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An experimental study on productivity, energy, and exergy efficiency improvement of inclined solar still using different uncoated wick materials

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Water scarcity and clean drinking water remain a global challenge, particularly in remote and off-grid areas. Solar stills offer a low-cost, sustainable method for water purification. However, its low productivity and low efficiency are the major concerns for using it for large-scale applications. It provides low productivity because the evaporation and condensation rates in conventional solar stills (CSS) are limited by low heat transfer efficiency and large thermal losses. Wick materials increase surface area and heat transfer by dispersing water into a thin layer, which increases productivity and evaporation. Due to this, the proposed study aims to improve the performance of the inclined solar still (ISS) using different uncoated wick materials such as Flannel Cloth, Cotton Cloth, Coconut Coir mat, Jute, and Polypropylene materials. The performance enhancement without coating approach was used to avoid the additional cost, complexity, and maintenance associated with surface treatments or advanced material modifications in solar stills. Wick materials were used over the absorber plate without any coatings and compared with conventional ISS. Among the tested materials, the coconut coir mat provides the best performance. ISS with coconut coir provides water productivity of 4323 ml, whereas conventional ISS provides only 3303 ml. This water productivity of ISS with coir is 30.88% higher than that of conventional ISS. The average energy and exergy of ISS with coconut coir are 43.46% and 2.53%, which shows 62.40% and 86.02% higher energy and exergy efficiency compared to conventional ISS. The economic study gives the distilled water cost of $0.0131 for ISS with coconut coir, and this water production cost is 28.24% less compared to conventional ISS.

Keywords Inclined solar still, Uncoated wick materials, Desalination, Energy efficiency, Exergy efficiency, Economic analysis

List of symbols

A	Water absorbency
AIC	Annual investment Cost ($)
AMC	Annual maintenance Cost ($)
ASV	Annual salvage value
ATC	Annual total cost ($)
ATY	Annual total yield ($)
A_{basin}	Basin area of the solar still (m^2)
A_{water}	Area of water in the basin (m^2)
C	Capital investment ($)
CHT	Convective heat transfer rate (W/m^2.K)

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CPL	Cost per lite ($)
CRF	Capital recovery factor
CSS	Conventional solar still
DSS	Double slope solar still
$\dot{E}_{ex, evap}$	Exergy for evaporation
$\dot{E}_{ex, in}$	Input exergy
$\dot{E}_{ex, sun}$	Exergy from sun
EHTC	Evaporative heat transfer coefficient ($W/m^2.K$)
FAC	Fixed annual cost ($)
FAC	Fixed annual cost ($)
g	Gravitational Acceleration
G_{solar}	Solar radiation (W/m^2)
h	Heat transfer coefficient/capillary height
$h_{evap, water-glass, in}$	Coefficient of evaporative heat transfer rate between water and glass inner surface
i	Rate of interest (%)
ISS	Inclined solar still
L_{water}	Enthalpy of evaporation of water
$m_{distilate}$	Hourly distillate (litres)
$M_{T, distillate}$	Total distillate per day (litres)
n	Life span of still (years)
PBP	Payback period (months)
PCM	Phase change materials
Profit	Net annual profit ($)
q	Heat Input
$Q_{evap, water-glass, in}$	Evaporative heat transfer rate between water and the inner glass surface (W)
RHT	Radiative heat transfer rate ($W/m^2.K$)
SFF	Sinking fund factor
SI	Sustainability index
SP	Selling price ($)
SSS	Single slope solar still
SV	Salvage value
t	Time of operation (h)
T	Surface Tension
$T_{ambient}$	Ambient air temperature (℃)
$T_{glass, in}$	Glass cover inner surface area temperature (℃)
$T_{glass, out}$	Glass cover outer surface area temperature (℃)
T_{sun}	Sun temperature (℃)
T_{water}	Saline water temperature (℃)
V_p	Volume of pore water
V_{bk}	Bulk volume of Wick
V_{wind}	Wind velocity (m/s)
W_{dry}	Dry weight
W_{sat}	Saturated weight
W_t	Final weight after absorption
W_o	Initial weight before absorption
η_{energy}	Energy efficiency (%)
η_{exergy}	Exergy efficiency (%)
Φ	Porosity
θ	Contact angle
ΔT	Temperature difference
ρ	Density (kg/m)
ΣG_{solar}	Cumulative solar radiation over the day (W/m^2)

Solar stills are widely used around the world to generate fresh water for domestic applications, especially in areas where access to clean water and traditional energy sources is limited. This approach is popular because of its affordable cost, simple construction, and environmentally friendly operation, as it operates completely on solar energy. However, the practical application of conventional solar stills (CSS) can be limited by their low efficiency and limited freshwater output. As a result, improving the productivity and efficiency of these systems is critical when choosing a solar still for a certain application[1,2]. To overcome these limitations, several structural designs, such as double-slope, inclined, pyramid-shaped, and hemispherical configurations, have been developed to improve solar energy absorption and overall system performance[3,4]. Furthermore, the use of technological developments such as expanded surfaces (fins)[5], baffles[6], wick materials for improved water distribution[7], porous medium[8], thermal energy storage materials such as PCM[9,10], crushed rocks[11], biomaterials[12,13], metal pieces[14,15], and nano-coatings[16] has demonstrated great potential for increasing the overall productivity and efficiency of solar stills.

A study on a tubular solar still [TSS] used a black cotton wick and parabolic solar tracking for the study, and by using all the modifications, it produced 29.11% and 24.45% improvement in productivity and efficiency[17]. By using black cotton wick alone, this system produced 19.44% and 22.72% improvement in productivity and efficiency. In a specific study, a hemispherical solar still was employed along with a reflector, fan, concentrator, nano PCM, and wick materials. A hemispherical solar still with cotton wick generates 4150 mL/m^2 without any additional modifications, whereas jute wick produces 4316 mL/m^2[18]. Tubular solar still studied along with V-corrugated aluminium basin, wick, carbon black nano fluid on wick and PCM under basin[19]. Results show that using all these modifications, the system obtained 88.84%, 82.16 and 221.8% improvement on productivity, energy and exergy efficiency. Double slope solar still (DSS) was investigated using fins, PCM, External Condenser, and wick materials[20]. These modifications provide 32.46% enhanced daily productivity over the CSS. Tubular solar still was studied using convex absorber, black jute, paraffin wax, oil heat exchanger and parabolic concentrator[21]. By using this setup, they achieved 233.25% improvement in productivity, 39.32% thermal efficiency, and 4.99% exergy efficiency. Tubular solar still performance was studied using a vertical wick, a reflector and nano PCM[22]. According to the results, TSS produced 8300 ml/m^2 daily yield and 57.3% thermal efficiency. Half-cylindrical solar still study uses a convex surface absorber, a corrugated convex surface absorber, cotton and jute wick materials, and Ag mixed nano PCM[23]. Study results show that by incorporating these modifications, a 184% productivity improvement was achieved. Solar still productivity was studied with black-coated cement fins wrapped in black cotton cloth[24]. The results showed that using this arrangement, 4440 mL/m^2 water productivity, 42.4% and 3.7% energy and exergy efficiency were achieved. Inclined solar still (ISS) was tested with a stepped absorber and wire mesh along with different wick materials[25]. Among the different wick materials tested, Water coral fleece achieved the highest of 4280 ml/day water productivity.

The Pyramid solar still (PSS) was studied using reflectors, wick material, glass cover cooling, and nano-Tio$_2$ particles. Study results revealed that using all these components provides 7000ml/m^2/day water productivity and 83.8% thermal efficiency[26]. Wick materials like sponge sheet, coir mat, cotton cloth, and waste cotton pieces were used to investigate DSS with rectangular fins[27]. The highest productivity was found to be 3.58 L while using cotton cloth along with rectangular fins in length wise. A closed-loop inclined wick solar still with an external reflector provides 6.106 kg/m^2 water productivity during the experiment day[28]. Wick material coated in black was used for the performance study of CSS. Results show that CSS and CSS with black coated wicks obtained 2.04 and 2.86 kg of water production[29]. The Pyramid solar still was used with different wick materials such as heavy cotton cloth, light cotton cloth, jute, and velvet fabric for the productivity study[30]. Results show that higher productivity of 1,476 mL/m^2·d and efficiency of 55.3% were obtained while using light cotton. Cotton and polyester wrapped around a vertical wood stick increased the productivity of single basin solar stills[31]. This composite wick material produced 2,450 mL/d of water. Using wick material that was 8 mm thick and entirely covered the basin, a hemispherical solar still was tested[32]. Results show that the system provides 4.55 L/m^2 of water while using the wick along with a still. LC rotating wick and inclined rotating wick solar stills were used with different wick materials, glass cooling and reflectors for the performance study[33]. Results show that the LC and inclined rotating wick obtained 52.8% and 57.3% thermal efficiency while using jute as a wick material. The sponge, jute cloth and luffa fiber wick materials' performance was compared for CSS[34]. Results reveal that while using jute, the CSS overall gain was improved by 23.49%, respectively. Cord wick tubular solar still and tubular solar still performance were tested and compared for productivity. Cord wick design outperforms conventional TSS by 102%, according to the results[35]. A detailed study on wick-type solar stills shows that using wick technology enhances the productivity of solar stills by 20–30%[7]. The blackened solar still was tested for its performance using wicks at different angles. Results show that the wick with a 30° angle provides the best productivity of 4.372 kg/m^2 among the investigated cases.

According to the literature, numerous studies have demonstrated that incorporating wick materials can enhance the water productivity of various solar still designs, including conventional, tubular, pyramid, double-slope, and inclined configurations. However, most of the studies have concentrated on pyramid, tubular, and conventional designs, with comparatively little work focusing on inclined solar stills (ISS). In particular, there is a lack of studies examining the use of different uncoated wick materials in ISS, despite the potential of this approach to enhance performance without the added cost, complexity, and maintenance requirements associated with coated or surface-modified materials. This research addresses this gap by experimentally evaluating five uncoated wick materials, such as flannel cloth, cotton cloth, coconut coir, jute, and polypropylene, and comparing their effects on water productivity, energy and exergy efficiencies, and economic performance.

Novelty and objectives of the study

This study presents a new experimental study of an inclined solar still using a variety of uncoated wick materials, including Polypropylene, cotton cloth, jute, flannel cloth, and coconut coir. Previous studies that enhanced solar still efficiency through the utilization of black coloured/coated materials[17,21,24,29], and nanomaterial coatings to increase solar absorption[26,41]. This study exclusively concentrates on the use of uncoloured natural wick materials. The study aims to provide a more sustainable, low-maintenance, and environmentally friendly solar desalination system suitable for isolated, off-grid, or resource-constrained areas. By avoiding coatings over the wick materials, this study also avoids challenges like material degradation and structural interference in the wick material.

The specific objectives of this study are as follows:

- To identify the most effective uncoated wick material for enhancing the performance of ISS in terms of water productivity, without requiring surface modification.
- To evaluate the energy and exergy efficiency of each wick material to understand the thermal performance of untreated natural wick materials.
- To conduct a detailed economic analysis to evaluate the cost of distilled water production for each wick material, accordingly determining their feasibility for real-world applications.

The use of natural wick materials without coatings provides an alternative solution for long-term, scalable, and cost-effective solar desalination. The findings of this study provide significant details on the design of efficient, sustainable, and renewable solar stills.

