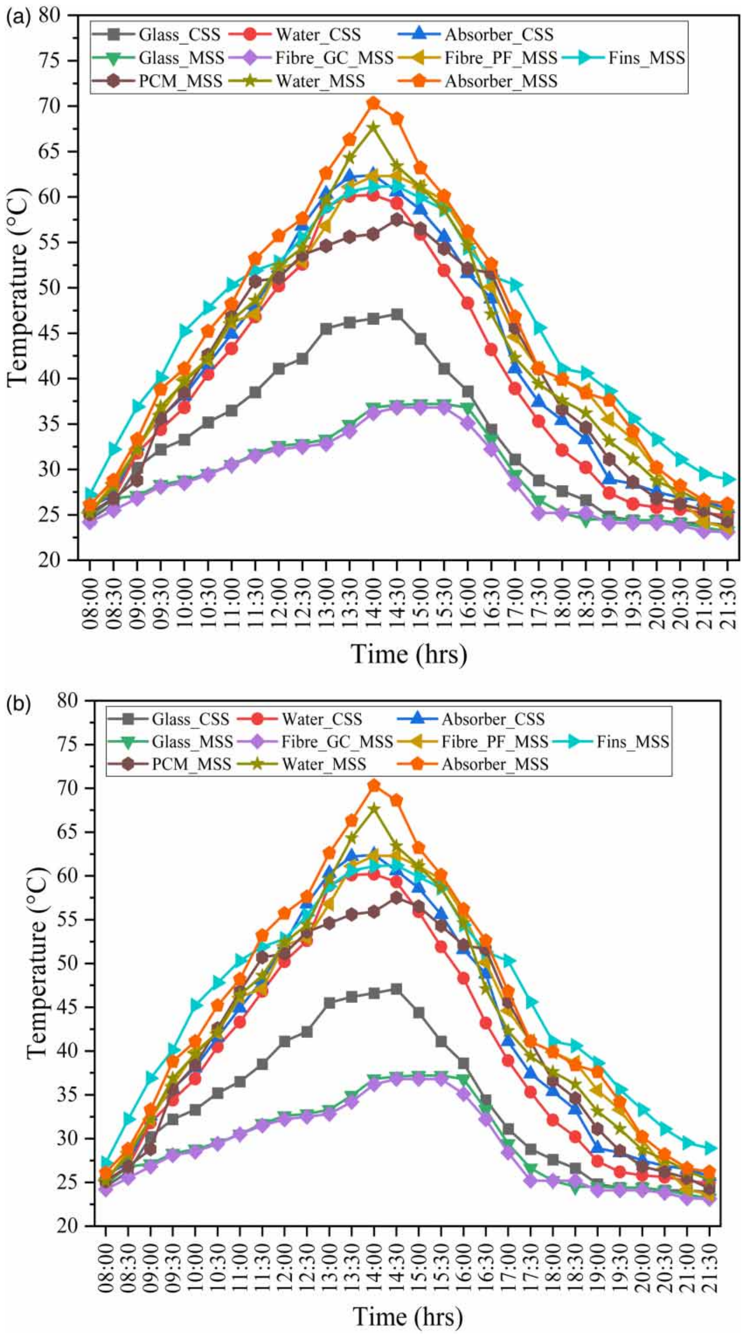


Figure 4 | (a) Solar still temperatures on Day 1 and (b) solar still temperatures on Day 2.

the MSS is augmented by about 13% compared to the CSS. Also, the maximum water temperatures of the CSS and MSS are reported as 60.2 and 67.6 °C, respectively. It is observed that the water temperatures of the MSS are augmented by about 12%. From Figure 4(b), the highest glass cover temperatures on the second day are observed as 51.3 and 37.2 °C, respectively, for the CSS and MSS during peak sunshine hours of the day. It is observed that the maximum temperature of the sisal fibre is about 36.7 °C, which reduced the glass cover temperatures significantly by about 32%. It is also noticed that the highest temperatures of PCM, fins, and novel pond fibres are about 58.9, 62.2, and 62.3 °C, respectively, which augmented the water and absorber temperatures of the MSS compared to the CSS. On the other hand, the highest absorber temperatures of the CSS and MSS are reported as 63.2 and 71.1 °C, respectively. The absorber temperature of the MSS is augmented by about 13% compared to the CSS. Also, the maximum water temperatures of the CSS and MSS are reported as 61.7 and 67.8 °C, respectively. It is observed that the water temperatures of the MSS are augmented by about 12%. Despite the reduced incoming solar radiation in the MSS due to sisal fibres over the glass cover compared to the CSS, the glass temperature in the MSS reduced effectively relative to the CSS. Also, the absorber and water temperatures are significantly raised because of hollow fins, PCM and pond fibres on both days of experimentation. Therefore, the raise in absorber and water temperatures increased the evaporation rate and the reduction in glass temperatures increased the condensation rate in the MSS.

