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# Augmentation of freshwater productivity in single slope solar still using *Luffa acutangula* fibres

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## ABSTRACT

The prime intention of the current research is to enhance the freshwater productivity of the solar still (SS) by using *Luffa acutangula* fibres *(LAF)*. The dried LA fibres were introduced into the absorber basin of a solar still to enhance the wet surface area through its porous structure that leads to augmented evaporation of water from the absorber basin. The effect of the number of *LAF* in the absorber basin such as 10,13,14,15,16,20 and 25 on freshwater productivity was estimated. The results revealed that SSLAF with 15 fibres in the absorber basin increased the yield by 25.23%. Besides, a solar still with 10,13,14,16,20 and 25 fibres in the absorber basin increased the yield by 12.27%, 17.45%, 22.04%, 22.69%, 14.64% and 4.09% respectively when compared to conventional solar still (CSS). The average thermal efficiency of the SSLAF with 15 *LAF* was increased by 28.35% whereas, for 10,13,14,16,20 and 25 LAF, the average thermal efficiency was increasedby 11.05%, 16.99%, 22.53%, 19.93%, 11.29% and 3.9% respectively when compared to CSS.The economic analysis resulted that the cost per litre freshwater yield from the SSLAF is 22.5% lower than CSS. Also, the payback period of SSLAF is comparatively lesser than that of CSS.

**Key words**: desalination, economic analysis, *Luffa acutangula*, natural fibre, solar still

## HIGHLIGHTS

- This study analysed the thermal and economic performance of SSLAF.
- The optimum number of fibres in the basin is observed as 15.
- The productivity of solar still with 15 LAF is increased by 25.23%.
- The energy efficiency of solar still with 15 LAF is increased by 28.35%.
- Economic analysis showed that the CPL of SSLAF is 22.5% less than that of CSS.

## INTRODUCTION

The world is running out of freshwater sources and the need for potable water is growing rapidly due to human, agricultural and industrial demands. A possible way to overcome the situation is to convert the available seawater into freshwater through desalination approaches. In the available seawater conversion techniques, the solar still is considered as one of the economical ways of desalination. Solar still is a simple system in design to fabricate and work (Thirugnanasambandam *et al.* 2010; Sharon & Reddy 2015). Solar Still is eco-friendly and economical such that it can be quickly adopted by anyone for desalination of water. However, the efficiency of solar still is comparatively less and many researchers across the world are working to enhance the efficacy of the solar still through several modifications in the system design and incorporations such as fins/ energy storage materials into the still (Muthu Manokar *et al.* 2014; Prakash & Velmurugan 2015).

In this regard, (Murugavel & Srithar 2015) inspected the influence of cover plate transmittance on the potable water yield of a solar still. It was noticed that there was almost an 18% energy loss from January to May and September to December. (Arunkumar *et al.* 2013) evaluated the performance of a concentrator integrated solar still with PCM. It was observed that there was an improvement in productivity by 26% in the modified solar still. (Hansen *et al.* 2015) investigated the various properties of wick materials to select the best material for enhancing the distillate yield. It was observed that maximum productivity was obtained as 4.28 L/day by using a weir mesh–stepped absorber plate with water coral fleece.

(Dhivagar *et al.* 2020) investigated the gravel coarse aggregate as energy storage in the solar still for better productivity. It was found that the yield of modified solar still was about 4.21 kg/m$^2$ which was comparatively higher than that of CSS. Belyayev *et al.* (2019) numerically investigated the performance of a heat pump assisted regenerative solar still with energy storage materials. It was observed from the numerical study that the modified solar still had a better efficiency with a higher yield relative to CSS. Dhivagar *et al.* (2021) studied the influence of graphite plates and block magnets on the productivity of solar still. It was observed that the hourly yield of modified solar still was increased by 19.6% and 22.8% during summer and winter days respectively. Dhivagar & Mohanraj (2021) studied the effect of graphite fins and magnets on the productivity of a solar still. It was observed that the productivity of the modified solar still was increased by 19.6%. Benoudina *et al.* (2021) studied the influence of Al$_2$O$_3$ micro/nanoparticles on the productivity of a solar still. It was reported that the solar still with nanoparticles of Al$_2$O$_3$ had better enhancement in productivity compared to the desalination system with micro-particles and CSS. Modi & Modi (2019) investigated the performance of a solar still with a pile of jute and cotton wick materials. It was found that there was a 21.46% improvement in the productivity of the solar still with jute cloth when compared with the pile of cotton cloth. Suraparaju & Natarajan (2020) analysed the impact of luffa fibres on the productivity of a single slope solar still. It was noticed that the productivity of the solar still was reduced due to there being more fibres in the absorber basin, which obstructed the solar radiation and also absorbed more seawater from the basin. Baskaran & Saravanane (2021) investigated the influence of Spirulina algae on the yield of a solar still. It was observed that the productivity of the solar still with Spirulina algae was increased by 30.24% when compared to CSS.