Materials and methods

Design and construction

The step-type inclined solar still was designed using SolidWorks software with proper dimensions. The ISS setup was fabricated using available materials in the local market. The base arrangements were fabricated using a 5 mm thickness of galvanized iron sheet metal. This sheet metal has been cut to the required dimensions, then it was bent and welded into the required shapes, and then it was painted. The stepped arrangement in the ISS has been fabricated with aluminium materials with had 0.5 mm thickness. the step arrangements were particularly designed to hold the water in the basin because of the inclined shapes, which were further used for the operation. The overall area of the absorber in the ISS was 0.9m^2. The absorber was coated with a black colour to absorb more radiation and retain the heat. The top of the solar still was covered with a pure class cover with had 6 mm thickness. The ISS was insulated for a thickness of 30 mm on the sides and bottom with the glasswool material to retain the heat losses. The saline water was flown over the absorber plate and was recirculated through the salt water tank. The condensed water droplets on the glass cover inner surface were collected at the end of the glass cover. The fabricated ISS was installed at the test site at an angle of 30° in the north-south direction to maximize the amount of solar energy that it can absorb. The inclination angle of the fabricated setup was fixed based on the previous study, which found the suitable inclination angle for the ISS in the particular test site[36]. The experimentation was carried out in Tuticorin district, Tamil Nadu, India, at the geographical coordinates of (8.7874° N, 78.1983° E). The experiment was conducted for about 12 h during May 2024, which was the summer climatic season. The dimensions of the setup are presented in detail in the schematic diagram depicted in Fig. 1.

Specification of instruments

K-type thermocouple sensors are fitted in various locations in the ISS. The temperature parameters of the experimental setup, such as the basin water temperature, absorber temperature, and glass cover temperature, are measured with the aid of the thermocouple sensors and digital temperature indicator. Apart from the temperature parameters of the ISS, the distillate collection is also measured using the calibrated measuring jar.

The meteorological parameters such as solar irradiation, wind velocity and the ambient temperature of the location are also measured regularly. The TM-207 Model Solar Meter was used to monitor the solar irradiation, and a handheld fan-type anemometer was used to measure the wind velocity. The data are recorded every thirty minutes for both the meteorological parameters and the ISS setup temperature, as well as productivity parameters.

The instruments used in the experimentation, along with their range and accuracy, are provided in Table 1. The uncertainties in these parameters are obtained using Eq. (1)[37].

$$Standard\,Uncertainity = \frac{a}{\sqrt{3}} \tag{1}$$

The error in the experimental values was calculated using the following equations from 2 to 4. According to the error analysis, the temperature, energy efficiency, exergy efficiency, and evaporative heat transfer coefficient all had errors of ± ±0.141 °C, 5.1%, 4.4%, and 3.2%, respectively.

The result R is a given function of the independent variables $\mathrm{x_1,\ x_2,\ x_3,\ \ldots.,\ x_n}$.

Thus, R = R ($\mathrm{x_1,\ x_2,\ x_3,\ \ldots.,\ x_n}$).

By considering the data logger and thermocouple accuracy, the total uncertainty in the temperature is calculated as

$$Total\,Uncertanity = \sqrt{\left[(U_1)^2 + (U_2)^2\right]} \tag{2}$$

U_1 and U_2 are the accuracy of the thermocouple and data logger device.

Let $_{\mathrm{R}}$ be the uncertainty in the result and $_{1},\ _{2},\ \ldots,\ _{\mathrm{n}}$ be uncertainties in the independent variables. The uncertainty in the outcome with these odds is expressed as follows if the uncertainties in the independent variables are all given with the same odds:

$$_{\mathrm{R}} = \sqrt{\left[\left(\frac{\mathrm{R}}{\mathrm{x_1}} \times {}_{1}\right)^2 + \left(\frac{\mathrm{R}}{\mathrm{x_2}} \times {}_{2}\right)^2 + \cdots + \left(\frac{\mathrm{R}}{\mathrm{x_n}} \times {}_{n}\right)^2\right]} \tag{3}$$

Applying Eq. (3) for Energy efficiency of the TWSS solar stills, it is written as

$$_{TWSS} = \sqrt{\left[\left(\frac{TWSS}{\mathrm{M_{T,distillate}}} \times {}_{\mathrm{M_{T,distillate}}}\right)^2 + \left(\frac{TWSS}{\sum G_{solar}} \times {}_{\sum G_{solar}}\right)^2\right]} \tag{4}$$

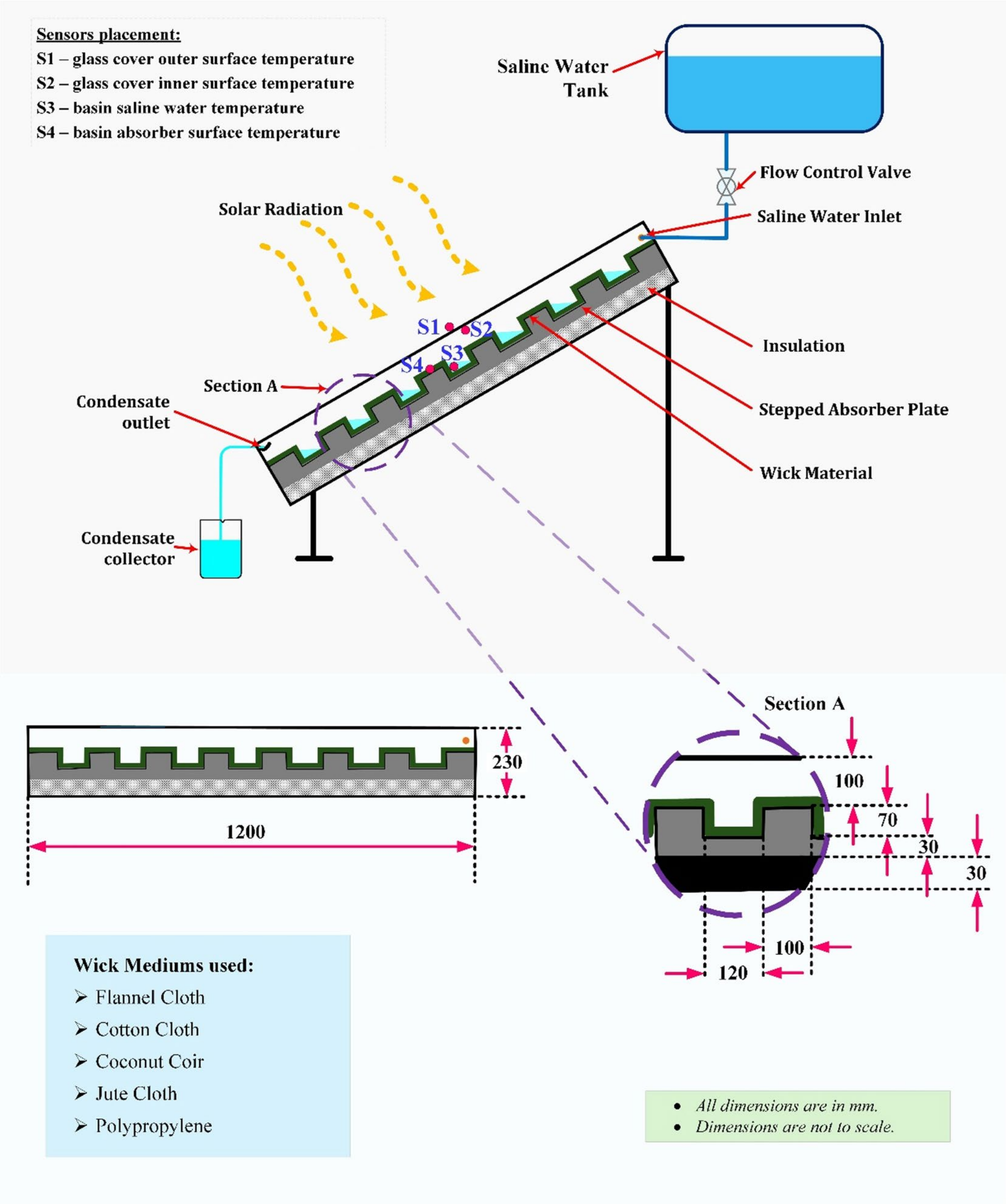

Fig. 1. Schematic diagram.

Experimentation

The fabricated experimental setup was integrated with the measuring instruments, and the system was placed in the outdoor site. The studies were conducted in May 2024, which was the peak summer month in the Tuticorin district, Tamil Nadu, India.The experimental studies were carried out throughout six continuous days for four time periods: May 6–11, May 13–18, May 20–25, and May 27-June 1. Each wick material was evaluated at one of the mentioned times. To verify the accuracy and reliability of the results, all experiments were carried out in similar surroundings, such as solar radiation, ambient temperature, and wind speed. This planned scheduling was intended to isolate the impact of wick materials on the performance of the inclined solar still. Special effort was given to selecting days with comparable weather patterns so that performance differences could be strongly attributed to wick materials rather than external factors.

Each material was tested individually using the same setup, which was thoroughly cleaned and reset between tests to ensure uniform starting conditions. A manual control valve connected to the feed tank was used to regulate the flow of saline water into the basin, ensuring a constant water level throughout each experiment. The wick materials were placed uniformly over the absorber plate, which had a step-like absorber used to retain water uniformly along the inclined surface, enhancing capillary action and evaporation by preventing water from flowing downward due to gravity. The saltwater tank was filled with the feed water. The flow valve regulated the

Fig. 2. (**a**) Experimental setup. (**b**) Different wick materials used in the study.

Instrument	Range	Accuracy	Relative error %	Standard uncertainty
TM-207 model solar meter	0–2000 W/m^2	± 2 W/m^2	0.1	1.155 W/m^2
Anemometer	0–25 m/s	± 0.05 m/s	0.2	0.029 m/s
Thermocouple	0–220 °C	± 1 °C	0.45	0.577 °C
Water collector	0–1.5 L	± 0.001 L	0.07	0.000577 L

Table 1. Instrumentation error.

flow from the tank to the ISS. The salty water flowed over the absorber of the ISS. A certain amount of water was retained in the step-like structure of the ISS absorber. To verify that all steps have been filled and that operating conditions are consistent, a calculated amount of 12 L of water was used for every experimental trial. The K-type thermocouples fixed in various locations of the solar still were monitored in the digital displays connected to these thermocouples. Condensate water, basin vapour, absorber and glass temperatures were measured using the thermocouple. The temperature readings were measured every half hour. The solar irradiation was measured using the solarimeter. The wind velocity was recorded using the fan-type anemometer. The yield collected every hour was measured using the measuring jar.

The experiment was divided into several cases to compare the performance. These cases included the following:

Case 1 Conventional ISS.

Case 2 Flannel Cloth with ISS.

Case 3 Cotton Cloth with ISS.

Case 4 Coconut Coir with ISS.

Case 5 Jute Cloth with ISS.

Case 6 Polypropylene with ISS.

Each case was studied for one day. The water in the ISS setups with the wick medium flowed over the wick medium through the basin. An inclined solar still works on the basic principle of evaporation and condensation, in which solar energy heats saline water, causing it to evaporate, and the vapour condenses on a cooler surface to produce distilled water. The use of wick materials improves this process by spreading the water thinly over the absorber surface, increasing heat absorption, evaporation rate, and overall productivity.

Figure 2a shows the real-time experimental setup with jute wick material (after distillation). As shown in the figure, the wick materials were placed over the absorber plate of the still. The different wick materials used in the system study are shown in Fig. 2b.

