



Enhancing the fresh water produced from inclined cover stepped absorber solar still using wick and energy storage materials

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Abstract

Renewable energy-based desalination (RED) technique is gaining more importance over the desalination techniques as it appeared to be a promising technique towards low-cost desalination for sustainable growth as the energy demand towards other developments is continuously increasing. This study aims to incorporate energy storage materials and wick materials in the inclined solar to improve the fresh water produced. In this work, the performance of inclined solar still using coconut coir disk and energy storage material is analyzed experimentally. Characterization results showed that the porosity, absorbency, capillary rise, and heat transfer coefficient of 1-year dried coconut coir disk were found as 73.25%, 2 s, 10 mm/h, and 37.21 W/m²K, respectively, which is higher as compared with that of other coconut coir disks. The experimental results on the performance showed that total distillate from novel inclined solar still with hybrid techniques (energy storage materials and wick materials) were recorded as 3645, 4080, 4570, and 4890 ml for 3 months, 6 months, 9 months, and 1 year, respectively. While the total distillate outputs of an inclined solar still with only wick materials were recorded as 2560, 2670, 2930, and 3390 ml for 3 months, 6 months, 9 months, and 1-year coconut coir disk wick materials. The novel hybrid techniques used in the inclined solar still with energy storage materials enhanced the yield from 82.25 to 144.5% than the conventional solar still, whereas the inclined solar still with only wick materials enhanced the yield from 28 to 69.5% than the conventional solar still.

Keywords Stepped absorber · Coconut coir disk · Solar still · Energy storage

Introduction

Water is a crucial requirement of a human, along with food and air. Water is one of the most important substances on

earth. About 97% of water resources on the earth are saline, and only the remaining 3% is fresh drinkable in condition (Attia et al. 2020a, b; Vaithilingam et al. 2020; Balachandran et al. 2020; Muthu Manokar et al. 2020). Nowadays, freshwater demand is increasing continuously because of industrial development, intensified agriculture, upgrading living standards, and a growing world population (Sathyamurthy et al. 2014, 2017). There is a great need to convert seawater into potable water to overcome and meet the current demand for freshwater. Solar still is a traditional, economical, and eco-friendly device that converts saline/brackish water into potable drinking water (Kabeel et al. 2019a, b, c, d; Mu et al. 2019; Sharon and Reddy 2015; Sathyamurthy et al. 2016, 2020; Nagarajan et al. 2017; Thakur et al. 2020). The solar still works on a process involving evaporation (by heating) and condensation as the rainfall occurs naturally (Essa et al. 2020; Taamneh et al. 2020; Chamkha et al. 2020). Solar still has much significance like high quality, negligible maintenance, suitable for all kinds of water, less wastage, and so forth. Like significance, solar still

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has few limitations like air leakage due to poor fitting and joining in structures, cracking or breakage of transparent cover (glass), algae formation, deposition of dust and bird droppings and salt deposits, and so forth. These factors affect the performance of the solar still (Muthu Manokar et al. 2020; Manokar et al. 2020a, b; Sasikumar et al. 2020; Madhu et al. 2018). Production of solar still can be improved in many ways as follows. In wick type solar distillers, insulation thickness plays an essential role in freshwater produced (Yeh and Chen 1986). In general, solar distillers without proper insulation, the distillate water production was lower. By using wick materials, the freshwater produced from the inclined solar still increased as the wick material reduced the mass flow rate of flowing water by absorbing the water (Sheeba et al. 2012). The mass flow rate of water was reduced by using wick material, and it improves the performance of the still (Mahdi et al. 2011). Instead of the single wick material, equipping with multi-wick materials was used as the material, which significantly enhanced the productivity (Sodha et al. 1981). Flowing the water over the transparent glass cover of the solar still improved the productivity slightly for about 10% over the conventional system (Dhiman and Tiwari 1990). Solar radiation plays a significant role in the performance of a solar still. During the year around comparison, the summer season gives higher productivity than in the winter season (Agboola and Egelioglu 2011). Integration of different still-like basin types with inclined wick types improves productivity (Minasian and Al-Karaghoulis 1995). Incorporating an external heat exchanger along with the solar still increases the productivity considerably (Badran et al. 2004). The addition of an external reflector along with the still increases the production of freshwater (Tanaka and Nakatake 2009). Instead of a flat plate, the incorporation of a stepped absorber plate reduced the mass flow rate and helps in increasing the productivity and even more, by the inclusion of a mini solar pond (Velmurugan et al. 2009a, b). Incorporation of the reflector in the still enhanced the productivity of the still and even with azimuth tracking in the tilted wick solar still (Aybar et al. 2005). Non-distilled water comes out from the still that have enough temperature for domestic usage. Water flowing over the transparent cover helps to increase the temperature difference between evaporate water and glass temperature. Due to the high-temperature difference, productivity also increases (Janarthanan et al. 2006). Incorporating the condenser in a solar still as an inbuilt component also increases the productivity considerably (Fath and Hosny 2002). Taamneh et al. (2020) used PV as basin material of inclined solar still and integrated a spiral tube collector for improved thermal efficiency at higher flow rates of water and compared the performance during summer and winter conditions. Results showed that solar thermal efficiency still improved with integration, and electrical efficiency drop was observed for an increased temperature of panel temperature. Sasikumar et al. (2020)

studied an inclined solar still with varied water flow rates in an inclined PV panel solar still under passive condition. Results exhibited that the thermal and electrical efficiency are inversely proportional as the flow rate increases the thermal performance decreases with improved electrical efficiency of PV panel. Hilarydoss et al. (2020) made thermal modeling and made a detailed enviro-economic investigation on inclined solar still for improved fresh water. Results showed that the proposed solar thermal and exergy efficiency still was superior while compared with other solar still. Similarly, the exergy destruction was lower and higher exergy efficiency over the glass cover material while the flat absorber and without a felt sheet. The greenhouse emission was reduced using felt sheet in the absorber with a lower payback period of 4 years with a CPL of 1.51 INR/l. Sharon (2020) compared the energy, environmental, and exergy of passive-type double-sided vertical solar distiller under different operating conditions such as salinity, absorber area, gap, and feed water flow. Results showed that solar distiller performance decreased with increased water, absorber area, and gap. The optimum feed water flow was found as 40 kg/day. The annual average energy, exergy, and recovery ratio for the proposed solar distiller were found as 62.16, 4.73, and 31.7%, respectively. The distiller's average yield was found as 4.18 kg/m² with CPL of 2 INR/l and reduced green house gas emission of 33 to 87 tons. Sharon et al. (2020) made a year around analysis on a novel vertical multi-chamber solar still. It was reported that the exergy efficiency of 23.15% using vertical multi-chamber solar still which produced a daily yield of 11.13 kg/m². Also, it was reported that the CPL of produced water was about 0.9 INR/l with 67.9 CO₂ mitigation for a period of 20 years.

Analyzing the characterization for wicking materials like black cotton cloth, jute cloth, coir mate, waste cotton pieces, wood pulp paper wick, water coral fleece fabric, and polystyrene sponge was used in solar still application. Few of them show higher productivity also (Anburaj et al. 2013). Analyzing wick material characteristics and its testing methods to select the best suit wick material for solar still application is done already. The characteristic analysis helps improve the productivity of the solar still (Hansen et al. 2015). A review of the literature reveals that there is no significant work carried out on characterizing the coconut coir disk as wick material and its application in solar still. This paper describes the critical wicking characters (like porosity, capillary rise, absorption, and heat transfer coefficient, and water repellency) to select wick material for solar distillate production application along with its performance statistics. The latest literature related to renewable energy has been studied (Mammeri and Lallam 2019; Hysa 2019; Nazir 2019; Topçuoğlu 2019). From the detailed literature survey, it is found that no research has been published on the incorporation of coconut coir disk and energy storage materials in the

Table 1 Wick characteristics of different phases of coconut coir disks

Seasoned period	Wick characteristics				
	Porosity %	Absorbency (s)	Repellent	Capillary rise (mm/h)	Heat transfer coefficient (W/m ² K)
3 months	59.41	4	0	60	18.2
6 months	61.36	3	0	45	28.4
9 months	68.8	2	0	20	33.3
12 months	73.25	2	0	10	37.21

inclined solar stills. The study aims to analyze the performance from the inclined solar still using biodegradable material along with energy storage materials. The present study also deals with the characterization of wick material, experimental setup and procedure, and a detailed analysis of the reported results followed by conclusions.

Wick and energy storage material characteristics

Based on the review of literature, wick material for a solar still application requires certain characters (Wang and Torng 2001; Pal et al. 2006; Glover 2001; Tanaka and Nakatake 2007). The characteristics of wick materials include porosity, capillary effect, absorbency, shrinkage, wrinkle, density, durability, absorptivity, spreading speed, water repellency, ability to conduct thermally, and heat transfer coefficient. In the present investigation, the characteristics of wick material, such as porosity, absorbency, repellent, capillary rise, and heat

transfer coefficient, are considered in selecting a suitable wick material for the application of solar desalination technique (Hansen et al. 2015). The coconut coir wick material under different seasoning conditions was tested in the South India Textile Research Association, Coimbatore, Tamil Nadu, India, and also at the department of chemistry, National Engineering College, Kovilpatti, Tamil Nadu, India.