Glass cover and water temperature difference

The difference between basin water and glass cover temperatures is a noteworthy factor in improving the condensation rate over the glass cover. The lower the glass cover temperature, the greater the condensation rate. It is mainly because the hot water vapours rise towards the glass cover from the absorber and stick to the interior of the glass cover. If the glass cover temperature is lower than that of water vapour temperature, then there is a possibility of more heat transfer and immediate condensation of water vapours. Hence, the lower glass cover temperatures lead to greater condensation rates.

The variations in the difference between the water temperature in the absorber and the glass cover temperature ($\Delta T = T_{water} - T_{glass}$), is graphically plotted and represented in Figure 5. The ΔT is plotted for all the experiment days for the CSS and MSS for better comparison. From Figure 5, the maximum ΔT for the CSS and MSS are observed as 14.2 and 31.4 °C, respectively. Also, the average ΔT of all the considered solar stills is plotted in Figure 6. It is reported that the average ΔT of the CSS and MSS are 6.2 and 13.6 °C, respectively. Moreover, it is also revealed that the ΔT of the CSS and MSS has a variation of about 8 °C which is a substantial factor in minimizing the glass temperatures. Therefore, the condensation rate over the glass is enhanced substantially and the distillate output from the MSS is also improved relative to the CSS.

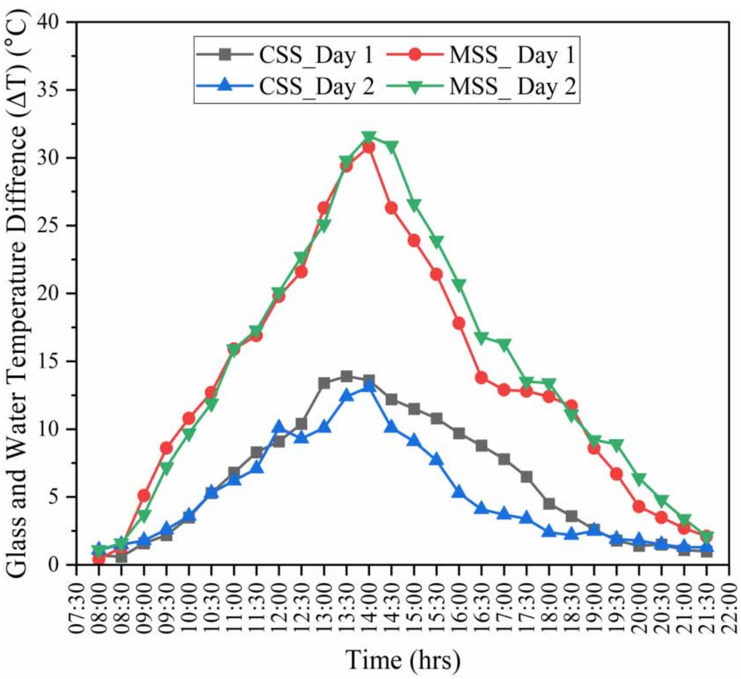


Figure 5 | Difference between water and glass temperatures.

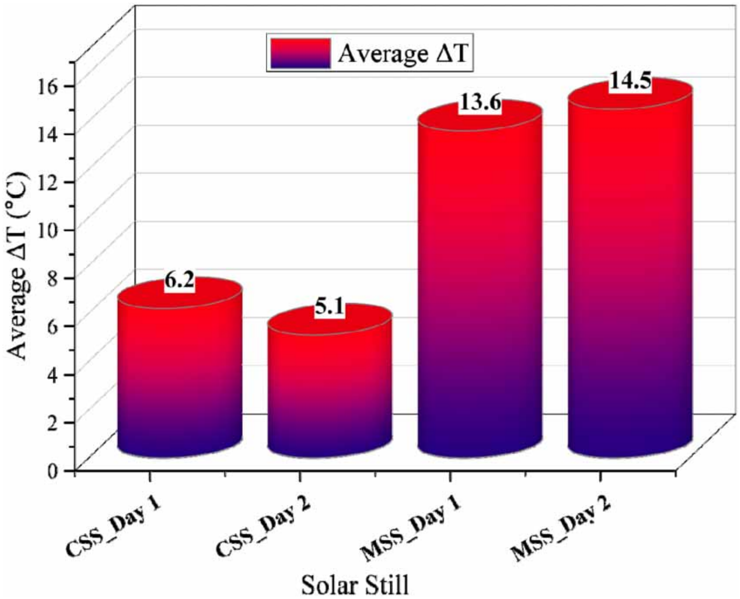


Figure 6 | Average difference between water and glass temperatures.