Properties of wick materials

The efficiency of solar stills with uncoated wicks is determined by physical and thermal properties like porosity, capillary rise, absorbency, and heat transfer coefficient. These qualities determine the material's ability to retain and transfer water, absorb heat, and enable steady evaporation. This study examined five uncoated wick materials: coconut coir, flannel cloth, cotton cloth, jute, and polypropylene. Coconut coir, flannel, and cotton have better porosity, absorbency, and capillary action, resulting in more thermal performance. In contrast, polypropylene had the lowest values, leading to lower water productivity. The physical and thermal properties of the uncoated wick materials are shown in Table 2. The equation used to find the properties of wick materials is shown below.

The volume of water in the wick (V_p) and wick volume (V_{bk}) used to evaluate the porosity (φ) of the material

$$V_p = W_{sat} - W_{dry} \tag{5}$$

$$V_{bk} = \pi\, r^2 * h \tag{6}$$

Porosity (φ) is calculated using.

$$\varphi = \frac{V_p}{V_{bk} * \rho_{\ w}} \tag{7}$$

ρ_w is the density of water (1000 kg/m^3).

Capillary rise (h) is calculated using

$$h = \frac{2T * \cos\theta}{r * \rho\ * g} \tag{8}$$

r is the radius of the pore in the wick materials, whereas T = 0.072 N/m, ρ = 1000 kg/m^3, g = 9.81 m/s^2.

Heat transfer coefficient is calculated using

$$h = \frac{q}{\varDelta\ \mathrm{T}} \tag{9}$$

q is the heat transferred per unit area (W/m^2) and $\varDelta$ T is the temperature difference (°C).

Water absorbency (A) of the different wick materials is calculated using

$$A = \frac{W_T - W_o}{W_o} \tag{10}$$

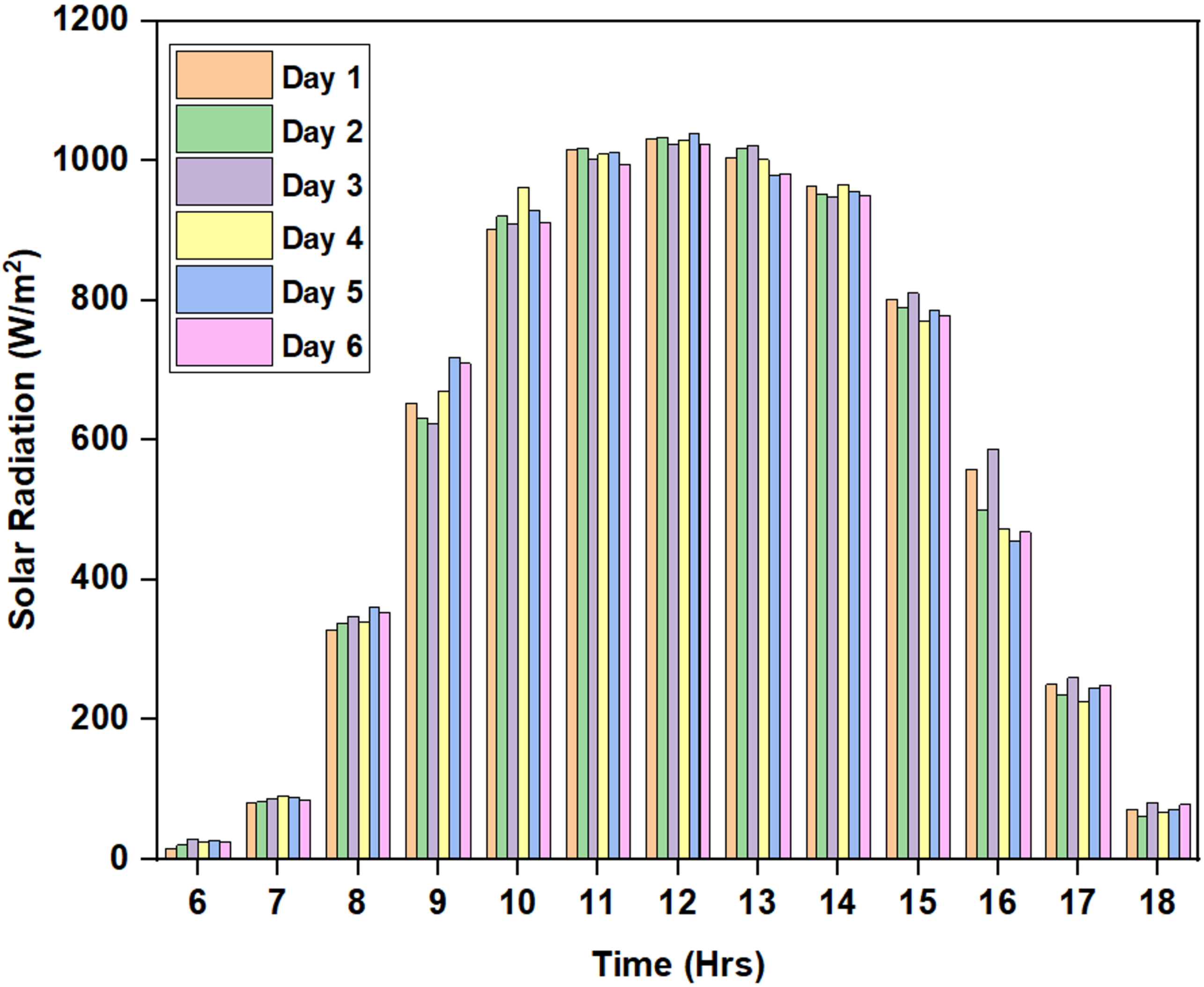

Fig. 3. Radiation vs time.

Wick material	Material type	Colour	Porosity (%)	Capillary rise (mm/h)	Heat transfer coeff. (W/m^2·K)	Water absorbency (%)
Coconut coir	Natural fibre	Brown	71.1	110	0.83	63.5
Flannel	Cotton-based	Gray	70.8	150	0.81	65.1
Cotton	Natural textile	Dark gray	65.3	120	0.72	62.2
Jute	Natural fibre	Brown	69.2	90	0.66	51.1
Polypropelene	Synthetic polymer	Off-white	57.1	50	0.57	47.1

Table 2. Physical and thermal properties of wick materials.

W_T is the final weight after absorption and W_o is the initial weight before absorption. Water absorbency is measured in %.

Performance study equations

Energy equations

The productivity of the solar still unit is calculated by measuring the hourly condensate rate, which is shown as follows[38]:

$$m_{distilate} = \frac{Q_{evap,water-glass,in}}{L_{water}} \tag{11}$$

where,

L_{water} is the enthalpy of evaporation of water,

$$L_{water} = 2.49 \times 10^{6} \left[1 - 9.48 \times 10^{-4} T_{water} + 1.31 \times 10^{-7} T_{water}^{2} - 4.8 \times 10^{-9} T_{water}^{3}\right] \tag{12}$$

Equation (4) yields the coefficient of evaporative heat transfer rate (hevap, water-glass, in) between the inner surface of the glass and water, which is shown below.

$$Q_{evap,water-glass} = h_{evap,water-glass,in} \times A_{water} \times (T_{water} - T_{glass,in}) \tag{13}$$

Equation (5) provides the total amount of distilled water produced by the still during the operational time (t) in hours.

$$M_{T,distilate} = \sum\nolimits_{0}^{t} m_{distilate}(t) = \sum\nolimits_{0}^{t} \frac{Q_{evap,water-glass,in}(t)}{L_{\mathrm{water}}} \tag{14}$$

The ability of converting solar energy into heat for the purpose of evaporating water and creating distillate is what determines a solar still's energy efficiency. The daily energy efficiency of the solar still is determined by

$$\eta_{\ e} = \frac{M_{T,distilate} \times L_{water}}{A_{\mathrm{basin}} \times \sum G_{solar} \times 3600} \tag{15}$$

. where,

G_{solar} is the solar radiation.

Exergy equations

The energy quality of any thermodynamic system can be systematically evaluated through the use of exergy analysis[38–40].

Input exergy equation

$$\Sigma\, \dot{\mathrm{E}}_{ex_{in}} = \Sigma\, \dot{\mathrm{E}}_{ex_{sun}} \tag{16}$$

.

Exergy from sun

$$\Sigma\, \dot{\mathrm{E}}_{ex_{sun}} = (A_{basin} \times \Sigma\, G_{solar}) \times \left[1 - \frac{4}{3} \times \left(\frac{T_{ambient}}{T_{sun}}\right) + \frac{1}{3} \times \left(\frac{T_{ambient}}{T_{sun}}\right)^{4}\right] \tag{17}$$

.

Exergy for evaporation

$$\Sigma\, \dot{\mathrm{E}}_{ex_{evap}} = \frac{M_{T,distillate} \times L_{water} \times \left[1 - \left(\frac{T_{ambient}}{T_{water}}\right)\right]}{3600} \tag{18}$$

.

Exergy efficiency

$$\eta_{\ exergy} = \frac{\Sigma\, \dot{\mathrm{E}}_{ex_{evap}}}{\Sigma\, \dot{\mathrm{E}}_{ex_{sun}}} \tag{19}$$

.

Exergy efficiency for ISS

$$\eta_{\ exergy} = \frac{\frac{M_{T,\ distillate}}{3600} \times L_{water} \times \left[1 - \left(\frac{T_{ambient}+273}{T_{water}+273}\right)\right]}{(A_{basin} \times \Sigma\, G_{solar}) \times \left[1 - \frac{4}{3}\left(\frac{T_{ambient}+273}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{ambient}+273}{T_{sun}}\right)^{4}\right]} \tag{20}$$

.

Economic equations

For all cases, the yearly interest rate has been set at 10% (i) on the initial investment, and the lifespan (n) of the solar still has been set at 15 years. The Annual Maintenance Cost (AMC) of the still is 15% each year[41,42].

$$CRF = \frac{i(1+i)^{n}}{(1+i)^{n} - 1} \tag{21}$$

$$FAC = C \times CRF \tag{22}$$

$$SFF = \frac{1}{(1+i)^{n}-1} \tag{23}$$

$$SV = 0.2 \times \ C \tag{24}$$

$$ASV = SFF \times \ SV \tag{25}$$

$$AMC = 0.15 \times \ FAC \tag{26}$$

$$ATC = FAC + AMC - ASV \tag{27}$$

Cost per liter of distilled water (CPL)

$$CPL = \frac{ATC}{Annual\ Total\ Yield\ (ATY)} \tag{28}$$

.

Payback period (PBP)

$$PBP = \frac{lnln\ \left(\frac{ATY\ \times\ Selling\ price}{(ATY\ \times Selling\ price)-(AIC\times\ i)}\right)}{lnln\ (1+i)} \tag{29}$$

$$Profit = \left(n - \frac{PBP}{12}\right) \times \ (SP - CPL) \times \ ATY \tag{30}$$

.