The characteristics of coconut coir disk under different seasoning conditions are tabulated in Table 1. The examined attributes of wick materials for the best stuff to use in solar still increase productivity. Concluding that 1-year coir disk has the right wick property under porosity, absorbency, capillary rise, and heat transfer coefficient and found as 73.25%, 2 s, 10 mm/h, and 37.21 W/m² K, respectively. The different seasoned coconut coir disk were made with a 50mm dimension and 25mm thick. Similarly, copper scraps with dimensions of 1 mm diameter, 18 wire gauge, and approximately 75 mm length are used as energy storage material. It is used to absorb the radiation from the source utmost. Its thermal conductivity is 394 W/m K, and specific heat is 0.398 kJ/kg K.

Fig. 1 A view of inclined type stepped absorber solar still

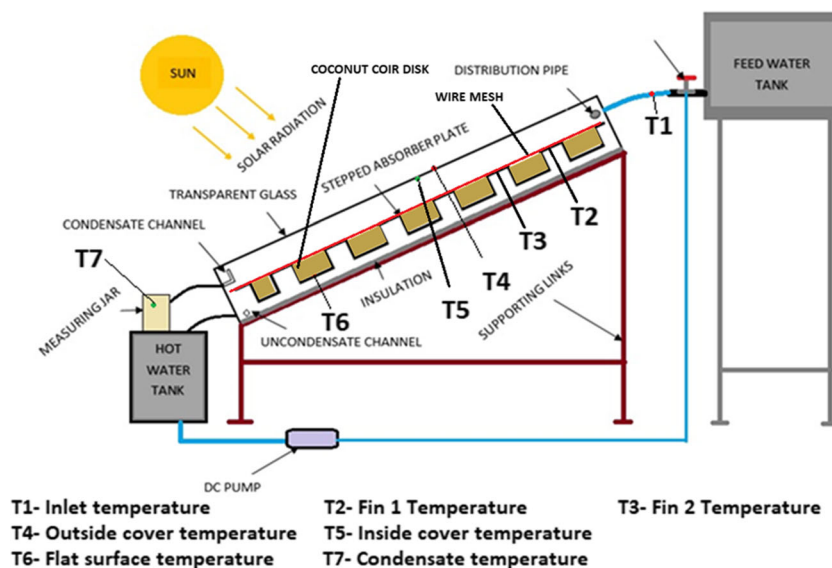


Table 2 Condition of basin and type of coconut coir disk used

S. No	Condition of basin and type of coconut coir disk used	Dates of the experiments
1.	Three-month seasoned coconut coir disk wick material without energy storage material.	10th March 2016
2.	Six-month seasoned coconut coir disk wick material without energy storage material.	07th March 2016
3.	Nine-month seasoned coconut coir disk wick material without energy storage material.	08th March 2016
4.	Year seasoned coconut coir disk wick material without energy storage material.	09th March 2016
5.	Three-month seasoned coconut coir disk wick material with energy storage material.	11th March 2016
6.	Six-month seasoned coconut coir disk wick material with energy storage material.	12th March 2016
7.	Nine-month seasoned coconut coir disk wick material with energy storage material.	13th March 2016
8.	One-year seasoned coconut coir disk wick material with energy storage material.	14th March 2016

Experimental system and procedure

The illustrative diagram of inclined type solar still with rectangular groove absorber is shown in Fig. 1. Furthermore, the heated wastewater collected in the outlet is re-circulated into the storage tank. The single slope stepped absorber plate inclined type solar still was constructed using locally available materials in the Kovilpatti market, and the fabricated system was tested at the Department of Mechanical Engineering, National Engineering College, Kovilpatti, Tamil Nadu, and India during March 2016. The total dimensions of the still are $1 \times 0.75 \times 0.157$ m. Two different absorbers, namely flat absorber and rectangular groove absorber, are fabricated and fitted into the basin. A transparent cover made of glass with a thickness of 3 mm is used to cover the rectangular tray. The bottom and side of the rectangular tray are packed with 10-mm thickness thermocol insulation. A 24 V DC water pump was used to pump the hot water from

the hot water storage tank to the main storage tank. Additional makeup water arrangements are made to maintain a constant pressure head. The rectangular groove absorber is made up of a 1-mm aluminum sheet and coated with black paint. A condensate channel is provided at the lower end, and the distributor pipe is provided at the higher end of inclined solar still for the free flow of water. The entire experimental setup is inclined at an angle of 30° . The details of the instruments used in the experimental investigation are tabulated in Table 3.

The instrumental uncertainty is calculated using the empirical formula of Rahbar et al. (2017) (Equation (1)) and it is mathematically expressed as

$$\text{Uncertainty, } U = \frac{a}{\sqrt{3}} \times 100 \tag{1}$$

The uncertainty associated with determining the daily efficiency of solar still depends on the distillate collected in the

Fig. 2 Experimental photograph of inclined type stepped absorber plate solar still. Detailed parts are (1) feed water tank, (2) temperature indicator unit, (3) thermocouple wires, (4) stepped absorber, (5) distribution pipe, (6) glass cover, (7) insulation, (8) supporting stand, (9) collecting jar, (10) DC pump, (11) hot water storage tank



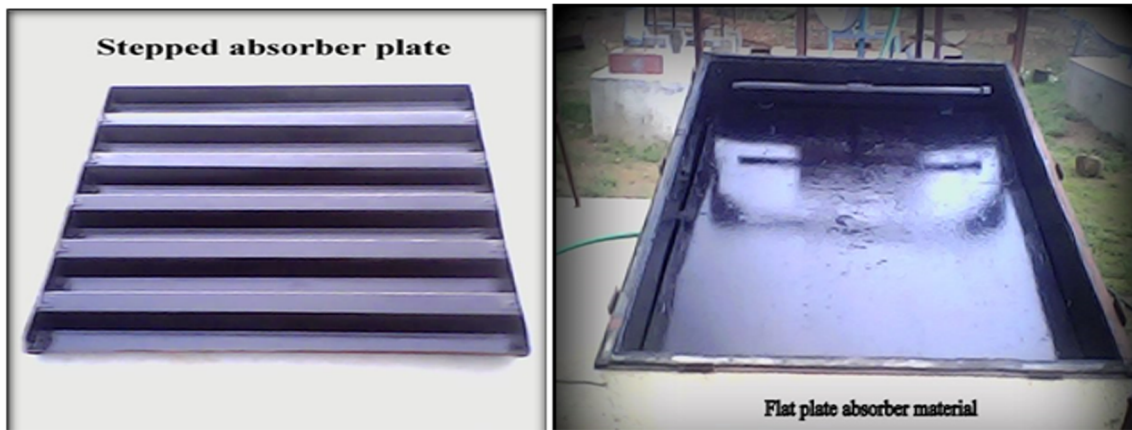


Fig. 3 Photograph of absorber materials

calibrated flask and the input solar radiation. Mathematically, it is given as

$$\text{Uncertainty on thermal efficiency, } U_{\eta} = \sqrt{U_{I(t)} + U_m} \quad (2)$$

The different phases of coconut coir disk-like 3 months, 6 months, 9 months, and 1 year are laid on the absorber plate to increase the water film thickness. The distributor pipe is made up of hardened polyvinyl chloride material. At the equal interval, 20 holes each of the 3 mm diameter are drilled in the