Productivities of solar stills

The cumulative distillate output of the CSS and MSS on all the days are graphically plotted and represented in Figure 7. It is noticed that the cumulative distillate output of the MSS is higher relative to the CSS. The cumulative yields of the MSS are about 5,750 and 5,780 ml/m^2 on the first and second days, respectively. The maximum distillate output of all solar stills is plotted in Figure 8. It is reported that the maximum distillate outputs of the CSS are 2,530 and 2,550 ml/m^2, respectively on the first and second days of the experiment. From the above corollaries, the distillate output is greater in the MSS. It is mainly due to an increase in the evaporation and condensation rates in the MSS. It is mainly due to the action of hollow fins, PCM, pond fibres, and sisal fibres in the solar still. The enhancement in the distillate output in the MSS is plotted as

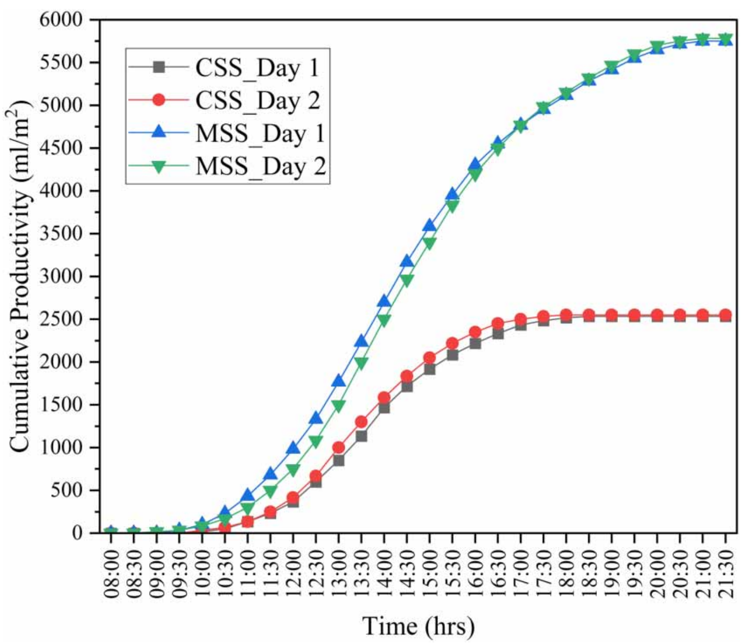


Figure 7 | Cumulative distillate output of solar stills.

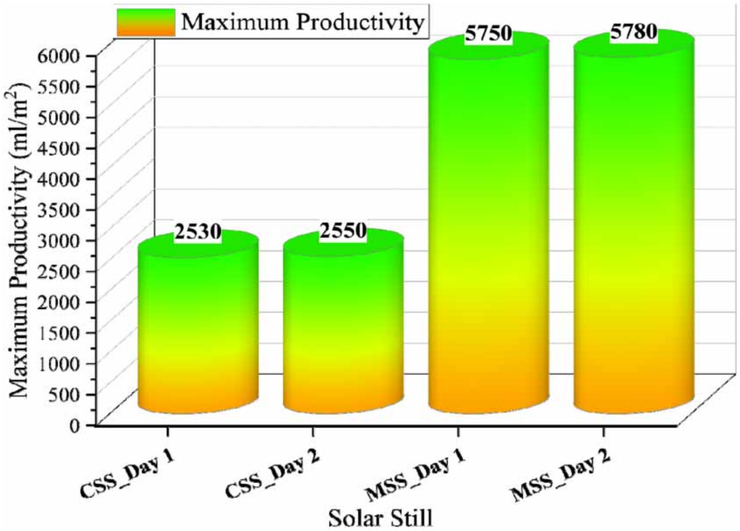


Figure 8 | Maximum productivity of solar stills.

a histogram in Figure 9. It is revealed from Figure 9 that the freshwater yield is augmented by 126% in the MSS compared to the CSS.