Results and discussion

The primary source of energy for solar still experiments is solar radiation. To determine the productivity of solar stills, the amount of solar radiation received in the South Tamil Nadu region has been regularly measured. Solar still efficiency is heavily dependent on radiation, which helps in the evaporation of water, providing purified water; hence, analyzing this radiation range is essential. Solar radiation recorded is shown in Fig. 3. Radiation varies from sunrise to sunset, reaching its highest at noon. Afterwards, it gradually declines during the experiment. Solar radiation range is higher during noon time during the study, and it gives maximum range up to 1038 W/m^2 during 12.00 p.m. The average solar radiation obtained during the investigation days is 590.15, 584.23, 594.53, 586.76, 589.38, and 585.15 W/m^2. The deviation between the maximum and minimum solar radiation range is only 1.76%. To ensure the reliability of comparisons between different wick materials, test days were carefully selected to maintain environmental consistency. The maximum deviation in solar radiation among all days was only 1.76%, and the variation in key ambient parameters remained below 5%. This methodological approach ensured that the observed performance differences among wick materials could be attributed primarily to their thermophysical properties rather than external environmental fluctuations.

The unique thermo-physical characteristics of the coconut coir mat are the main cause of the higher condensed water temperature seen in Fig. 4 when employing it in a solar still. The increase in condensate water temperature is due to enhanced vapour development within the solar still during periods of strong solar input. As the saline water inside the still absorbs solar energy and heats, the rate of evaporation increases. This vapour then condenses on the cooler inner surface of the transparent cover, releasing latent heat and slightly increasing the temperature of the collected distilled water. Because of its extremely high porosity and water-retention ability, coconut coir can retain more water close to the surface for extended periods. A more thermally saturated vapour is produced by continuous evaporation made possible by this continuing moisture availability. Its limited thermal conductivity also contributes to a warmer water interface by keeping heat in the upper evaporative layer rather than releasing it downstream. In contrast to thinner materials like cotton or jute, the fibrous and thick structure of coir mats also serve as an insulating layer, reducing heat loss and enabling the evaporating surface to reach higher temperatures. Because of their superior capillarity, water retention, and moderate thermal conductivity, Cases 2 and 3 generate warmer condensate water in solar stills. These characteristics enable the evaporation surface to heat effectively in the presence of sunlight and maintain a constant moisture content. Cotton heats rapidly and produces vapour steadily, whereas flannel, with its brushed texture, retains more water. In comparison with materials like jute (Case 5) or polypropylene (Case 6), this results in warmer condensed water due to greater vapour temperatures and a higher dew point.

The average condensate water temperature obtained during the investigation is 48.92, 57.84, 56.53, 58.51, 52.07, and 51.01 °C for Cases 1, 2, 3, 4, 5 and 6.

The absorber plate temperature measured during the investigation is shown in Fig. 5. A moist and thermally insulated evaporative surface is created by the thick, fibrous structure, high porosity, and superior water retention of the coconut coir mat, which has the highest absorber temperature among wick materials. This variation can be attributed to differences in the thermal conductivity, thickness, and water retention properties of the wick materials placed over the absorber surface. Materials with higher water retention and better thermal absorption capabilities led to increased heat transfer to the water film, resulting in higher surface temperatures. It is more effective than thinner or less absorbent materials at raising the local temperature because of its poor thermal conductivity, which reduces heat loss to the basin water and concentrates solar energy close to the surface. Dense, brushed fabric with good capillarity, flannel holds more water and traps heat effectively, allowing it to stay

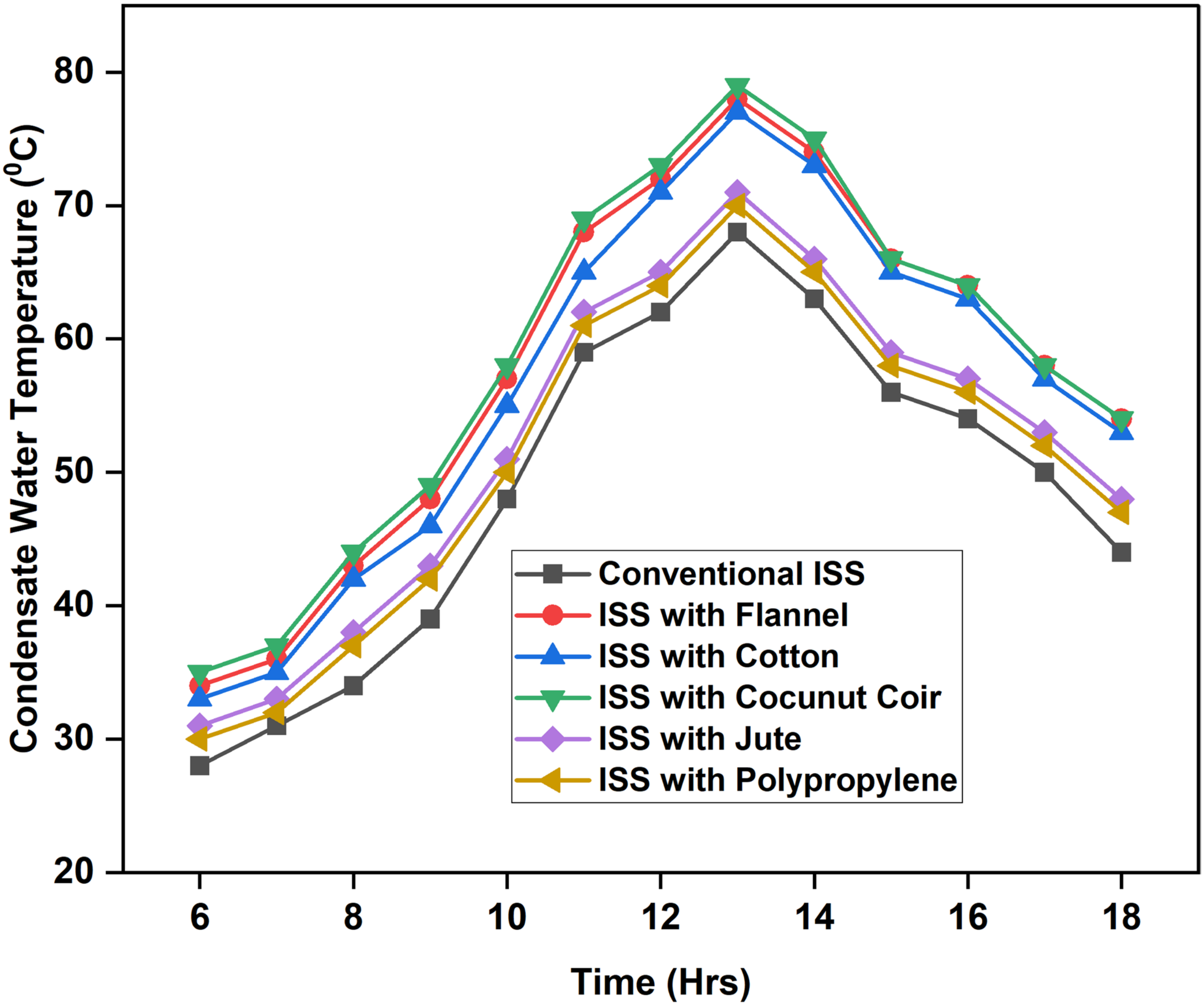

Fig. 4. Condensate water temperature for all cases.

warm for longer when exposed to the sun. Cotton has a lower water retention and a thinner weave than flannel and coir, which results in rapid loss of heat and a somewhat lower absorber surface temperature. The average absorber plate temperature of Cases 1, 2, 3, 4, 5 and 6 is 51.92, 60.07, 58.69, 61.76, 55.46, and 54.46 °C. it clearly shows that case 4 provides a higher absorber temperature compared to the other investigated cases.

The transparent glass temperature obtained by all the investigated cases during the study is shown in Fig. 6. The unique water retention and insulation qualities of the coconut coir mat result in extended and intense evaporation, creating a large volume of warm, moist vapour that rises and condenses on the glass surface, raising the glass temperature in a solar still using Case 4. The glass stays warmer for longer due to the constant flow of hot vapour. Although not quite as much as coir, flannel fabric promotes consistent evaporation. Although cotton has a moderate thermal sensitivity and good capillarity, its rapid cooling rate and reduced water-holding capacity lower the amount and temperature of vapour that reaches the glass. Therefore, in terms of glass temperature performance, coir has the highest vapour effect and consequent heat transfer to the glass. The average glass temperature during the investigation day is 45.69, 50.30, 49.07, 51.53, 48.92 and 47.90 °C for Cases 1, 2, 3, 4, 5 and 6.

The basin vapour temperature of all the investigated cases is shown in Fig. 7. The basin vapour temperature is vital because it is directly linked with the evaporation and condensation process, which are the core mechanisms of water production in a solar still. When using a coconut coir mat in a solar still, the basin vapour temperature is higher than when using other wick materials. Because of the characteristics of coir, a continuously moist surface can be kept heated for longer when exposed to sunlight. Its insulating, fibrous structure efficiently concentrates heat close to the evaporation interface while reducing downward heat loss to the basin water. The overall vapour temperature in the basin area rises as a result of the warmer and denser vapour produced by this prolonged heating. Compared to less wick materials like cotton, jute, or polypropylene, the coir mat also guarantees constant evaporation throughout the day, maintaining high humidity and thermal saturation, which raises the vapour temperature even more. Among the studied materials, coconut coir and flannel cloth had

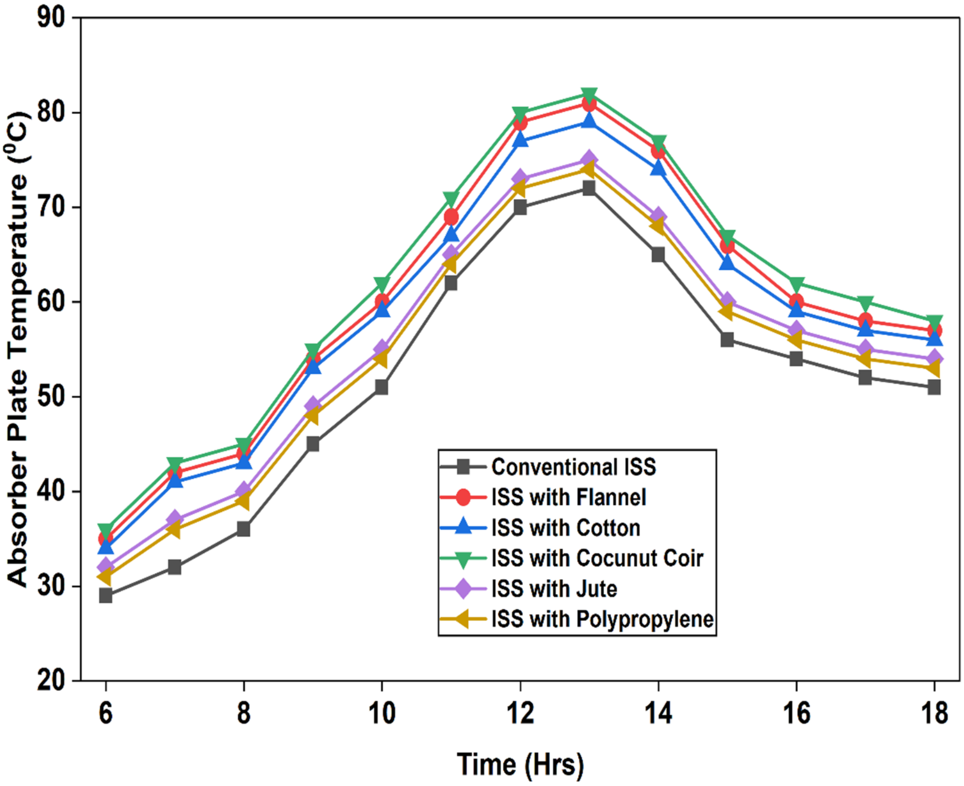

Fig. 5. Absorber temperature for all cases.