Fig. 4 Research methodology

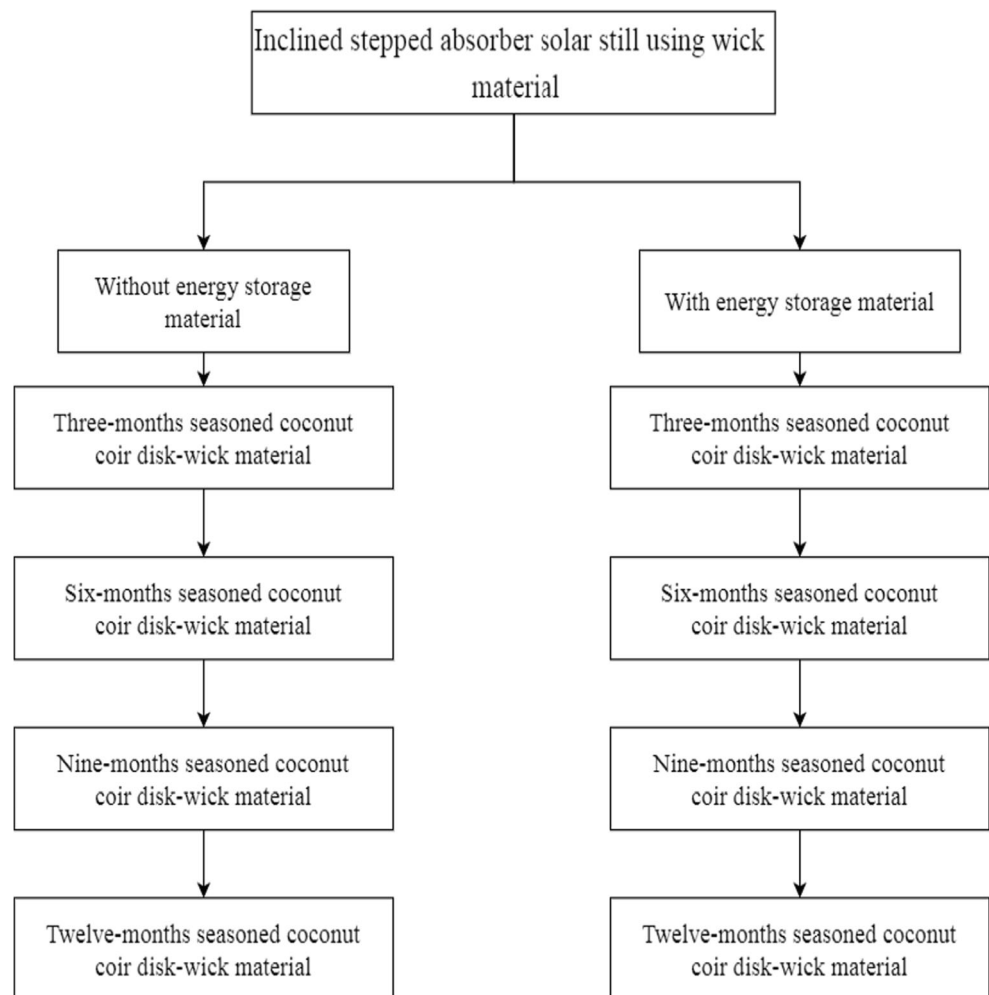


Table 3 Details of instruments with make, range, accuracy

S.No.	Instrument	Make	Range	Accuracy	Instrument uncertainty (%)
1	Solar power meter	TES132 solar power meter	0–2500 W/m ²	± 10 W/m ²	5.77
2	Thermocouple	RTD (PT-100 type)	0–250 °C	± 0.02 °C	1.21
3	Anemometer	AM4836	0–45 m/s	± 0.0545 m/s	3.15
4	Measuring jar	-	0–1500 ml	± 7 ml	4.04

distributor pipe to make the water flow on the entire absorber area through gravity. Through the distributor pipe, the water is evenly distributed, covering the entire absorber plate, and it is ensured that the layer of water is formed on the entire surface of the absorber plate. The transmitted solar radiation heats the absorber, and thereby the flowing water is heated. The evaporated water from the absorber surface is condensed in the inner cover surface as water droplets. By gravity, the water droplets flow to the lower end of the glass and get collected in the condensate channel. The measuring jar collects the condensate collected in the channel. The un-evaporated hot water from the still was stored in an insulated tank and re-circulated using a DC powered water pump for a regular time interval. Figures 2, 3, and 4 show the photographic view of the inclined type stepped absorber solar still, photograph of absorber materials, and research methodology of the inclined type stepped absorber solar still, respectively. Experiments are conducted on inclined solar still using different seasoned wick materials (3 months, 6 months, 9 months, and 1 year). The copper scraps are spread in the absorber’s entire surface area while the coconut coir disk is placed in the rectangular grooves. The total mass of the copper scraps used in the basin is 1.24 kg. The performances are analyzed experimentally on the respective dates mentioned in Table 2.

Wick materials in the basin area are the most crucial parameter, affecting the still’s performance. In addition to the inclined type stepped absorber plate solar still, the yield and efficiency are enhanced using wire mesh with the wick material. Various temperatures like inlet water temperature, absorber plate temperature (Fin-1 and Fin-2), condensate temperature, and glass inside and outside temperature, un-condensate water temperature is measured with the help of K-type thermocouple (chromel-alumel) that ranges from – 40 to + 375 °C with an error of 0.4% that is used in the present study, along with digital temperature indicator. Solar radiation is measured by PV type sun meter (TES-1333). A standard measuring jar is used to estimate daily productivity by collecting the condensate.

Results and discussion

The performance analysis is carried out for various stages of seasoned coir disk wick materials like 3, 6, 9, and 12 months

in a stepped absorber plate under the actual solar condition. The hourly variations in solar intensity and wind velocity during the experimentations are shown in Fig. 5

Performance analysis of solar still using various phases of wicked coir disk without energy-storing materials

Figure 6 shows that the productivity varies of different wick materials incorporated solar still hour to hour from morning 6 am to next day morning 6 am for 1-h time interval. On an

Table 4 Cost analysis for the inclined solar stills

S.No	Components	Price (Rs.)
Inclined stepped absorber solar still with coconut coir disk		
1	Feed water tank and stand	Rs 1000
2	Stepped absorber	Rs 1000
3	Distribution pipe	Rs 200
4	Glass cover	Rs 500
5	Solar still supporting stand	Rs 1500
6	DC pump	Rs 500
7	Hot water storage tank	Rs 400
8	Insulation	Rs 100
9	Coconut coir disk	Rs 100
Accessories and fabrication cost		Rs 2000
Total cost		Rs 7300/-
Inclined stepped absorber solar still with coconut coir disk and energy-storage materials		
1	Feed water tank and stand	Rs 1000
2	Stepped absorber	Rs 1000
3	Distribution pipe	Rs 200
4	Glass cover	Rs 500
5	Solar still supporting stand	Rs 1500
6	DC pump	Rs 500
7	Hot water storage tank	Rs 400
8	Insulation	Rs 100
9	Coconut coir disk	Rs 100
10	Wire mesh	Rs 300
Accessories and fabrication cost		Rs 2000
Total cost		Rs 7600/-

Table 5 Economic analysis of the inclined stepped absorber solar still with wicked coir disk

Particulars	Three-month coconut coir disk wick materials	Six-month coconut coir disk wick materials	Nine-month coconut coir disk wick materials	One-year coconut coir disk wick materials
Fabrication cost	7300 Rs.	7300 Rs.	7300 Rs.	7300 Rs.
Maintenance cost	5 Rs./day	5 Rs./day	5 Rs./day	5 Rs./day
Operating cost	4 Rs./day	4 Rs./day	4 Rs./day	4 Rs./day
Feed water cost	1 Rs./day	1 Rs./day	1 Rs./day	1 Rs./day
Distilled water cost	15 Rs./L	15 Rs./L	15 Rs./L	15 Rs./L
Water produced	2560 ml/day	2670 ml/day	2930 ml/day	3390 ml/day
Cost of water produced/day	38.4 Rs./day	40.05 Rs./day	43.95 Rs./day	50.85 Rs./day
Net profit	28.4 Rs./day	30.05 Rs./day	33.95 Rs./day	40.85 Rs./day
Payback period	7300/28.4 = 257 days	7300/30.05 = 243 days	7300/33.95 = 215 days	7300/40.85 = 179 days

hourly basis, the different temperatures involved in the production enhancement of the inclined solar still with different seasoned wick materials are shown in Fig. 6a–d. Here, solar radiation is low in morning hours, reaches a maximum at around 14:00 h, and gradually reduces in evening hours. Similarly, the different water and absorber plate temperatures gradually increase from morning to peak hours and gradually decrease towards the evening. Compared with 1-year seasoned coconut coir disk, wick material-trialed experiments obtained the maximum temperatures in all aspects than others. The reduced temperature of inner glass and absorber temperature were noticed with 6- and 9-month seasoned coconut coir wick material as the absorbency, and capillary rise is higher. Similarly, the level of porosity increases with different seasoning coconut coir increases, which affects the coconut coir's wettability.

The hourly variations of productivity from the solar still with different coir disk phases without any energy-storing material are shown in Fig. 7. One-year seasoned coconut coir

disk wick material obtained maximum hourly productivity of 360 ml between 13:00 and 14:00 h. Others obtained lower productivity at the same time interval, like 290 ml for 9 months, 280 ml for 6 months, and 270 ml for 3-month dried coconut coir disk wick materials. The increased capillary effect and heat transfer coefficient by the wick material improved the fresh water yield from inclined solar still. Furthermore, the yield from 12-month seasoned coconut coir is improved by 19.4, 22.2, and 25% than 9-, 6-, and 3-month seasoned coconut coir disk. It is also depicted that the yield from solar still during lower solar intensity using 12-month seasoned coconut coir is higher. The absorbance of the water with the coconut coir is higher in the case of increasing the seasoning of coconut coir with the absorber of solar still.