Combined effect of fins, PCM, and natural fibres

The incorporation of fins, PCM, and novel pond fibres enhanced the water and absorber temperatures significantly and enhanced the evaporation rate in the solar still. Also, the sisal fibres with water dripping reduced the glass cover temperatures effectively and enhanced the condensation rate in the solar still. The primary reason for the enhancement of evaporation in the solar still is the hollow structured fins with more space for extensive heat transfer between absorber and PCM during sunshine hours and vice-versa during non-sunshine hours. However, the inclusion of PCM increased the working time of the solar still by providing additional heat to the absorber after the sunset. In addition to fins and PCM, the porous pond fibres enhanced the wet surface in the absorber basin and increased the evaporation rate enormously which led to higher productivity. It is observed that the absorber and water temperatures of the MSS are augmented by about 13 and 12%, respectively. Besides evaporation, the sisal fibres significantly reduced the glass cover temperatures throughout the experiment and enhanced the condensation rate. The primary reason for the reduction in glass cover temperatures of the MSS is the dripping

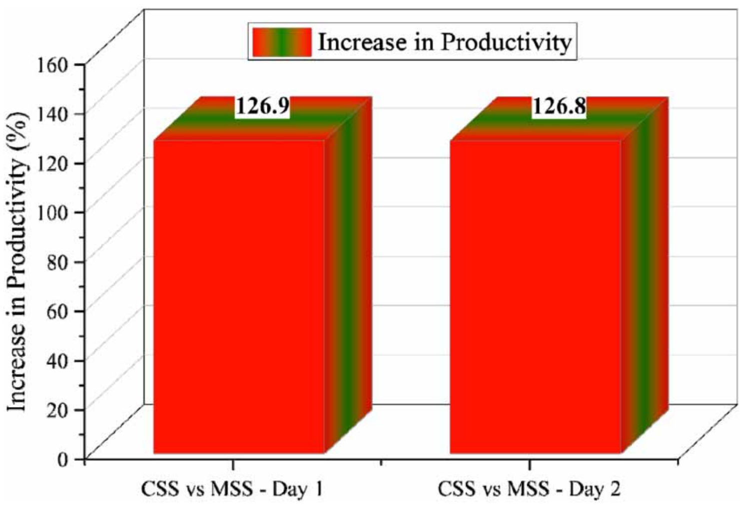


Figure 9 | Increase in the productivity of the MSS compared to the CSS.

of water over the glass cover. In addition to water dripping, the porosity and water absorption behaviour of fibres over the glass cover absorb the water during every drip and make the glass cover temperatures reduced until the next drip. It is observed from the results, that the integration of a water dripping arrangement with natural fibres minimized the glass temperatures by about 30% which significantly augmented the condensation rate over the glass. The continuous cooling effect from the natural fibres reduced the glass cover temperatures significantly which further enhance the freshwater output of the solar still. The combined enhancement of evaporation and condensation lead to an improvement in distillate output by about 126% in the MSS compared to the CSS. Though 20% of the area is covered by the sisal fibres over the glass cover, the combined enhancement of evaporation and condensation effectively enhanced the distillate production relative to the CSS.

Energy efficiency

The overall energy efficiency of the solar stills is evaluated and the energy efficacy of the CSS and MSS is plotted in Figure 10. From the figure, it is reported that the efficacy of the CSS on the two testing days is about 22%. The efficiencies of the MSS on the two testing days are about 51%. From the above observations, it can be summarized that the presence of fins, PCM, pond fibre in the absorber basin, and sisal fibres over the glass cover improved the effectiveness of the solar still in terms of distillate output, system temperatures, and energy efficiency. It is observed that the energy efficiency of the MSS is significantly enhanced despite the reduced incoming solar radiation compared to the CSS. This phenomenon is mainly due to the effective utilization of available solar radiation for enhancing the water and absorber temperatures by using fins, PCM, and pond fibres. Nevertheless, the effect of sisal fibres also enhanced the efficiency to an extent compared to the CSS. It is noticed that the effective modification in the solar still enhanced the thermal efficiency even though the top cover is covered by fibres that hindered the incoming solar radiation.