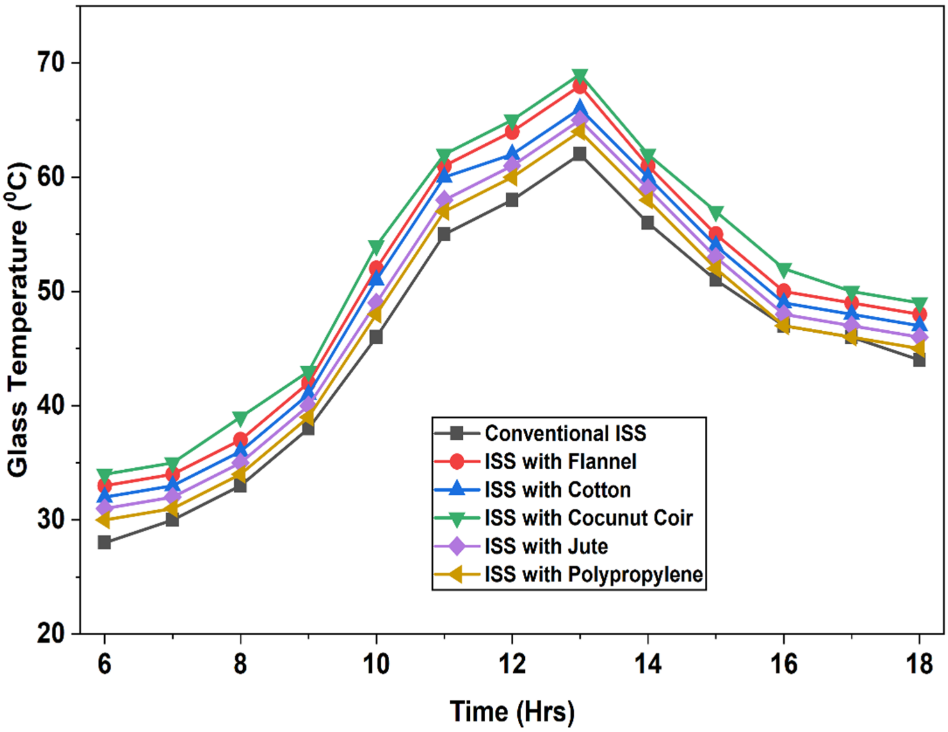

Fig. 6. Glass temperature for all cases.

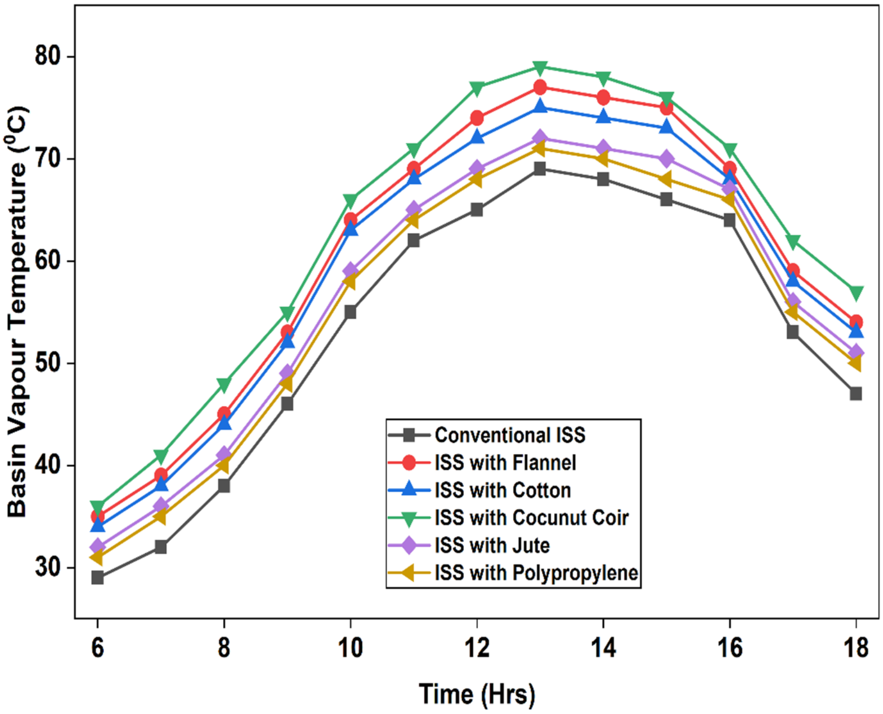

Fig. 7. Basin vapour temperature for all cases.

higher vapour temperatures. This can be due to their improved water retention and capillary action, which enabled more uniform and effective heat distribution, resulting in increased evaporation. Maintaining a high vapour temperature is essential because it increases the partial pressure differential between the vapour and the condensation surface, hence increasing the condensation rate. The findings reveal that wick materials not only help absorb and transfer heat but also play a crucial role in increasing vapour temperature, thereby improving the performance of the inclined solar still. The average basin vapour temperature of cases 1, 2, 3, 4, 5, and 6 is 53.38, 60.53, 59.22, 62.84, 56.81 and 55.69 °C. The results clearly show that the case 4 basin vapour temperature range is much higher than the other investigated cases.

Water productivity obtained by all the cases is shown in Fig. 8. The outstanding water retention, excellent porosity, and strong natural capillary action of the coconut coir mat provide higher performance compared to other materials. Because of its thick, fibrous nature, water is constantly wicked to the surface, keeping the evaporation surface wet. While having a low heat conductivity, its capacity to hold onto a lot of water makes up for it by maintaining evaporation for longer. Additionally, it has natural absorptivity, which gives better productivity. Flannel (Case 2) is a thick cotton fabric with a brushed surface that improves capillarity and moisture retention. Because of its modest thermal conductivity, it may heat up effectively in the presence of the sun. It performs better than ordinary cotton or jute because of its capacity to remain moist and constantly provide water to the evaporation surface, despite its low natural absorptivity. Uncoated cotton's fine weave (Case 3) and hydrophilic properties give it excellent capillarity and outstanding thermal conductivity. But because of its natural white or off-white colour, it has a low solar absorptivity, which restricts how much more heat it can absorb from the sun. In comparison with jute, it maintains a relatively high evaporation rate because of its quick water movement and limited retention. Compared to cotton or coir, jute (Case 5) has lesser porosity and absorptivity due to its natural roughness and fibrousness, but it has strong capillarity. Its open weave reduces the amount of water it retains, and its colour reflects more sunshine. Furthermore, jute biodegrades more readily in warm, humid conditions. Although polypropylene (Case 6) is quite resilient, they are inefficient in terms of heat and water. Particularly when light-colored, they feature low absorptivity, poor capillarity, and low porosity. They have a sufficient thermal conductivity, but they don't have the moisture-transporting capabilities needed for solar stills to function effectively. Because of this, when uncoated, they generate the least amount of water out of all the wick materials. The maximum water production is attained in the afternoon between 12.00 and 13.00 p.m., and water productivity is continuous from morning 6.00 a.m. to night 20.00 p.m., after which water productivity becomes zero in all of the investigated cases. The maximum water productivity during the afternoon time is 520, 635, 624, 649, 601, and 589 ml for conventional, flannel, cotton, coconut coir, jute and polypropylene used systems.

Figure 9 shows the cumulative water productivity of an inclined solar still using different wick materials. An inclined solar still with a coconut coir mat has a better cumulative water productivity because it can provide uniform evaporation, faster heating, higher vapour temperatures, efficient heat use, and long-term stability. These factors ensure steady and sustained water production throughout the day, leading to higher overall water yield compared to Flannel Cloth, cotton cloth, jute, and Polypropylene. The cumulative water productivity of conventional ISS is 3303 ml, whereas coconut coir gives a maximum cumulative water productivity of 4323 ml.

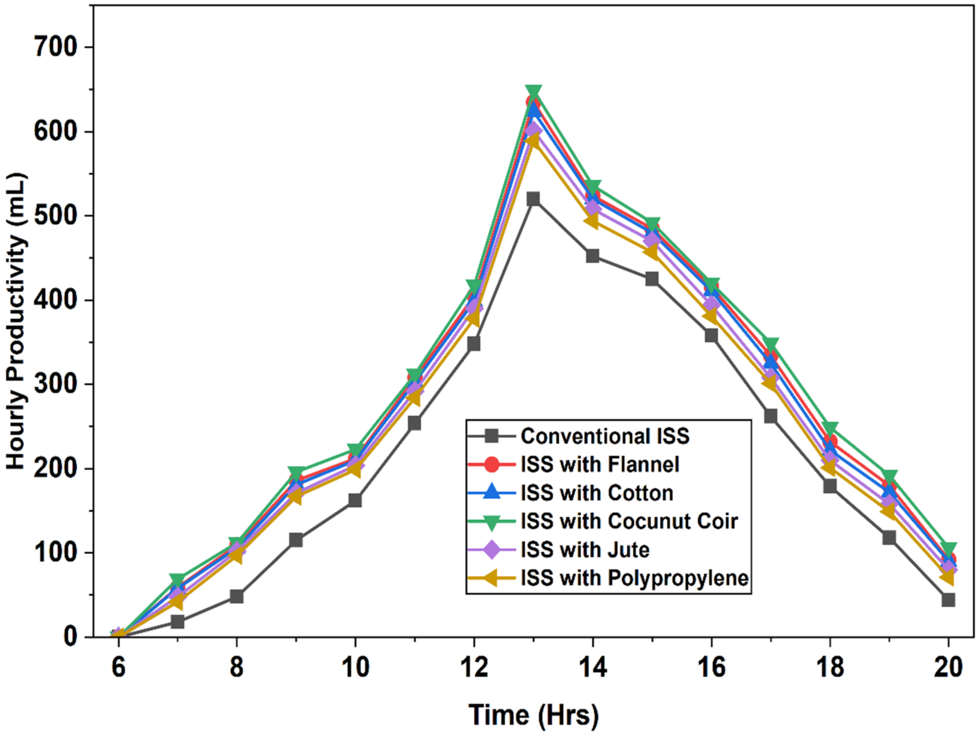

Fig. 8. Hourly based productivity for all cases.

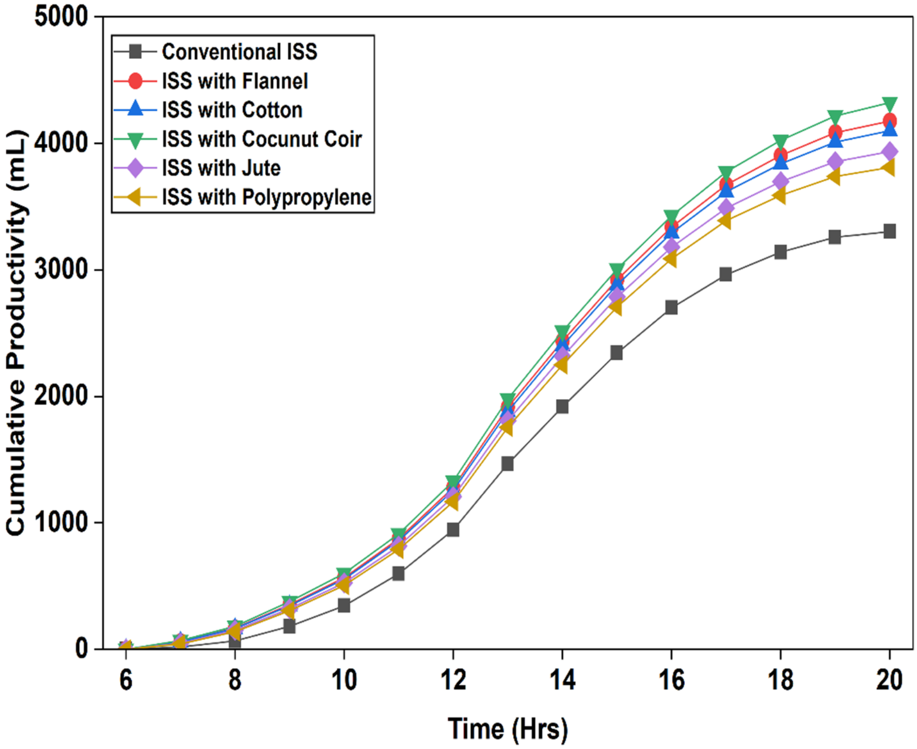

Fig. 9. Cumulative productivity.