Cumulative production of the solar still with different phased coconut coir disks is given in Fig. 8. Moreover, the result shows that solar still using 1-year phased coconut coir disk wick material gives higher productivity of 3390 ml per day. Comparably, other wick materials provide lower

Table 6 Economic analysis of the inclined stepped absorber solar still with wicked coir disk and energy storage materials

Particulars	Three-month coconut coir disk wick materials and energy storage materials	Six-month coconut coir disk wick materials and energy storage materials	Nine-month coconut coir disk wick materials and energy storage materials	One-year coconut coir disk wick materials and energy storage materials
Fabrication cost	7600 Rs.	7600 Rs.	7600 Rs.	7600 Rs.
Maintenance cost	5 Rs./day	5 Rs./day	5 Rs./day	5 Rs./day
Operating cost	4 Rs./day	4 Rs./day	4 Rs./day	4 Rs./day
Feed water cost	1 Rs./day	1 Rs./day	1 Rs./day	1 Rs./day
Distilled water cost	15 Rs./L	15 Rs./L	15 Rs./L	15 Rs./L
Water produced	3645 ml/day	4080 ml/day	4570 ml/day	4890 ml/day
Cost of water produced/day	54.6 Rs./day	61.2 Rs./day	68.5 Rs./day	73.3 Rs./day
Net profit	44.6 Rs./day	51.2 Rs./day	58.5 Rs./day	63.3 Rs./day
Payback period	7600/44.6 = 170 days	7600/51.2 = 148 days	7600/58.5 = 130 days	7600/63.3 = 120 days

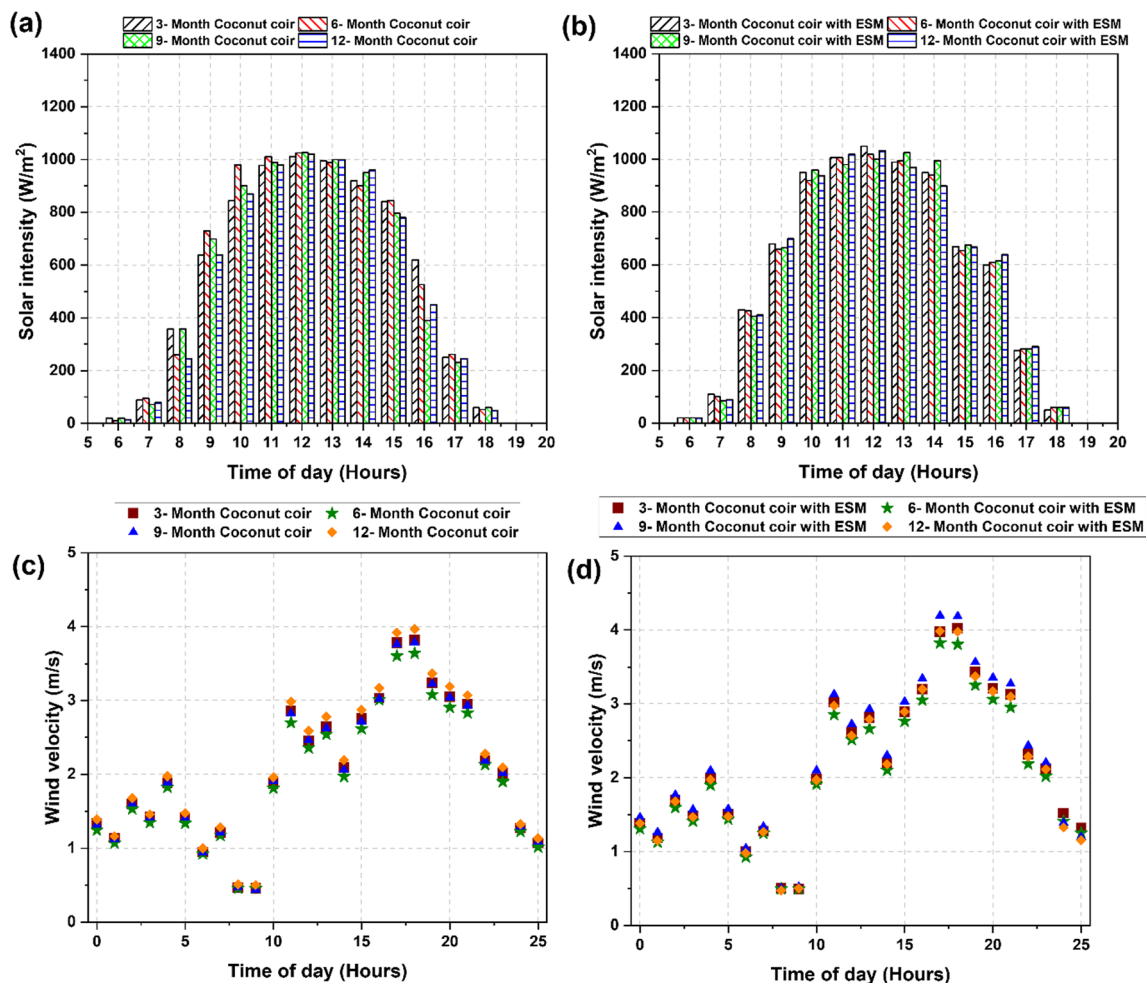


Fig. 5 Hourly variations in a, b solar intensity and c, d wind velocity for coconut coir disk with and without ESM during the experiment

productivity, such as 2930 ml for 9 months, 2670 ml for 6 months, and 2560 ml for 3-month dried coconut coir disk wick materials. The improvement in fresh water yield using 1-year seasoned coconut coir disk as wick material is found as 16% higher than 9 months, 27% higher than 6 months, and 32% higher than 3-month dried wick materials.

Performance of inclined stepped absorber plate using various phases of wicked coir disk with energy-storing materials

The inclined solar still with different seasoned coconut coir disk is also investigated with energy storage materials under the same climatic condition on the respective dates mentioned in Table 2. The hourly variations in temperatures involved in enhancing the freshwater produced from inclined solar still with different seasoned wick materials and energy-storing material are shown in Fig. 9a–d. Here, solar radiation is low in morning hours, reaches a maximum at around 14.00 h, and gradually reduces in evening hours. Similarly, the different water and absorber plates’ different temperatures gradually

increase from morning to peak hours and then gradually decrease towards the evening. Comparably, 1-year seasoned coconut coir disk as the wick material-trialed experiments obtained the maximum temperatures in all aspects than others. In the modified solar still, basin temperature and water temperature are higher than the conventional solar still. The higher temperature difference between the modified solar still resulted in higher water and glass temperature, resulting in higher productivity than the conventional solar still.

Figure 10 shows that the productivity varies of the various wick materials used in the still with an energy storage material hour to hour from morning 6 am to next day morning 6 am for a 1-h interval. One-year coir disk was obtained the maximum hourly productivity of 550 ml between 1:00 PM and 2:00 PM. While others obtained lower productivity at the same time interval like 500 ml for 9 months, 460 ml for 6 months, and 400 ml for 3-month dried coconut coir disk wick materials with energy storage material.

Figure 11 shows the increasing production of distilled water per day in the inclined type stepped absorber plate solar still with various staged coconut coir disk and energy storage