Based on the above literature review, it can be outlined that many researchers have been focused on enhancing the freshwater productivity yield of solar stills through various approaches like optimising geometric parameters such as basin water depth, the tilt angle of the glass cover, the orientation of reflectors and so on. A few researchers augmented the performance of solar still by using various kinds of energy storage materials, nanomaterials and fins. Also, very few researchers have been working on porous materials such as wicks and cloths for wet surface area enhancement, which leads to an increase in the evaporation rate. Besides this, the previous work of authors Suraparaju & Natarajan (2020) on *Luffa acutangula* fibres in the absorber basin of a solar still reported that there was a minor decrease in freshwater productivity relative to CSS. This was mainly due to the occupancy of more space in the absorber (almost 65% with 40 fibres), which hindered the solar radiation coming onto the water. Therefore, the heating of seawater in the absorber basin was not rapid and productivity was adversely affected. In this aspect, the current research investigated the incorporation of the possible number of *Luffa acutangula* fibres which occupies optimum space in the absorber basin of the solar still for enhancing the freshwater yield. Hence, two single slope solar stills were designed and developed to estimate the effect of *Luffa acutangula* fibres on the productivity enhancement of a solar still. The number of fibres in the absorber basin was chosen according to the percentage of space occupancy in the absorber basin of the solar still. The experiments were conducted with 10, 13, 14, 15, 16, 20 and 25 *Luffa acutangula* fibres and compared with the results of CSS at Karaikal, India, during September 2020.

## EXPERIMENTAL SYSTEM AND EXPERIMENTATION

In the current research, two single-slope solar stills were designed and developed for estimating the effect of the number of *Luffa acutangula (Ridge Gourd)* fibres on the enhancement of yield of the solar still. The two solar stills developed for experimentation were as follows:

1. Conventional solar still (CSS)
2. Solar still with *Luffa acutangula* fibres (SS-LAF)

### Materials and fabrication

The two solar stills were made of waterproof plywood and the inner surface of the solar still was covered with an aluminium sheet of 2 mm thickness to restrict the direct contact of water vapour and plywood. Also, the covered aluminium sheet was coated with normal black paint such that it absorbed more radiation into the solar still. The absorber basin inside the system was made of a 1 mm copper sheet, and the dimensions of the absorber basin were 1 m × 0.6 m × 0.05 m (length × breadth × height 0.6 m$^2$ absorber area). The solar still was covered with transparent glass to trap the incoming solar radiation. The glass was kept at an angle equal to the latitude of Karaikal (11°) for efficient working of the system. According to the literature (Suraparaju & Natarajan 2021a), the percentage occupancy of the absorber basin by fibres was almost 65%, which reduced the productivity of the solar still. Therefore, in the current research, the percentage of space occupancy in the absorber by

fibres was chosen from 45, 35, 25, 20 and 15% respectively, for which 25, 20, 15, 13, and 10 number of fibres were selected. Later, based on the results, 14 and 16 fibres were also tested to find out the exact and optimum number of fibres to be utilized for enhancement of freshwater yield. The absorber basin of SS-LAF was filled with seawater and then Ridge Gourd/*Luffa acutangula* fibres were introduced into the absorber basin. The different numbers of LAF (10,13,14,15,16,20 and 25) in the water basin were placed to study the effect on the freshwater yield of the solar still. The entire outer part of the system was covered with Thermocol sheets to reduce the heat losses. The fabricated two experimental set-ups were installed at the Solar Energy Laboratory, NIT Puducherry, Karaikal, India, for experimentation. The photograph of the two developed single-slope desalination systems is as shown in Figure 1(a).