Other investigated cases, such as flannel, cotton, jute and polypropylene are produced 4177, 4101, 3936, and 3810 ml cumulative water productivity during the study. The maximum cumulative water productivity of the coconut coir is 30.88, 3.49, 5.41, 9.83, and 13.46% higher compared to conventional, flannel, cotton, jute and Polypropylene wick materials.

The efficiency of the inclined solar still for all the investigated cases is shown in Fig. 10. Inclined solar still with coconut coir wick materials provides the maximum efficiency compared to other wick materials such as flannel, cotton, jute and Polypropylene. This improved performance is due to coconut coir's high porosity, excellent water retention, and efficient capillary action, which all contribute to increased heat absorption and rapid evaporation. Other materials, such as flannel fabric, jute, cotton, and polypropylene, demonstrated higher energy efficiency when compared to the conventional ISS. The conventional method had the lowest energy efficiency due to the lack of a wick, which restricted heat distribution and evaporation surface area. Coconut coir provides maximum efficiency because coconut coir has an excellent water transport capacity, thermal properties, high evaporation rate and durability. These properties of coconut coir make it more efficient than the other wick materials. Similar to solar radiation, the maximum efficiency is achieved during the afternoon, around 12.00 to 13.00 p.m., then it starts to decline till the day ends. The maximum efficiency of the conventional, flannel, cotton, coconut coir, jute and polypropylene used systems is 55, 77, 75, 80, 70, and 67% for the investigated days. The comparison investigation reveals that employing wick materials, particularly uncoated ones such as coconut coir, significantly improves the thermal performance of the solar still. This increase in energy efficiency leads directly to increased freshwater production, indicating the suitability of such materials for efficient solar desalination in real-world situations.

The average efficiency for the investigated day is shown in Fig. 11. The average efficiency of coconut coir is much higher than the other investigated materials. Flannel cloth provides second-best results, followed by cotton during the investigation. The conventional inclined solar still produces an average efficiency of 26.76%. Coconut coir provides a maximum average efficiency of 43.46%. The other examined materials, flannel, cotton, jute, and polypropylene, had an average efficiency of 40.92, 39.07, 35.84, and 33.61%. Coconut coir 4 has a maximum efficiency of 62.40, 6.2, 11.23, 21.26, and 29.3% higher than the conventional, flannel, cotton, jute, and polypropylene used systems.

Table 3 represents the comparative analysis of the present study with previously published literature. Results show that different wick materials performed well for different types of solar stills like CSS, DSS, PSS and TSS. Most studies achieved productivity between 3 and 13.58 L/m^2/day and efficiency from 29.72 to 61.5%, using advanced enhancement techniques apart from the black coated wick mediums. Also, results show that the proposed study offers better productivity and efficiency while comparing with other published works without any additional components like external condenser, glass cooling, nano PCM and fan. The present study, utilizing an ISS with coconut coir, achieved 4323 ml productivity and 43.46% efficiency, outperforming many previous designs in both simplicity and effectiveness. Although the absolute productivity is lower than that of significantly improved systems, the simplicity, sustainability, and cheap maintenance of this uncoated design make it a viable option for dry, off-grid locations.

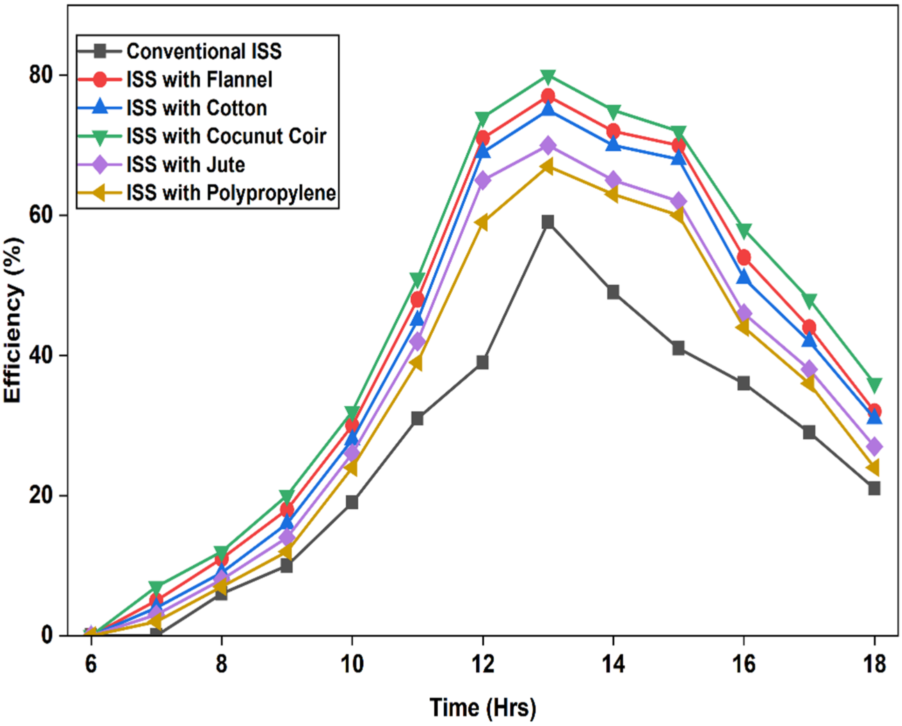

Fig. 10. Efficiency variations for all cases.

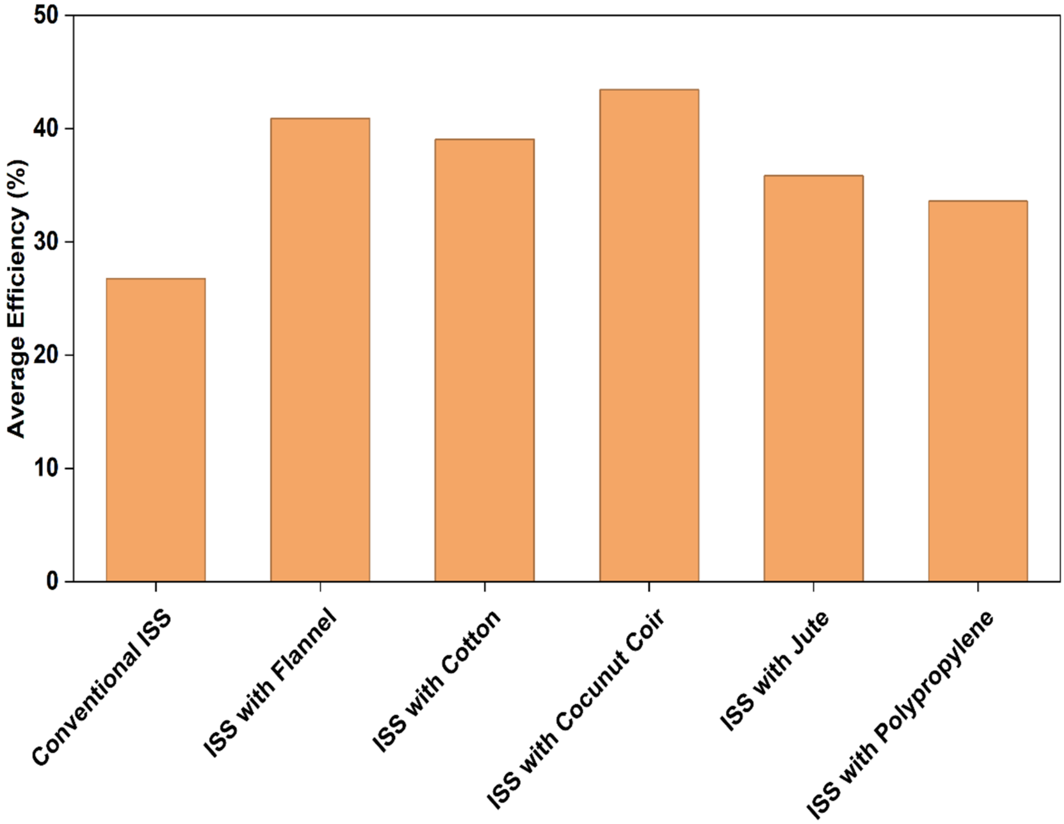

Fig. 11. Average efficiency.

Authors	Solar still and Wick material type	Productivity	Efficiency (%)
Ahmed et al.[17]	TSS with black cotton and parabolic tracking system	5.1 L/m^2	39.7
Alqsair et al.[18]	Hemi spherical solar still with reflector, fan, concentrator, nano PCM, and jute wick	11,150 mL/m^2·day	59.5
Abdelaziz et al.[19]	TSS with V-corrugated aluminium basin, wick, carbon black nano fluid and PCM	5.92 kg/m^2	40.95
Tuly et al.[20]	DSS with fins, PCM, External Condenser, and wick	3.02 L/m^2	48.68
Bacha et al.[21]	TSS with convex absorber, black jute, paraffin wax, oil heat exchanger and parabolic concentrator	13.58 L/m^2/day	39.32
Younes et al.[22]	TSS with vertical wick	8300 ml/m^2	57.3
Abdullah et al.[23]	Half-cylindrical solar still with convex absorber, a corrugated convex absorber, jute wick, and Ag mixed nano PCM	9100 mL/m^2	61.5
Kumar et al.[24]	Solar still with black-coated cylindrical cement fins wrapped in black cotton cloth	4440 mL/m^2	42.4
Hansen et al.[25]	ISS with stepped absorber, wire mesh and water coral fleece wick	4280 ml/day	-
Sharshir et al.[26]	PSS with hanging wick	3690 ml/m/day	29.72%
Kalidasa Murugavel et al.[27]	DSS with rectangular fins and cotton cloth	3580 ml	–
Abdelgaleel et al.[43]	Still with reflectors and woven wires	–	45.04%
Present Study	ISS with coconut coir	4323 ml	43.46%

Table 3. Comparison of the proposed study with the literature.