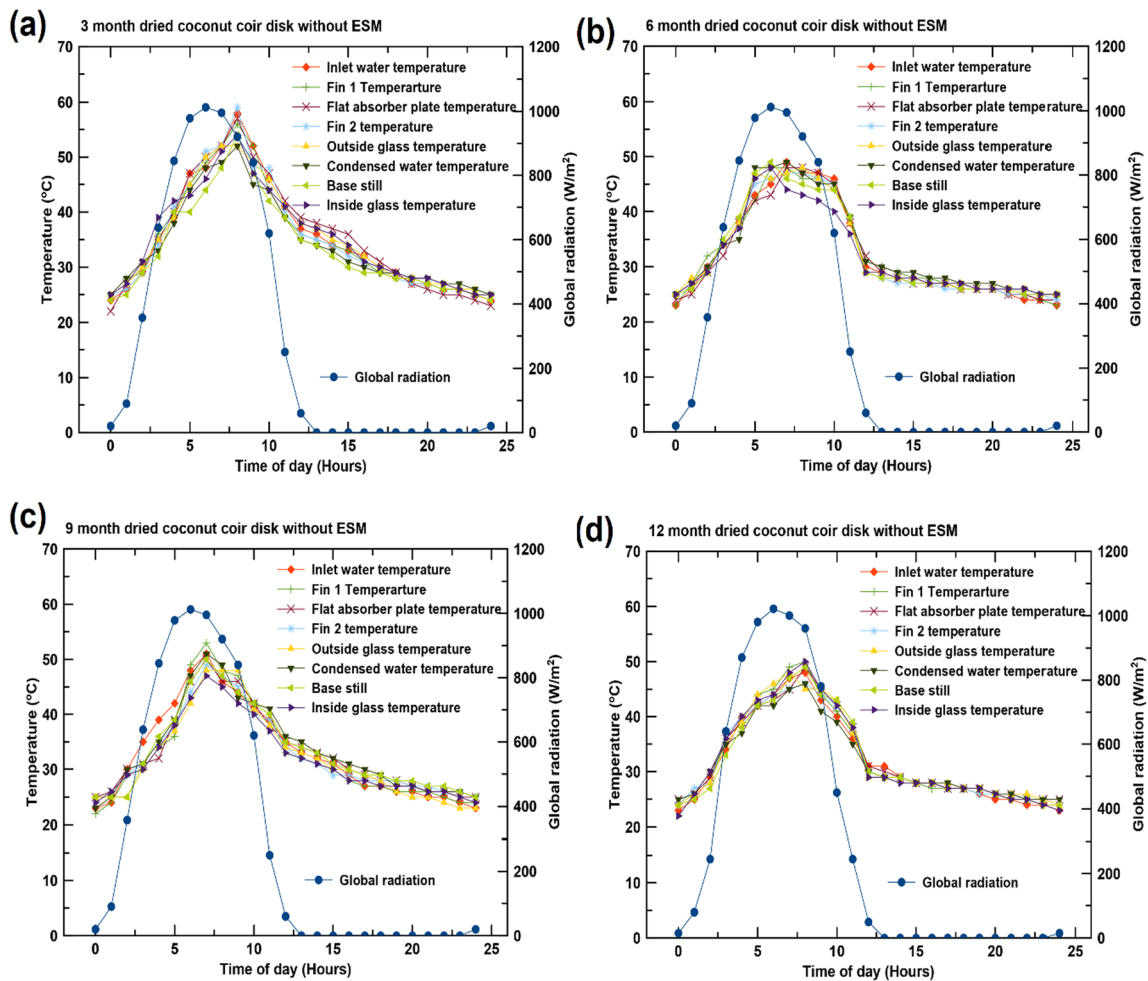


Fig. 6 Variation of different temperature and global radiation concerning time for **a** 3-month coconut coir disk, **b** 6-month coconut coir disk, **c** 9-month coconut coir disk, and **d** 12-month coconut coir disk

Fig. 7 Hourly variations of productivity from the solar still with different phases of coir disk without any energy storing material

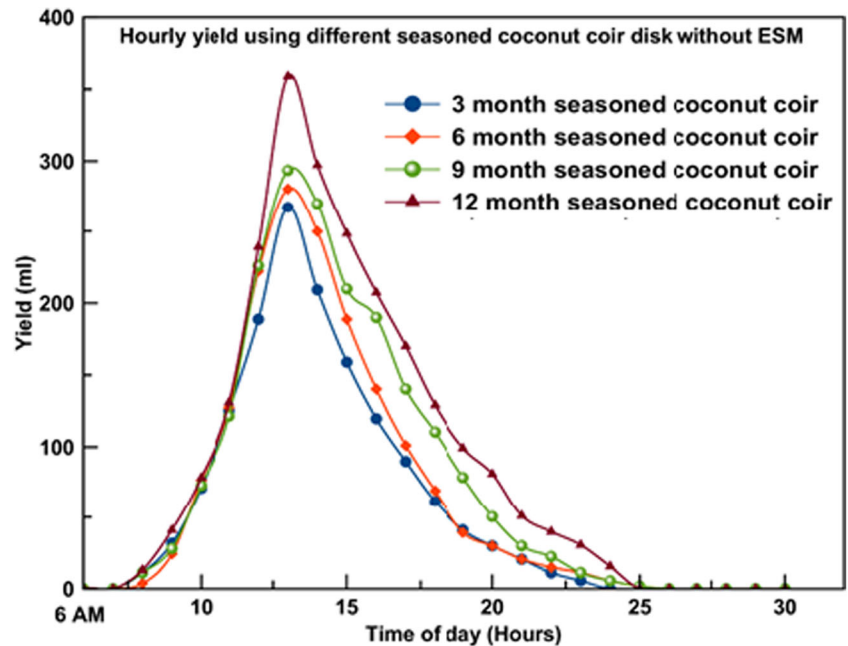


Fig. 8 The productivity of the solar still for various wick materials

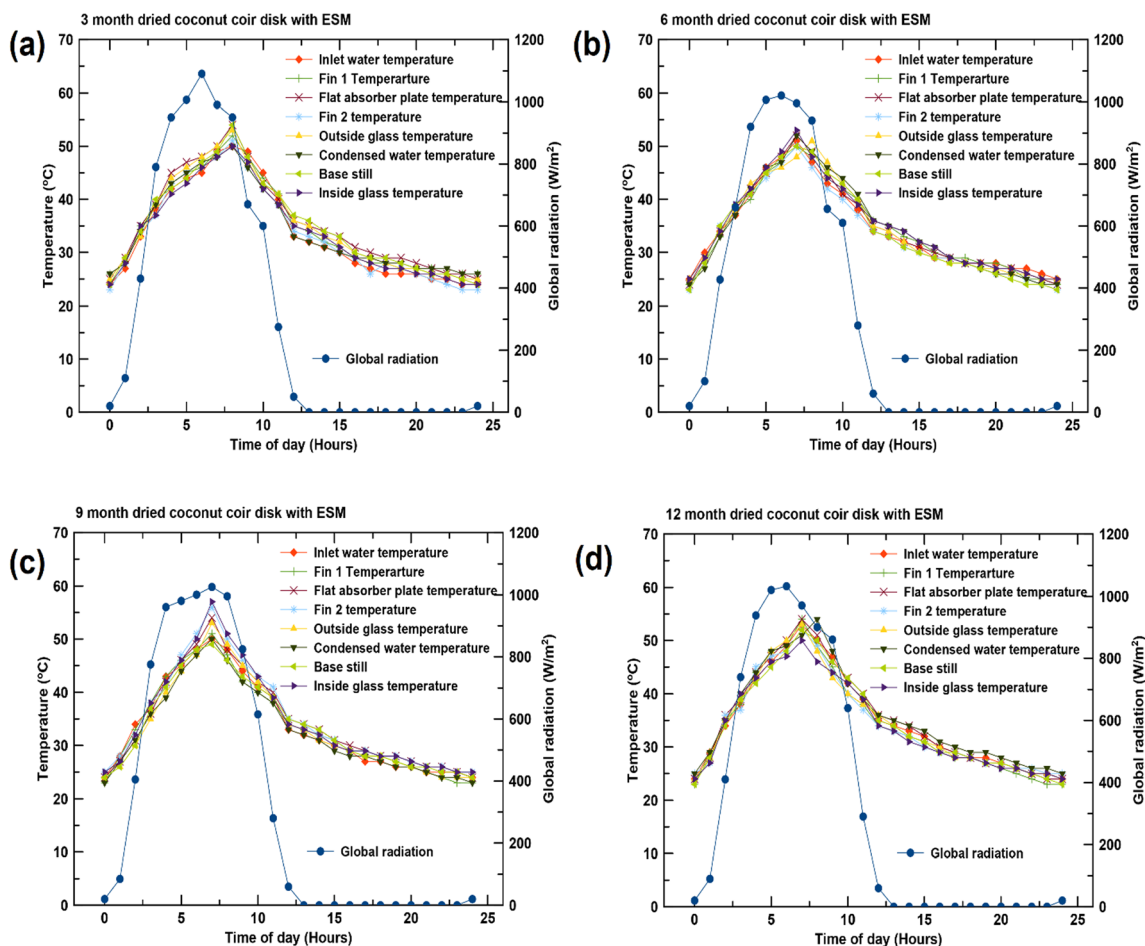
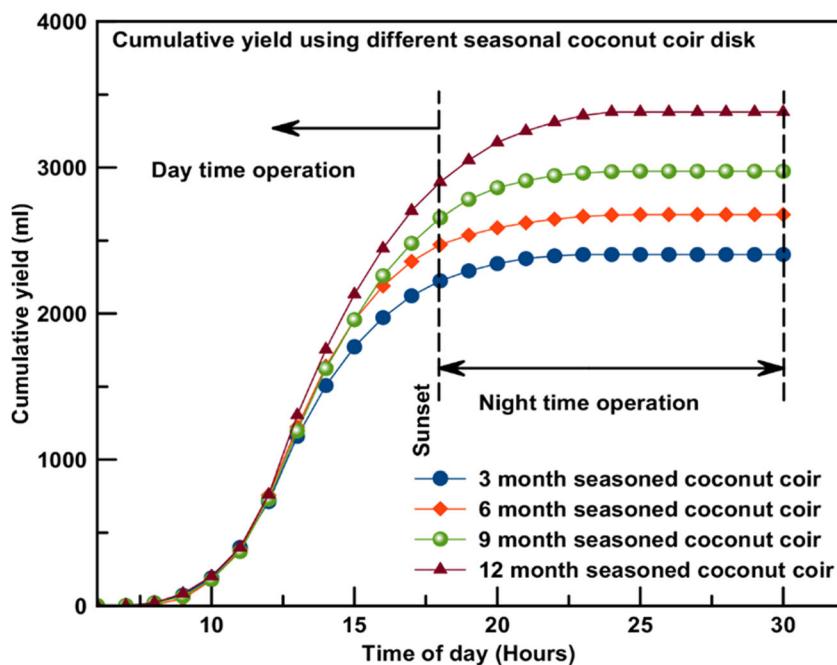
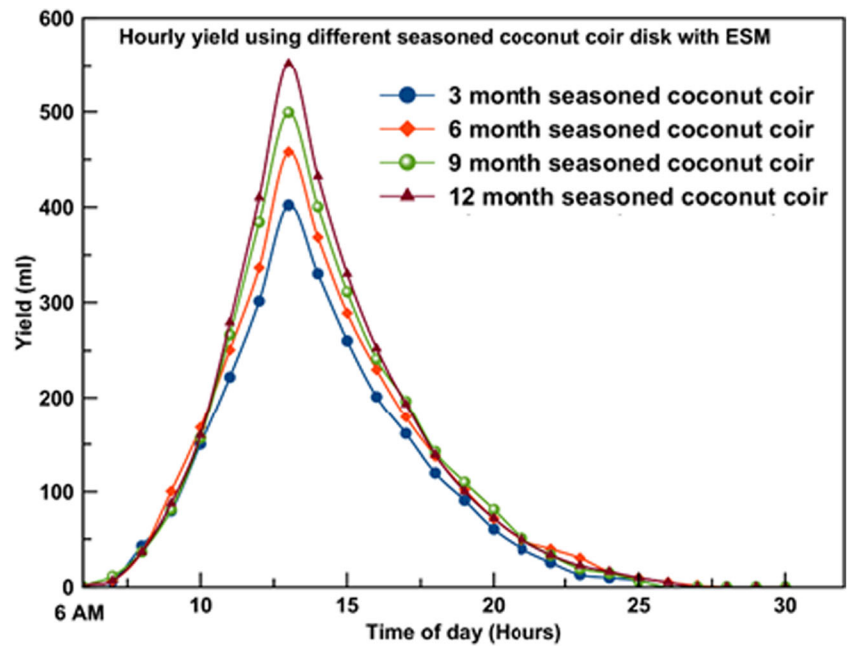