Economic analysis

The viability of the CSS and MSS is assessed using economic analysis, and the observations of the assessment are presented in Table 2. The parameters and costs of the analysis are considered as per the Indian market. It is noticed in Table 2 that the CPL/m^2 is ₹2.7 and ₹1.6 and the PP is 7.1 and 3.6 months for the CSS and MSS, respectively. It was found from the table that the MSS is economically viable and sustainable for potable water production compared to the CSS. It is also noticed that the MSS is more viable and sustainable than the solar stills in the previous literature and the comparison is presented in Table 3.

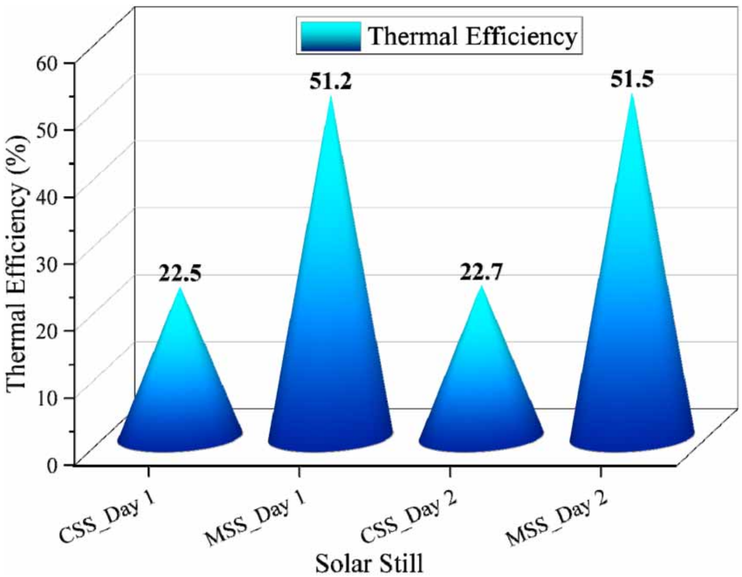


Figure 10 | Comparison of thermal efficiencies.

Table 2 | Parameters and outcomes of cost assessment

Parameters	CSS	MSS
Principal investment (₹)	9,000	12,500
Lifetime of solar still (years)	10	10
Interest rate	0.15	0.15
Capital recovery factor	0.2	0.2
First annual cost	1,800	2,500
Salvage factor	88.66	123.1
Maintenance cost	270	375
Total cost	1,981.34	2,751.9
Annual yield	790	1,710
CPL/m^2 (₹)	2.7	1.6
PP (months)	7.1	3.6

Table 3 | **Comparison of the outcomes of the current study with the** literature

Parameters	Current study (MSS)	Sampathkumar & Natarajan (2022)	Nayi & Modi (2020)	Modi & Modi (2019)	Suraparaju & Natarajan (2022)	Natarajan *et al.* (2022b)
Productivity enhancement (%)	126.9	26.24	11.35	21.46	45	62.8
CPL (₹)	1.6	4.05	2.6	2.6	2.1	1.9
PP (months)	3.6	4.8	11.28	15	4.7	4.4

CONCLUSION

In the current study, the thermo-economic assessment of two single-slope solar stills has been analyzed. The solar stills considered are (i) CSS and (ii) MSS with hollow fins with PCM, novel pond fibre, and sisal fibre. The inferences made from the present study are as follows:

- A significant increase in water temperatures and reduction in glass cover temperatures enhanced the evaporation and the condensation rate simultaneously by fins, PCM, pond fibre, and sisal fibre.
- It is observed that the water temperatures of the MSS are increased by about 12% and glass temperatures of the MSS are almost reduced by about 30% relative to the CSS.
- The augmentation of evaporation and condensation rate by using the fins, PCM, pond fibre, and water dripping arrangement with natural fibres over the glass cover resulted in a remarkable improvement of distillate output.
- It is observed that the distillate yields of the CSS and the MSS are about 2,550 and 5,780 ml/m^2, respectively. The increment in freshwater production is about 126% more than the output of the CSS. The thermal efficiencies of the CSS and MSS are about 22.7 and 51.5%, respectively.
- It is observed that the CPL of the MSS is about $0.022 (₹1.6) with a PP of 3.6 months, whereas the CSS has a CPL of $0.036 (₹2.7) with a PP of 7.1 months.
- It is concluded that the MSS with hollow fins with PCM, novel pond fibre, and sisal fibre contributed a better thermo-economic operation when compared to the CSS due to significant augmentation of evaporation and condensation rates.

ACKNOWLEDGEMENTS

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CONFLICT OF INTEREST STATEMENT

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

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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