The evaporative heat transfer coefficient is an important parameter for evaluating the performance of the inclined solar still because it indicates the heat transfer efficiency from the water to the vapour. The EHTC value obtained during the investigation is shown in Fig. 12. The values varied from 5.23 to 201.77 W/m^2K. This variation shows how the heat transfer coefficient changes with time and in different cases. During morning and evening hours, the EHTC values are relatively low due to minimal solar radiation and water temperature. Evaporation is low during this time because the water in the solar still is not absorbing enough heat to reach maximum evaporation. The highest EHTC values are observed in the afternoon, with the highest value between 12 p.m. and 2 p.m., indicating maximum heat transfer and evaporation. The water temperature is at its highest during this time, resulting in a significant increase in evaporation rate. Coconut coir provides higher EHTC

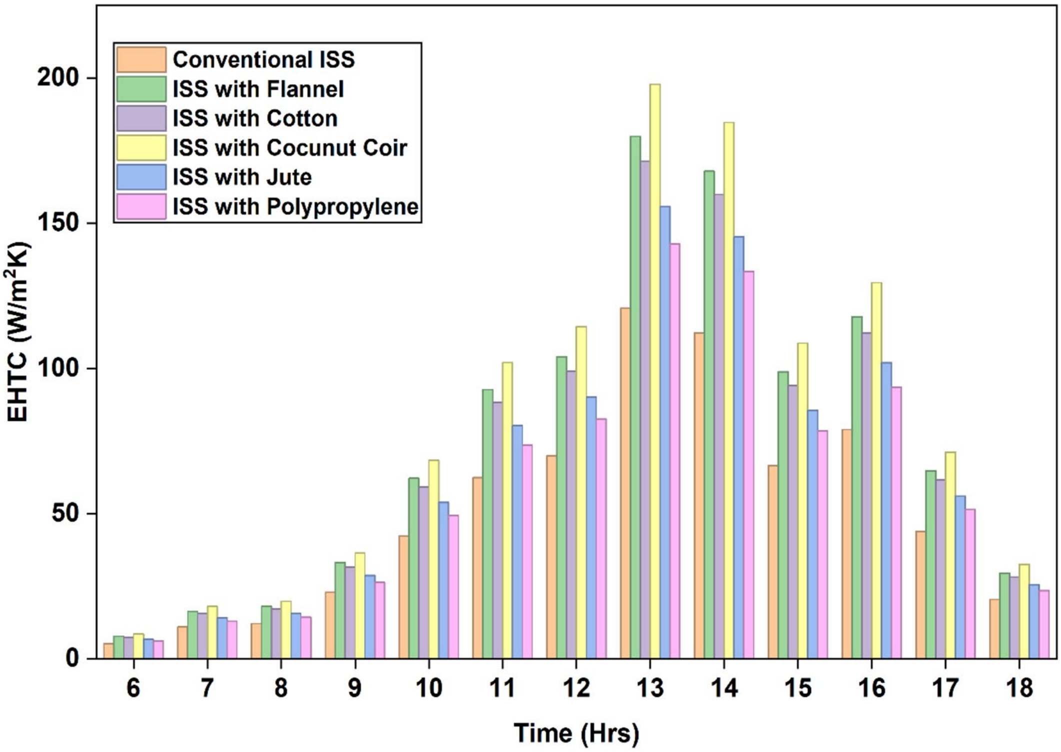

Fig. 12. Evaporative heat transfer coefficient for all cases.

values compared to other studied materials. The maximum EHTC value of ISS with coconut coir is 201.77 W/m^{2}K, whereas other investigated cases, such as conventional, flannel, cotton, jute and polypropylene used systems, provide maximum EHTC of 120.66, 179.79, 171.26, 155.66, and 142.81 W/m^{2}K.

The average EHTC value obtained for every case that is examined is shown in Fig. 13. The average EHTC value of coconut coir is much higher compared to all other materials under investigation. The conventional inclined solar still (Case 1) provides only a 51.38 W/m^{2}K average EHTC value. But the maximum EHTC obtained by coconut coir used ISS, and the value for coir is 84.25 W/m^{2}K. however, other investigated materials, such as flannel, cotton, jute and polypropylene, provide average EHTC values of 76.31, 72.68, 66.07, and 60.62 W/m^{2}K. The maximum EHTC value of coconut coir is 63.97, 10.4, 15.91, 27.51 and 38.98% higher compared to conventional, flannel, cotton, jute and polypropylene used systems. This data clearly shows that using ISS with coconut coir wick provides higher evaporation compared to flannel, cotton, jute and Polypropylene wick materials.

The exergy efficiency of a solar still is used to determine how effectively radiation is converted into fresh water through evaporation and condensation. This exergy efficiency considers both the quantity and quality of energy involved in this process. The exergy efficiency obtained by all the investigated cases is shown in Fig. 14. According to the results, the case 4 exergy efficiency is higher compared to other studied cases. Coconut coir structure provides a larger surface area for evaporation compared to other investigated materials. This larger evaporation area provides a higher exergy transfer by making more water available for evaporation in a testing period. Exergy efficiency ranges have been varied from 0 to 5.56% during the investigation of all the cases. The maximum exergy efficiency is obtained during noon time, around 12.00 to 13.00 p.m., The maximum exergy efficiency of conventional, flannel, cotton, coconut coir, jute and polypropylene used systems is 3.20, 4.97, 4.73, 5.56, 3.94, and 3.52%. it indicated coconut coir has a maximum exergy efficiency compared to other wick materials.

The average exergy efficiency obtained during the investigation is shown in Fig. 15. From the results, it is evident that using coconut coir with an inclined solar still provides higher exergy efficiency compared to other wick materials investigated. Conventional inclined solar still provides only 1.36% average exergy efficiency, which is lower than the other investigated cases. Coconut coir provides a higher average exergy efficiency of 2.53% during the investigation. Flannel, cotton, jute and polypropylene used ISS provide average exergy efficiency of 2.25, 2.15, 1.89 and 1.7%. Coconut coir's average exergy efficiency is 86.02, 12.44, 17.67, 33.86, and 48.82% higher compared to conventional, flannel, cotton, jute and polypropylene used systems.

Figure 16 shows the cost of distilled water for different cases. The cost of distilled water is dependent on capital cost, maintenance cost, interest rate, salvage value, lifetime, and productivity of the still. The conventional ISS has a water production cost of $0.0168, which is the highest value among all the investigated cases. During the study, coconut coir had the least water production cost of $0.0131 because of its improved water productivity. Flannel, cotton, jute and polypropylene used systems have distilled water costs of $0.0134, $0.0138, $0.0142, and $0.0147.

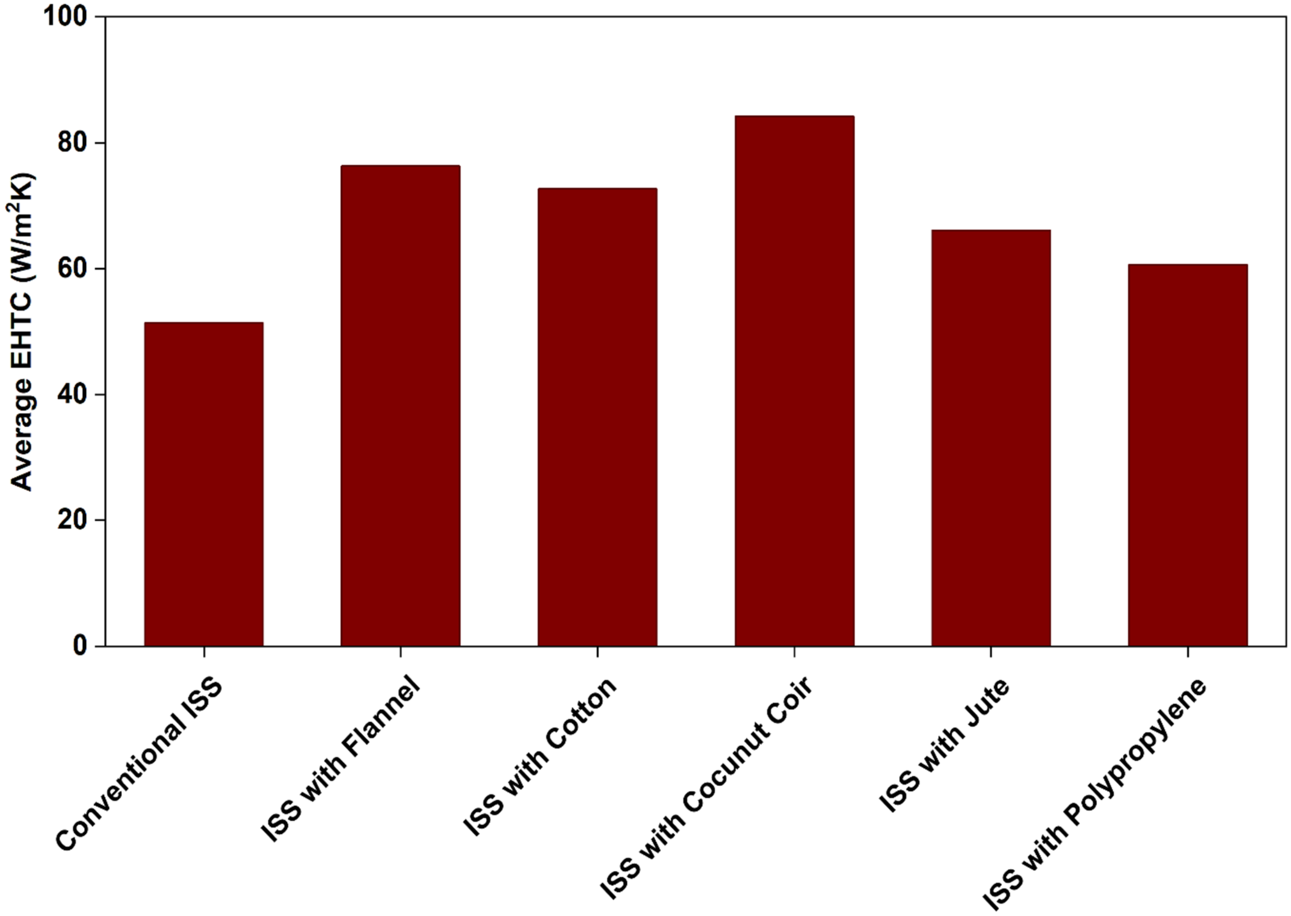

Fig. 13. Average evaporative heat transfer coefficient.

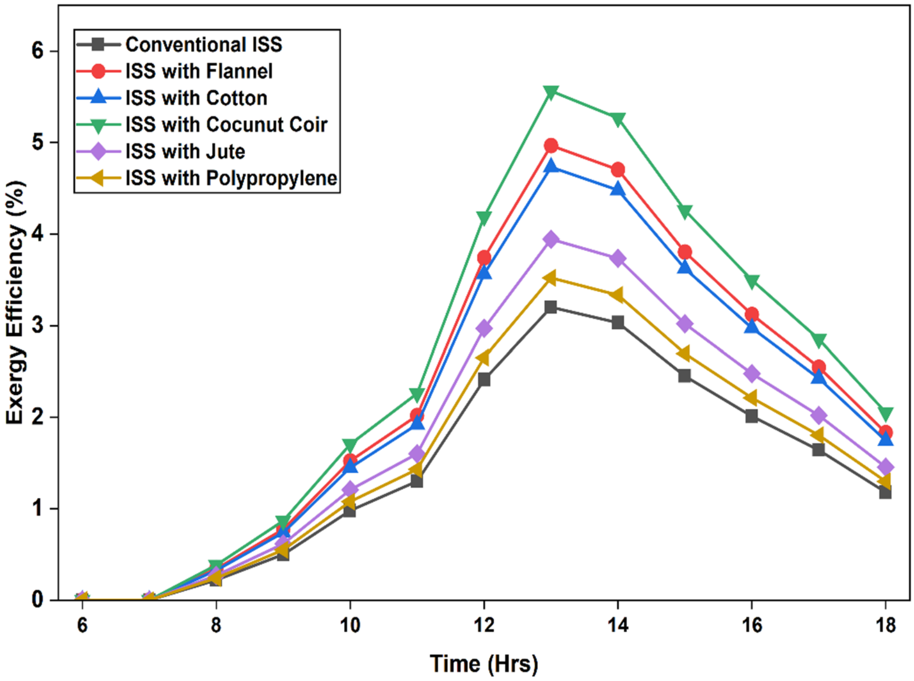

Fig. 14. Exergy efficiency variations vs time.