Fig. 9 Hourly variation of different temperature and global radiation for **a** 3-month coconut coir disk, **b** 6-month coconut coir disk, **c** 9-month coconut coir disk, and **d** 12-month coconut coir disk along with energy storage material

Fig. 10 The hourly productivity of solar still with different phases of coir disks with energy-storing materials



material. The daily productivity from the inclined stepped absorber solar still using wick materials with energy storage material at 12-month, 9-month, 6-month, and 3-month coir disk was 4890, 4570, 4080, and 3645 ml, respectively. Similarly, without energy, storage material produced the yield of 3390, 2930, 2670, and 2560 ml, respectively.

In this experimentation, the various stages of coir disk such as 3 months, 6 months, 9 months, and 1 year were used to

analyze the maximum yield of fresh water produced. The cumulative yield of fresh water produced from inclined type solar still is increased using a rectangular stepped absorber plate with wick materials and energy storage material. The still with 1-year coir disk and energy storage productivity gives maximum value than other stages of coir disk materials used as a wick. The capillary effect brings the maximum distillate in the still, which is comparable 7% higher than 9

Fig. 11 The increasing productivity of stepped absorber plate with various stages of seasoned coir disks

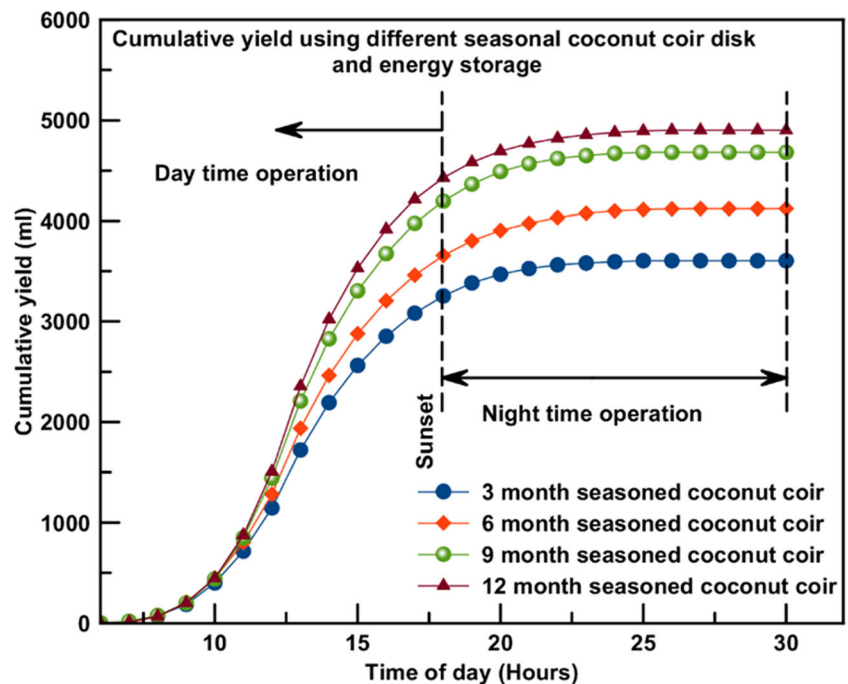
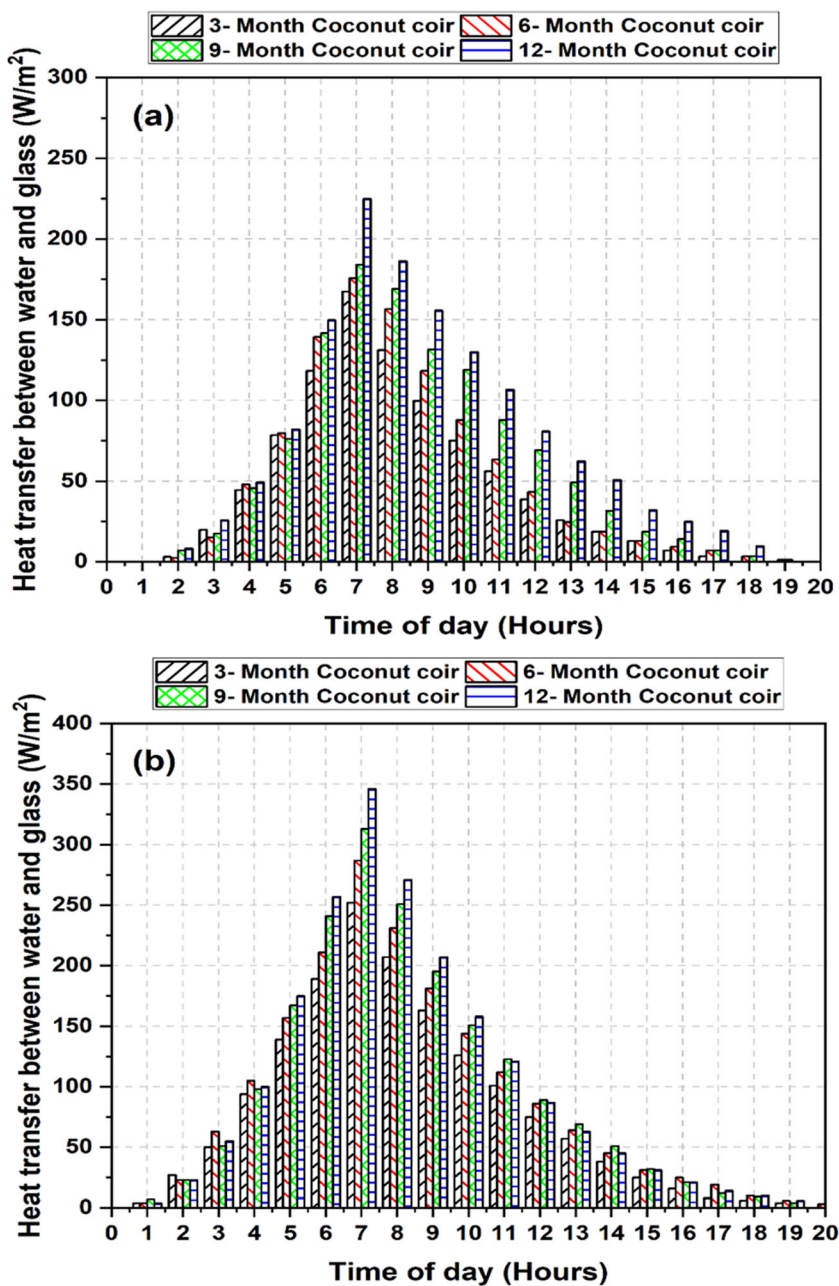


Fig. 12 Variations on evaporative heat transfer using **a** coconut coir disk and **b** coconut coir with ESM as energy storage



months, 16% higher than 6 months, and 34% higher than 3-month older wick material with energy storage material.