## Preparation of *Luffa Acutangula* fibres

The study is mainly focused on the use of *Luffa Acutangula*/Ridge Gourd fibres for enhancing the yield of the solar still. The *Luffa* fibre is readily available in the market and the cultivation of *Luffa* throughout the world has been constantly rapidly growing in the past 20 years due to the transformation towards clean and sustainable materials that can be used as substituent materials to conventional materials. It is most commonly found in India, China, Pakistan, Indonesia, Africa, and South America. The *Luffa* fibre is attained from the cultivated species of the genus *Luffa*, *Luffa cylindrica* (smooth fruit) and *Luffa acutangulaor aegyptiaca* (angled fruit). The fresh and green Luffa is taken as a vegetable and the ripened/dried luffa is the
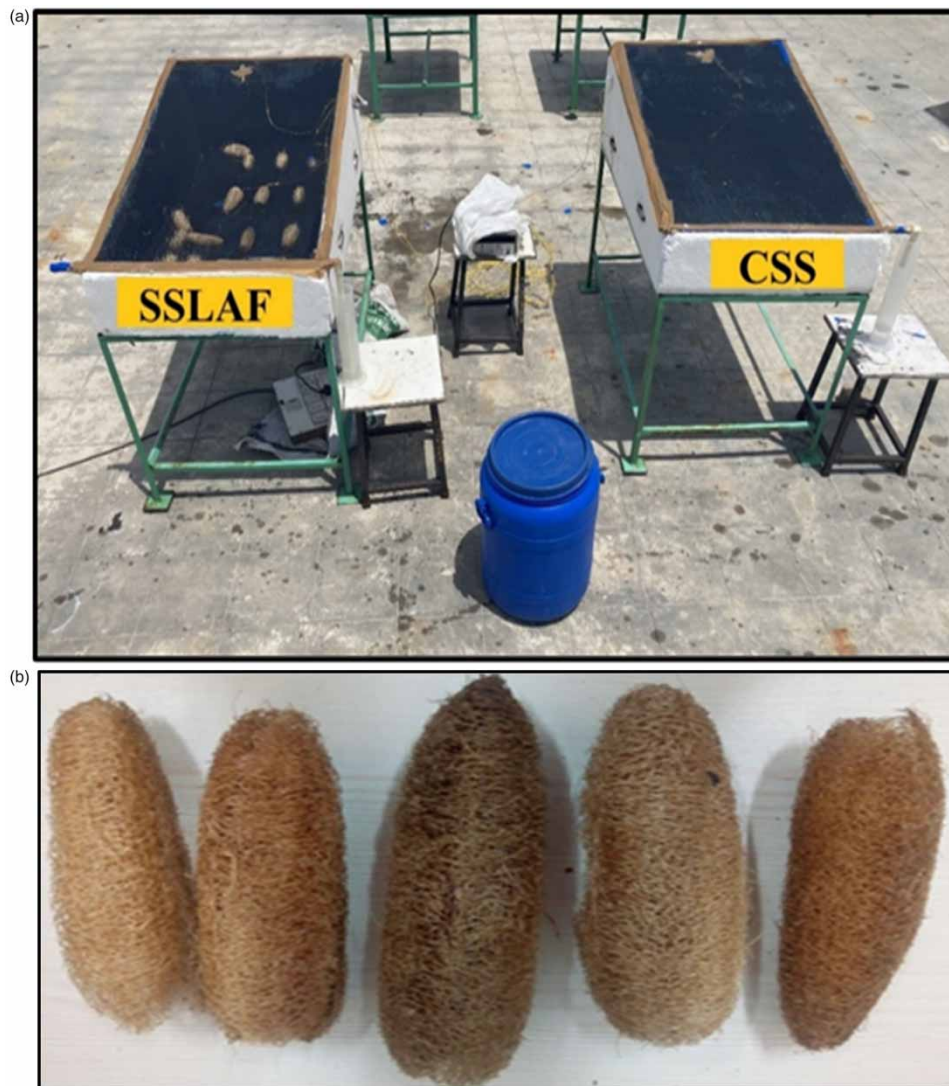