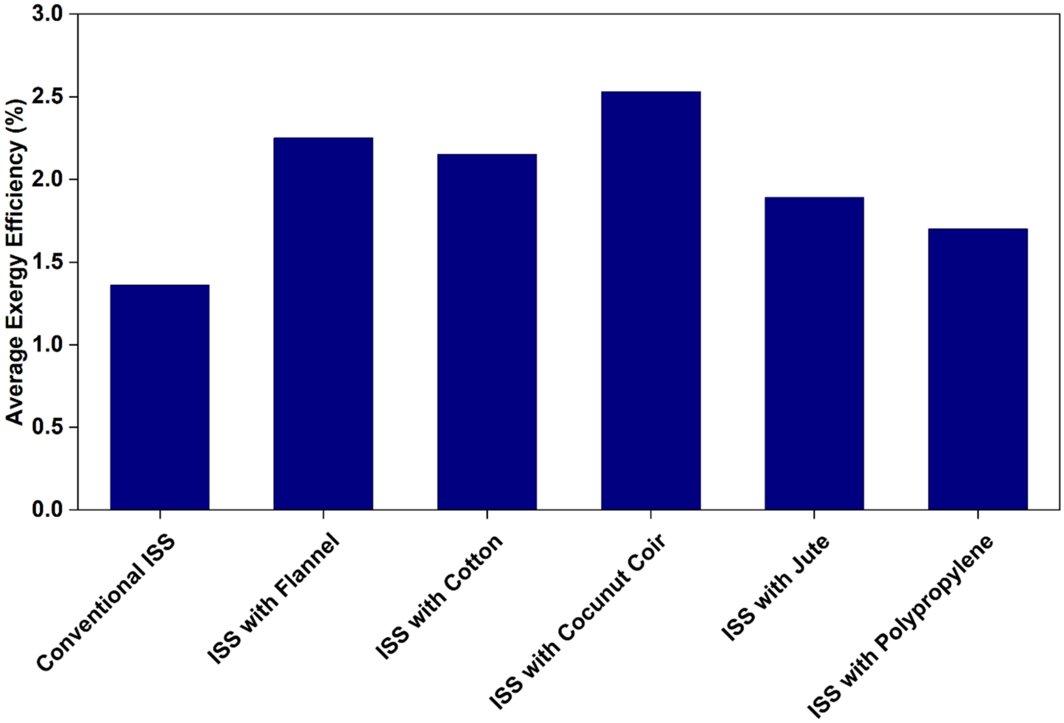

Fig. 15. Average exergy efficiency.

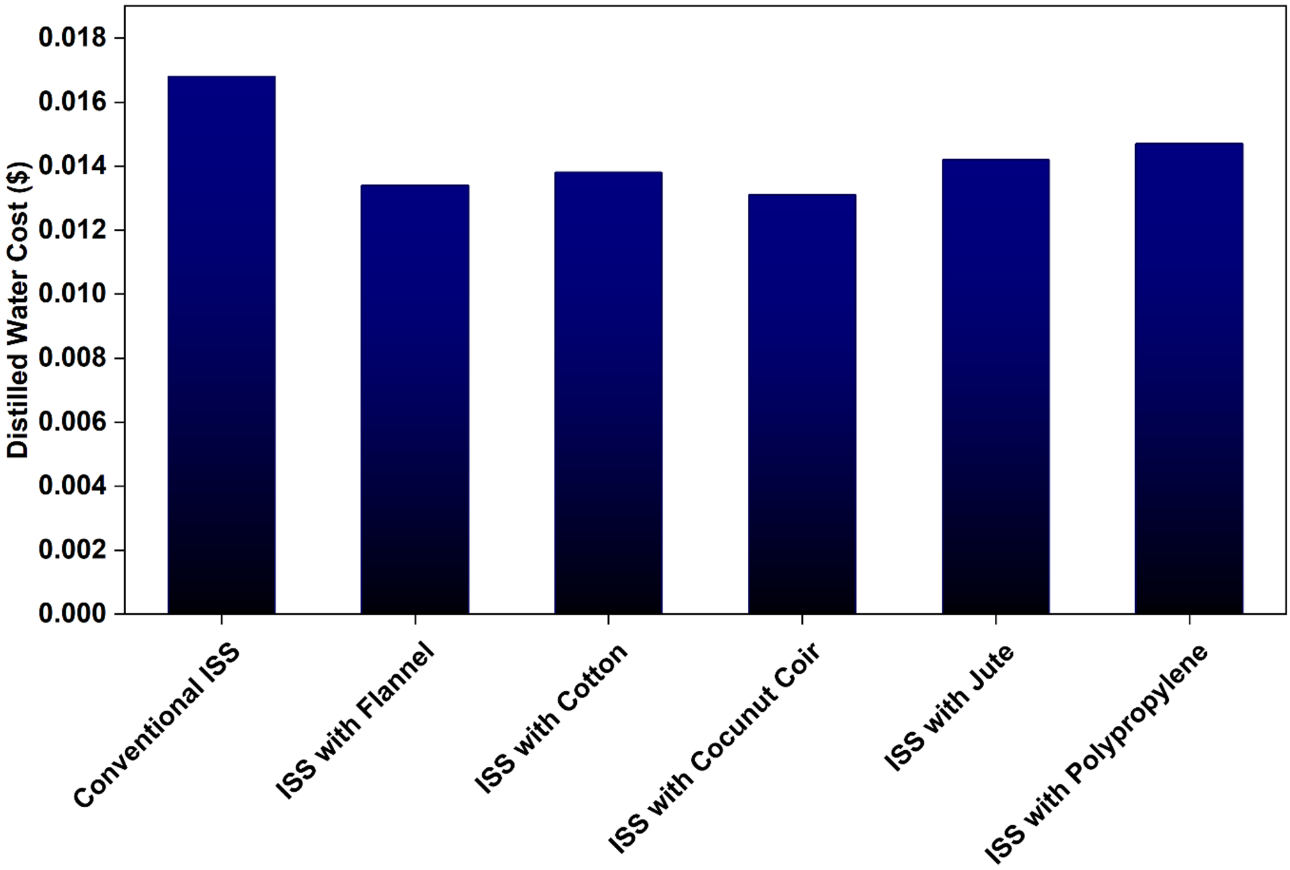

Fig. 16. Distilled water cost.

Parameters	ISS	ISS with flannel	ISS with cotton	ISS with coconut coir	ISS with jute	ISS with polypropylene
Yield per day (m)	3.30	4.18	4.10	4.32	3.94	3.81
Annual yield (M)	990.90	1253.10	1230.30	1296.90	1180.80	1143.00
Capital cost (C)	$115.00	$116.00	$117.00	$117.00	$116.00	$116.00
Interest per year (i)	10%					
Life span (n)	15 years					
Capital recovery factor (CRF)	0.13					
Fixed annucal cost (FAC)	15.12	15.25	15.38	15.38	15.25	15.25
Sink fund factor (SFF)	0.03					
Salvage value (SV)	23.00	23.20	23.40	23.40	23.20	23.20
Annual salvage value (ASV)	0.72	0.73	0.74	0.74	0.73	0.73
Annual maintenance (AMC)	2.27	2.29	2.31	2.31	2.29	2.29
Annual cost (AC)	16.66	16.81	16.95	16.95	16.81	16.81
Cost of distilled water production per liter (CPL)	$0.0168	$0.0134	$0.0138	$0.0131	$0.0142	$0.0147
Selling price (SP)	$0.24					
Payback period (in months)	6.2	5.0	5.1	4.8	5.3	5.4

Table 4. Economic study results:

The detailed results obtained from the economic study are given in Table 4. Among all studied materials, the ISS combined with coconut coir had the lowest CPL of $0.0131, indicating the most cost-effective water production. This was followed by flannel cloth ($0.0134), cotton cloth ($0.0138), jute ($0.0142), and polypropylene ($0.0147). The conventional ISS, with no wick enhancement, had the highest CPL of $0.0168, demonstrating the economic benefits of using wick materials. Assuming a selling price of $0.24 per litre, using wick materials significantly lowered the payback period, the time required to recover the initial investment. Coconut coir had the shortest payback period, at 4.8 months, compared to 6.2 months for the conventional system. This reduced payback period demonstrates how natural wick enhancements increase both technical performance and financial feasibility.

Conclusion

Productivity, energy and exergy efficiency of the Inclined Solar Still (ISS) were studied using different wick materials. Coconut coir provides the best result among the other investigated wick materials due to its better absorptivity, prolonged heat and its capillary rise characteristics. The detailed results obtained from the present study are listed below:

- Coconut coir gave the best performance when analyzing the system without any coating over the wick materials.
- Conventional ISS provides water productivity of 3303 ml, whereas other investigated wicks offer 4177, 4101, 4323, 3936, and 3810 ml for cases used flannel, cotton, coconut coir, jute and polypropylene wick material. Coconut Coir's water productivity is 30.88% higher than the conventional ISS.
- The conventional ISS produces an average efficiency of 26.76%. Coconut coir provides a maximum average efficiency of 43.46%. The other examined materials, flannel, cotton, jute and polypropylene, had an average efficiency of 40.92, 39.07, 35.84, and 33.61%. Coconut Coir has a maximum efficiency of 62.40, 6.2, 11.23, 21.26, and 29.3% higher than conventional, flannel, cotton, jute and polypropylene wick materials.
- The evaporative heat transfer coefficient values are higher for coconut coir compared to the other materials. The conventional system, flannel, cotton, coconut coir, jute and polypropylene used systems have the average EHTC value of 51.38, 76.31, 72.68, 84.25, 66.07, and 60.62 W/m^2K.
- The average exergy efficiency of conventional ISS is only 1.36%. The wick combined ISS provides 2.25, 2.15, 2.53, 1.89 and 1.7% for flannel, cotton, coconut coir, jute and polypropylene materials. Coconut coir average exergy efficiency is 86.02, 12.44, 17.67, 33.86, and 48.82% higher compared to conventional, flannel, cotton, jute and polypropylene wick materials.
- The economic study also reveals that the use of coconut coir provides the lowest distilled water production cost of $0.0131.

Possible future work

To further enhance the thermal performance and water productivity of inclined solar stills using natural, uncoated wick materials, future studies may explore the integration of hybrid enhancement techniques such as phase change materials (PCMs) for thermal energy storage, nanoparticles to improve thermal conductivity, and solar tracking systems to maximize solar input throughout the day.

Furthermore, to ensure the practicality and long-term reliability of uncoated wick materials such as coconut coir, comprehensive field testing should be done under various kinds of climatic and seasonal conditions. These studies will assist in analyzing the durability, maintenance requirements, and consistent performance of natural wicks over time, giving essential information for real-world deployment in separated and resource-constrained locations.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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V.R.—Writing original draft, Methodology, W.J.A.—Investigation, resources, V.K.S.—Methodology, conceptualization, J.S.—Supervision, P.M.—Validation, S.P.—Project execution and correspondence.

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Competing interests

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Additional information

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