Evaporative heat transfer

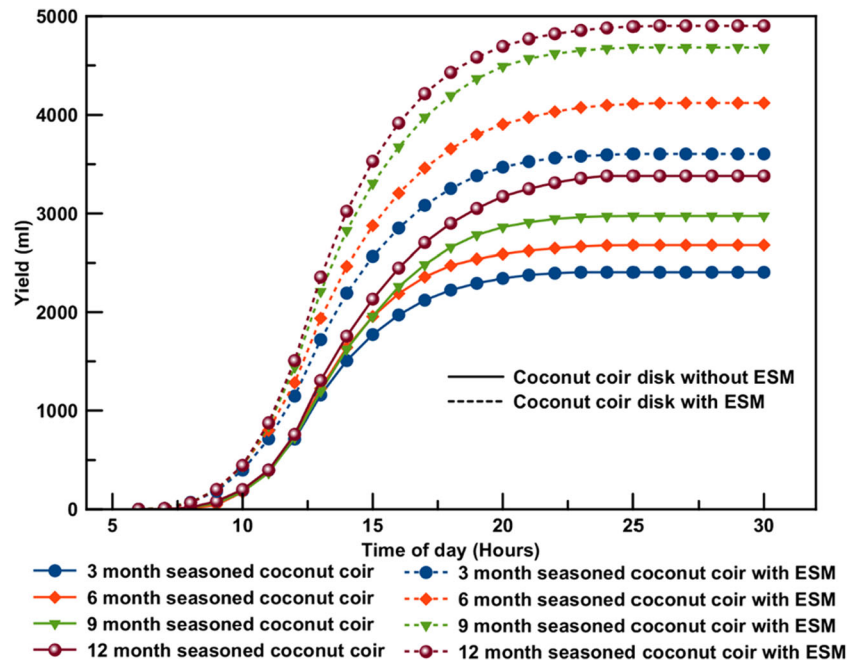
Figure 12 shows the evaporative heat transfer variation from inclined solar with different seasoned coconut coir disk and coconut coir disk with wire mesh as energy storage. The evaporative heat transfer between water and glass using seasoned coconut coir disk is lower than coconut coir disk with wire mesh energy storage material. This is due to the higher absorption of water with coconut coir and energy heat absorption by the wire mesh, which simultaneously increased water

evaporation rate from the absorber surface. Also, the heat transfer between water and glass follows a similar curve followed by the hourly yield.

Overall productivity comparison, instantaneous and daily thermal efficiency of various phases of coir disk with and without energy-storing materials

Figure 13 shows the cumulative productivity from the solar still at different periods of coir disk with and without energy-storing materials. Comparing with all phases of coir disk, 1-year coir disk with energy-storing material on a rectangular stepped absorber plate produced the maximum distillate output.

Fig. 13 Cumulative productivity of solar still with varying stages of coconut coir disks with and without energy storing material



The result shows that 1-year seasoned coconut coir disk as wick material along with energy storage material gives higher productivity of 4890 ml. On comparing the cumulative yield from solar still using different seasoned coconut coir with energy storage material, the yields obtained using 3, 6, and 9 months are found as 3645, 4080, and 4570 ml, respectively. Similarly, the cumulative yields obtained using 3-, 6-, 9-, and 12-month seasoned coconut coir without ESM are found as 2560, 2670, 2930, and 3390 ml, respectively. The still with 1-year dried coconut coir disk with energy storage material shows an improvement of about 6.5% which is higher compared with the 9 months. Similarly, about 20.2% and 10.6% in fresh water yield improvement while using 6- and 3-month seasoned coconut coir disk, respectively, along with energy storage material. It is also observed using 12-month seasoned coconut coir disk without energy storage material; the cumulative yield from the solar still is improved by 24.4% than 3-month seasoned coconut coir. The improvement in fresh water yield using 6- and 9-month seasoned coconut coir without ESM is found as 4.1 and 12.6%, respectively. The improvement in fresh water using increased coconut coir disk increased seasoning due to the fact that coconut coir increased heat transfer coefficient and higher porosity.

The hourly instantaneous thermal efficiency of the system is estimated using Equation (3).

$$\eta_{\text{thermal}} = \frac{\beta \times \sum m_e}{3600 \times \sum I(t) \times A_w} \times 100 \tag{3}$$

whereas β -latent heat of vaporization (kJ/kg K)

$$\beta = a_1 + a_2 T_w + a_3 T_w^2 + a_4 T_w^3 + a_5 T_w^4$$

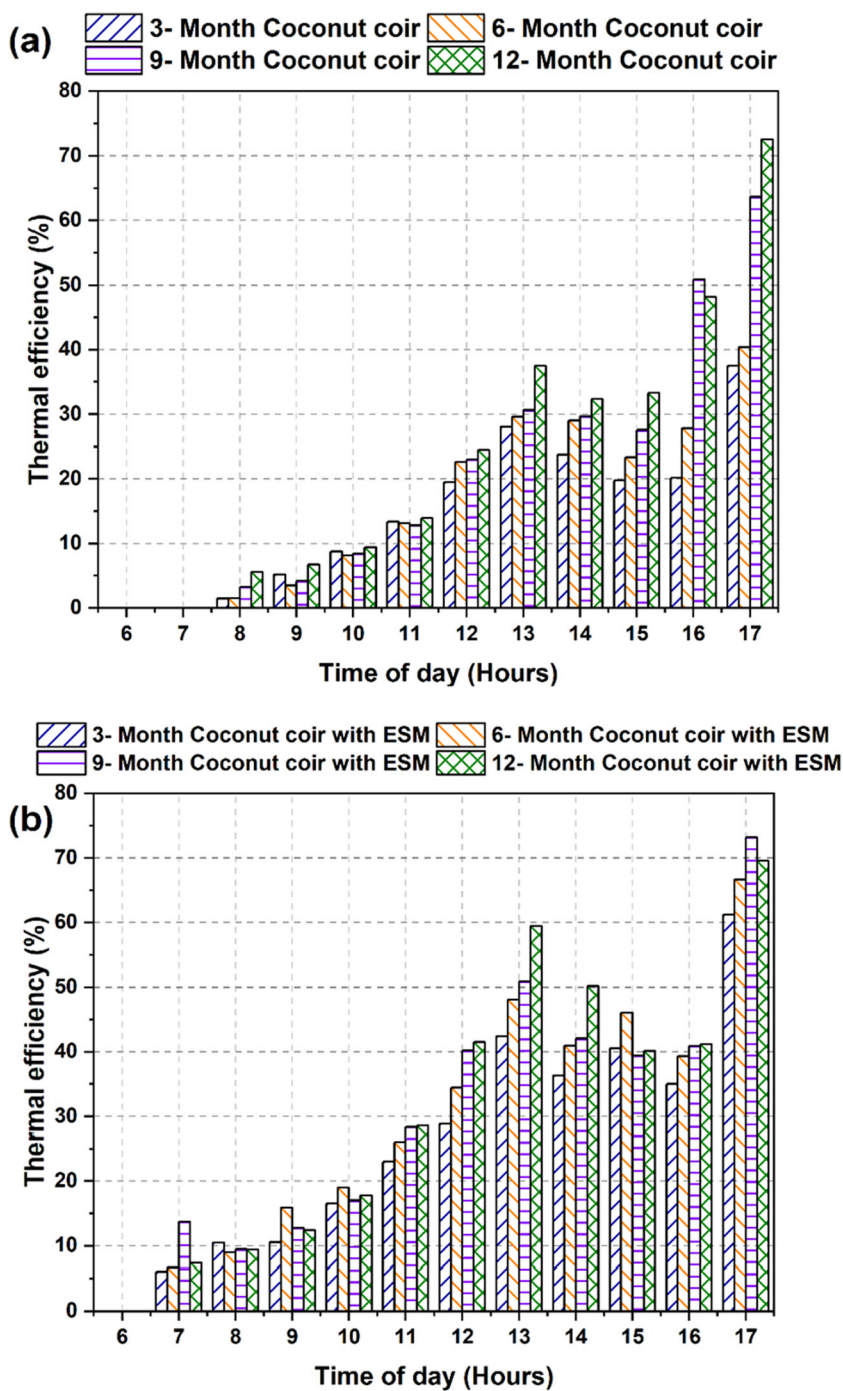
where

$$a_1 = 2.5 \times 10^6, a_2 = -2.369 \times 10^3, a_3 = 2.678 \times 10^1, a_4 = -8.103 \times 10^{-3}, a_5 = -2.079 \times 10^{-5}$$

The variations on thermal efficiency from inclined solar still using coconut coir disk and coconut coir with ESM as energy storage are plotted in Fig. 14a, b. It is seen that the peak hourly thermal efficiency occurs with the maximum solar intensity of the inclined solar still using 3-, 6-, 9-, and 12-month seasoned coconut coir disk and found as 28.08, 29.57, 30.65, and 37.48%, respectively. This is due to the excellent absorption of higher seasoned coconut coir disk for better evaporation. Similarly, from Fig. 14b, it is seen that on adding wire mesh along with the coconut coir, the maximum hourly thermal efficiency of 42.42, 48.07, 50.89, and 59.45% is observed for 3, 6, 9, and 12-month seasoned coconut coir disk with ESM, respectively. It is also seen that the hourly thermal efficiency beyond the lower intensity period is higher in both cases as the coconut coir disk absorbs the energy with and without energy storage for efficient evaporation.