**Figure 1** | (a) Photograph of experimental arrangement with CSS and SSLAF. (b) *Luffa acutangula*/Ridge Gourd Fibre.

source for *Luffa acutangula* fibres. The Luffa fibres are light in weight and can be used in various engineering and medical applications such as impact energy absorption, acoustic and vibration isolation, packaging, bath or kitchen sponges, a natural remedy (juice) for jaundice, insulating material, and are also used as fillers in the production of composites, materials of adsorption in water treatments (Khusairy & Bakri 2014; Karthik & Ganesan 2016). The Luffa fibre can be obtained from the Ridge Gourd (LUFFA) plant in two approaches by either drying the ridge gourd on the plant or separately drying the ridge gourd under the sun after removing it from the plant. The dried ridge gourd is then processed to extract the *Luffa acutangula* fibre. The density of ridge gourd fibres is $0.92 \pm 0.10$ gm/cc and the diameter of each fibre is $270 \pm 20$ μm (Shen *et al.* 2012). The *Luffa acutangula* fibres used in the experiments are as shown in Figure 1(b).

## Characterization of the *Luffa acutangula* fibre

The porosity, absorbency, capillary rise and heat transfer coefficient of the material are significant properties for enhancing the evaporation rate by any material. The properties of the material can be found by using various approaches mentioned in the literature (Hansen *et al.* 2015).

### Porosity

The porosity of the natural fibre is the main property that plays a major role in the process of seawater desalination. The porous space in the natural fibre absorbs the seawater and enhances the evaporation of heated seawater from the absorber basin. The porosity of the LAF is determined by the porous space in the material and this is calculated by using the following Equations (1)–(4), (Murugan *et al.* 2020). It was found that the porosity of each *Luffa acutangula* fibre was 6.7%.

$$\Phi = \frac{V_p}{V_{bk}} \tag{1}$$

where, $V_p$- pore volume (m³) and $V_{bk}$- bulk volume (m³).

$$V_p = \frac{W_w}{\rho_w} \tag{2}$$

$$W_w = W_{sat} - W_{dry} \tag{3}$$

where, $W_w$ - Weight of water in pore space; $W_{\text{sat}}$ – saturated weight; $W_{\text{dry}}$ – Dry weight; $\rho_w$ – Density of water (kg/m³).

$$V_{bk} = l * b * t \tag{4}$$

### Capillary rise

The respective capillary rise in *Luffa acutangula* fibre is given by Equation (5) and the surface tension of water was considered as 72 mN/m (milli Newton per metre) (Hauner *et al.* 2017).

$$h = \frac{2 T \cos \theta}{r \rho g} \tag{5}$$

where $h$ = liquid height in the capillary; $T$ = surface tension; $\rho$ = density; $r$ = bore radius of the capillary; $g$ = gravity; $\theta$ = Angle of contact.

### Heat transfer coefficient

The heat transfer between the wet wick absorber and the glass cover can be given as

$$h = \frac{q}{\Delta T} \, (\text{W/m}^2 \, \text{K}) \tag{6}$$

where, $h$ is heat transfer coefficient; $q$ is the heat transfer rate of solar radiation (W/m²); $\Delta T$ is the temperature difference between material and glass cover.

### Water absorbency

Water absorbency is the rate at which water is taken into, and morphed into another object or phase. The water absorbency was evaluated as the time recorded until the water drop is absorbed completely from the surface of the material.

Further, it was found that the capillary rise was about 5.8 mm/h. Also, the properties of luffa fibre are tabulated in Table 1 compared with other fibres available in the literature (Hansen *et al.* 2015; Ramalingam *et al.* 2021).

### Experimentation & uncertainty analysis

The single slope solar stills of two different configurations as mentioned above were arranged in such a way that the system was facing towards the south as the testing location (Karaikal – 10.92°N,79.83°E) is located in the Northern Hemisphere.The experiments were carried out on the terrace of the solar energy laboratory, at NIT Puducherry, Karaikal. The feed water for the experiment is collected from the Bay of Bengal sea, which is located adjacent to the NIT Puducherry. The seawater in the absorber basin is filled to an optimum depth of 2 cm for better productivity (Suraparaju & Natarajan 2021a). The experiments on CSS and SSLAF were conducted in September 2020 to study the effect of *Luffa acutangula* fibres on the yield of a solar still. The temperatures of the glass cover, seawater, absorber basin, *Luffa acutangula* fibres and ambient temperature were measured using K- type thermocouples connected to the 'data acquisition system'. The global radiation of the particular testing day at the testing location was noted using the 'Pyranometer'. The increased surface of the *Luffa acutangula* fibres enhanced the absorption phenomenon, which augmented the evaporation of water, and more productivity of freshwater was achieved compared to CSS. The experiments were conducted for seven days in September 2020, and readings were recorded from 08:00 am to 05:30 pm (Indian Standard Time) for every half an hour.

Several precautions were taken to minimize errors during the experimental investigation. The precautions were as follows:

i. The solar still and the absorber basin were thoroughly checked and ensured that there were no leaks.
ii. The transparent glass was appropriately cleaned for removing dust and other radiation obstructing materials.
iii. The seawater was filled into the absorber basin up to the appropriate depth with utmost care.
iv. The readings of temperature, global radiation and fresh-water yield were appropriately noted at regular intervals of every half an hour for precise analysis.

The uncertainty in the efficiency and hourly freshwater yield is given by the following formulae; (Suraparaju & Natarajan 2021a)

$$u_\eta = \left[ \left( \frac{\partial \eta_d}{d_w} \times u_{d_w} \right)^2 + \left( \frac{\partial \eta_d}{I(t)} \times u_{I(t)} \right)^2 \right]^{\frac{1}{2}} \tag{7}$$

The uncertainty in hourly yield ($u_{dw}$) is given by

$$u_{d_w} = \left[ \left( \frac{\delta d}{\delta y_1} u_y \right)^2 \right]^{\frac{1}{2}} \tag{8}$$

$$u_{d_w} = \left[ \left( \frac{d_i - d_f}{\delta y_1} u_y \right)^2 \right]^{\frac{1}{2}} \tag{9}$$

**Table 1** | Properties of *Luffa acutangula* fibre in relative to other fibres/wick materials

| Material | Porosity (%) | Absorbency (s) | Capillary rise (mm/h) | Heat transfer coefficient (W/m² K) |
|---|---|---|---|---|
| *Luffa acutangula* fibres | 6.7 | 3 | 5.8 | 45.72 |
| Jute cloth | 16.7 | 128 | 10 | 15.4 |
| Wood pulp paper | 17 | 2 | 65 | 37.3 |
| Coconut coir disks | 73.25 | 2 | 10 | 37.21 |
| Cotton | 28.5 | 1 | 120 | 36.0 |

where $d_i$ and $d_f$ are the initial and final hourly yield in mL at any period and $u_y$ is the uncertainty of yield in percentage. It was evaluated that the uncertainty in hourly yieldwas 1% and further taking all other uncertainties into the account, the error in total yield was about $\pm 1.5\%$. Besides that, the error in solar radiation and temperature measurement was 0.05% and 0.1%. Thus, the total error percentage in the solar still efficiency was about $\pm 2\%$

## THERMO – EXERGO-ECONOMIC ANALYSIS

### Thermal analysis

The instantaneous thermal efficiency of the passive solar still is calculated by using the following formula (Kabeel & Abdelgaied 2016; Suraparaju et al. 2021)

$$\eta_{th} = \frac{P \times \lambda}{A_b \times G \times \Delta t} \tag{10}$$

where P is the overall freshwater productivity in kg, $\lambda$ is the latent heat of evaporation of water in J/kg, $A_b$ is the absorber basin area in m$^2$, G is daily overall incident solar energy in W/m$^2$ and $\Delta t$ is the duration of the cumulative readings in sec.