The variations on daily efficiency from inclined solar still using coconut coir disk and coconut coir with energy storage material under different seasoning period are plotted in Fig. 15. It is seen that the daily efficiency of the solar still increases with the increased seasoning period. The daily efficiency of solar still using 3-, 6-, 9-, and 12-month seasoned coconut coir disk is found as 32.8, 36.39, 41.46, and 48.13%, whereas, in addition of wire mesh as energy storage material along with coconut coir, the daily efficiency is improved and found as 47.46, 55.95, 61.78, and 64.54%, respectively. Figure 16 shows the improvement in the yield of fresh water produced from the inclined solar still using different seasoned coconut coir disk and energy storage

Fig. 14 Variations on thermal efficiency from inclined solar still using coconut coir disk and coconut coir with ESM as energy storage

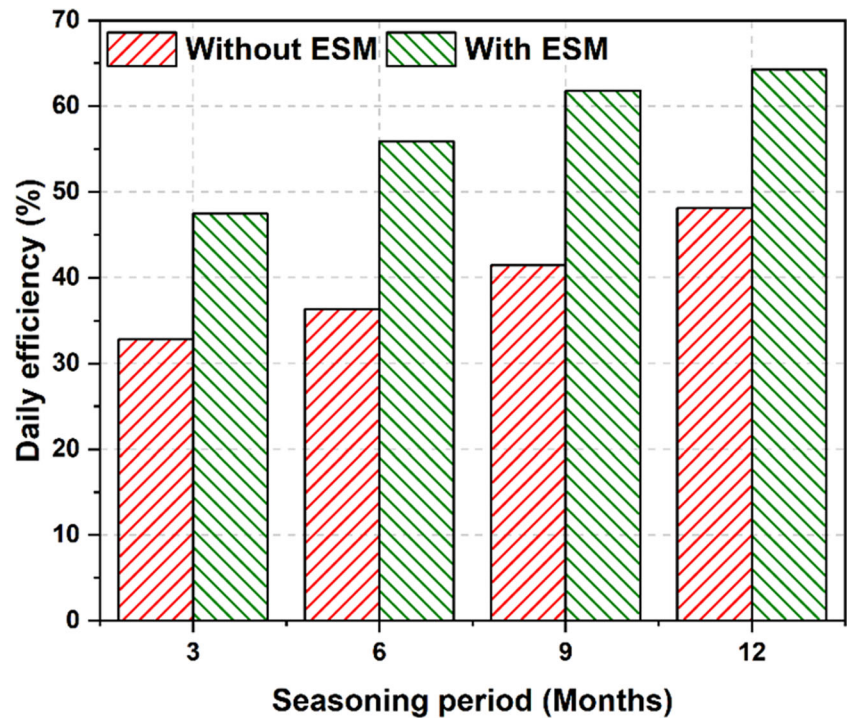


materials in the absorber. It is clear that the amount of fresh water produced using ESM along with the coconut coir disk is improved compared with that of coconut coir disk alone. The 1-year seasoned coconut coir disk with ESM produced a daily improvement of about 66.32% in fresh water compared with coconut coir disk alone. The solar still using 3-, 6-, and 9-month seasoned coconut coir disk with ESM improved the fresh water to about 77.8, 80.1, and 82.07%, respectively, while compared with coconut coir disk alone.

Economic analysis

Cost and economic analysis of the inclined stepped absorber solar still with wicked coir disk and inclined stepped absorber solar still with coconut coir disk and energy-storage materials are tabulated in Tables 4, 5, and 6. The payback period of inclined solar still includes manufacturing (fabrication), maintenance, feed water cost, operating cost, and the rate of distilled water cost. Tables 5 and 6 show that in all the cases of

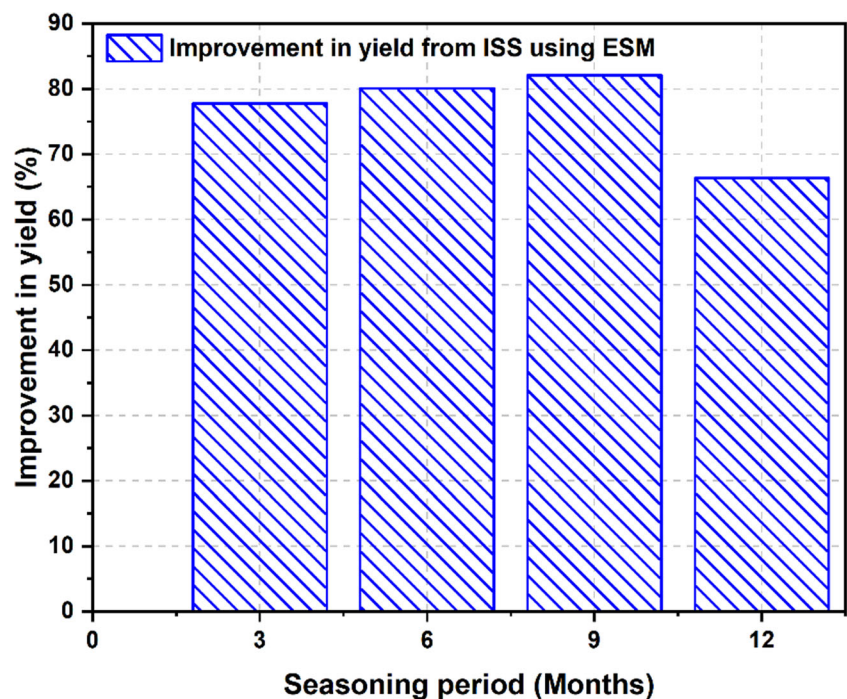
Fig. 15 Variations on daily efficiency from inclined solar still using coconut coir disk and coconut coir with ESM as energy storage



inclined solar still with coconut coir disk and ESM, the payback period is less as compared with the inclined stepped absorber solar still with coconut coir disk. The payback period of the novel inclined solar still with hybrid techniques (energy storage materials and wick materials) was calculated to be 170, 148, 130, and 120 days for 3-month, 6-month, 9-month, and 1-year coconut coir disk wick materials with energy

storage materials, respectively. The payback period is calculated as 257, 243, 215, and 179 days for 3-month, 6-month, 9-month, and 1-year seasoning period, respectively. It is also observed that the inclined stepped absorber solar still with 1-year wicked coir disk and energy storage materials is 59 days less than the inclined stepped absorber solar still with only wicked coir disk.

Fig. 16 Improvement in yield from modified solar still using different seasoned coconut coir disk with ESM



The net profit is calculated using Equation (4),

$$\text{Net profit} = \text{water produced cost} - \text{feed water cost} - \text{operating cost} - \text{maintenance cost} \quad (4)$$

Conclusion

This research reported the investigation on inclined stepped type solar still for increasing the availability of freshwater in remote areas. The performance of the still was studied with varying phases of coconut coir disk as wick materials (3-month, 6-months, 9-months, 1-year dry condition incorporated with wire mesh) in a stepped absorber plate with and without using energy-storing materials. From the experiments, the following conclusions have arrived.

- The freshwater production from the inclined stepped type solar still using 1-year, 9-month, 6-month, and 3-month coconut coir disk wick materials was 3390, 2930, 2670, and 2050 ml per day, respectively.
- The freshwater production from the inclined stepped type solar still using 1-year, 9-month, 6-month, and 3-month coconut coir disk wick materials with energy storage materials were 4890, 4570, 4080, and 3645 ml per day, respectively.
- It is found that the 1-year seasoned coir disk material obtained maximum productivity from the modified solar still than other seasonings of wick materials due to the higher absorbency, capillary rise, and heat transfer coefficient.
- The 1-year seasoned coir disk inclined stepped type solar still with energy-storing material increased the freshwater production rate by 30.6% as compared with the without energy-storing material.

From the analysis, it is found that the proposed solar still is more suitable in the production of fresh water in the locations where there is a great need for fresh water (ground water too salty, coastal region, rural). From the economic analysis, it is clear that solar still maintenance is more reliable by incorporating a low-cost biodegradable material mixed with energy-storing wire mesh in the stepped absorber plate.

Authors' contributions Conceptualization, methodology, resources, formal analysis, and investigation were carried out by Vignesh Kumar Ramalingam, Alagar Karthick, Manoj Praveen Vijayan Jeyalekshmi, Arul Marcel Moshi Antony Joseph Decruz, Athikesavan Muthu Manokar; writing-original draft preparation, review and editing, supervision were carried out by Ravishankar Sathyamurthy.

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Compliance with ethical standards

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Competing interest The authors declare that they have no competing interest.

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