Here,

$$\lambda = 3.1615 \times (10^6 - 761.6 * T_a), \quad \text{if } T_a > 70, \tag{11}$$

Else,

$$\lambda = 2.4935 \times (10^6 - 947.79*T_a + 0.13132*T_a^2 - 0.0047974*T_a^3), \tag{12}$$

where,

$$T_a = \frac{T_{\text{water}} + T_{\text{glass}}}{2} \tag{13}$$

### Exergy analysis

The exergy balance equation of the desalination setup can be given as (Dhivagar et al. 2020),

$$\sum \dot{E}_{x.\text{in}} - \sum \dot{E}_{x.\text{out}} = \sum \dot{E}_{x.\text{des}} \tag{14}$$

The exergy input can be given as,

$$\dot{E}_{x.\text{in}} = \dot{E}_{x.\text{sun}} = A_b I_t \left( 1 - \frac{4}{3} \left( \frac{T_{\text{Ambient}} + 273}{T_{\text{Sun}}} \right) + \frac{1}{3} \left( \frac{T_{\text{Ambient}} + 273}{T_{\text{Sun}}} \right)^4 \right) \tag{15}$$

where $A_b$ is the area of the basin in m$^2$, $I_t$ is hourly incident solar energy in W/m$^2$ and $T_{\text{sun}} = 5{,}777$ K.

Exergy output of the solar desalination setup can be given by,

$$\dot{E}_{x.\text{out}} = \dot{E}_{x.\text{evapo}} = \frac{\dot{m}_{ew} \lambda_{fg}}{3{,}600} \left[ 1 - \left( \frac{T_{\text{ambient}} + 273}{T_{\text{water}} + 273} \right) \right] \tag{16}$$

where $\dot{E}_{x.\text{evapo}}$ and $\lambda_{fg}$ is the output evaporative energy and latent heat of evaporation respectively.

The exergy efficiency is given by,

$$\eta_{\text{ex}} = \frac{\dot{E}_{x.\text{out}}}{\dot{E}_{x.\text{in}}} = \frac{\dot{E}_{x.\text{evapo}}}{\dot{E}_{x.\text{in}}} \tag{17}$$

## Economic analysis

The key objective of the cost evaluation is to determine the cost per litre (CPL) per one $m^2$ area of the solar still by following ways (Suraparaju & Natarajan 2021b),

The first annual cost (F) of the solar still is given by,

$$F = C \times I \tag{18}$$

where C is the capital recovery factor and I is the initial investment,

$$C = \frac{r(1+r)^l}{(1+r)^l - 1} \tag{19}$$

where r is the rate of interest and l is the lifespan of the solar still

$$\text{The annual savage factor } A = S_s \times S \tag{20}$$

where S is the salvage value and $S_S$ is the sinking fund factor

$$S = 0.2 \times I \tag{21}$$

$$S_s = \frac{r}{(1+r)^l - 1} \tag{22}$$

The annual maintenance cost ($A_m$) is anticipated to be 15% of the F,

$$A_m = 0.15 \times F \tag{23}$$

$$\text{The annual cost } A_c = F + A_m - A \tag{24}$$

$$\text{CPL} = \frac{A_c}{Y_l} \tag{25}$$

where $Y_l$ is the average yield per annum

$$\text{Payback period (days)} = \frac{\text{Investment}}{\text{Total revenue per day}} \tag{26}$$

$$\text{Total revenue} = \frac{\text{Market water price}(L) \times \text{Productivity } (L)}{\text{day } m^2} \tag{27}$$

## RESULTS AND DISCUSSION

The experimentations were conducted with SSLAF and CSS during September 2020 to analyze the evaluate the effect of fibres on the productivity of the solar still. The observed results of SSLAF were compared with CSS. The number of LA fibres in the absorber basin of SSLAF were 10, 13, 14, 15, 16, 20 and 25 numbers respectively. The seven sets of readings were noted at the same time along with a conventional solar still.

### Global radiation and system temperatures

The measurements were recorded from morning 8.00 am to evening 17.30 pm (Indian Standard Time) on every testing day. The variation of global solar radiation and ambient temperature for different days starting from 7th September 2020 to 13th September 2020 (seven days) is shown in Figure 2(a) and 2(b) respectively. It was observed from Figure 5 that the solar radiation of all the days of experiments in the testing location was fluctuating between 300 and 670 W/$m^2$. The highest average solar radiation of 666 W/$m^2$ was obtained whereas the lowest average solar radiation was 312 W/$m^2$. The maximum solar radiation was obtained during noon and 14.00 pm on all days and it was about 1,000 W/$m^2$. From Figure 6, the ambient
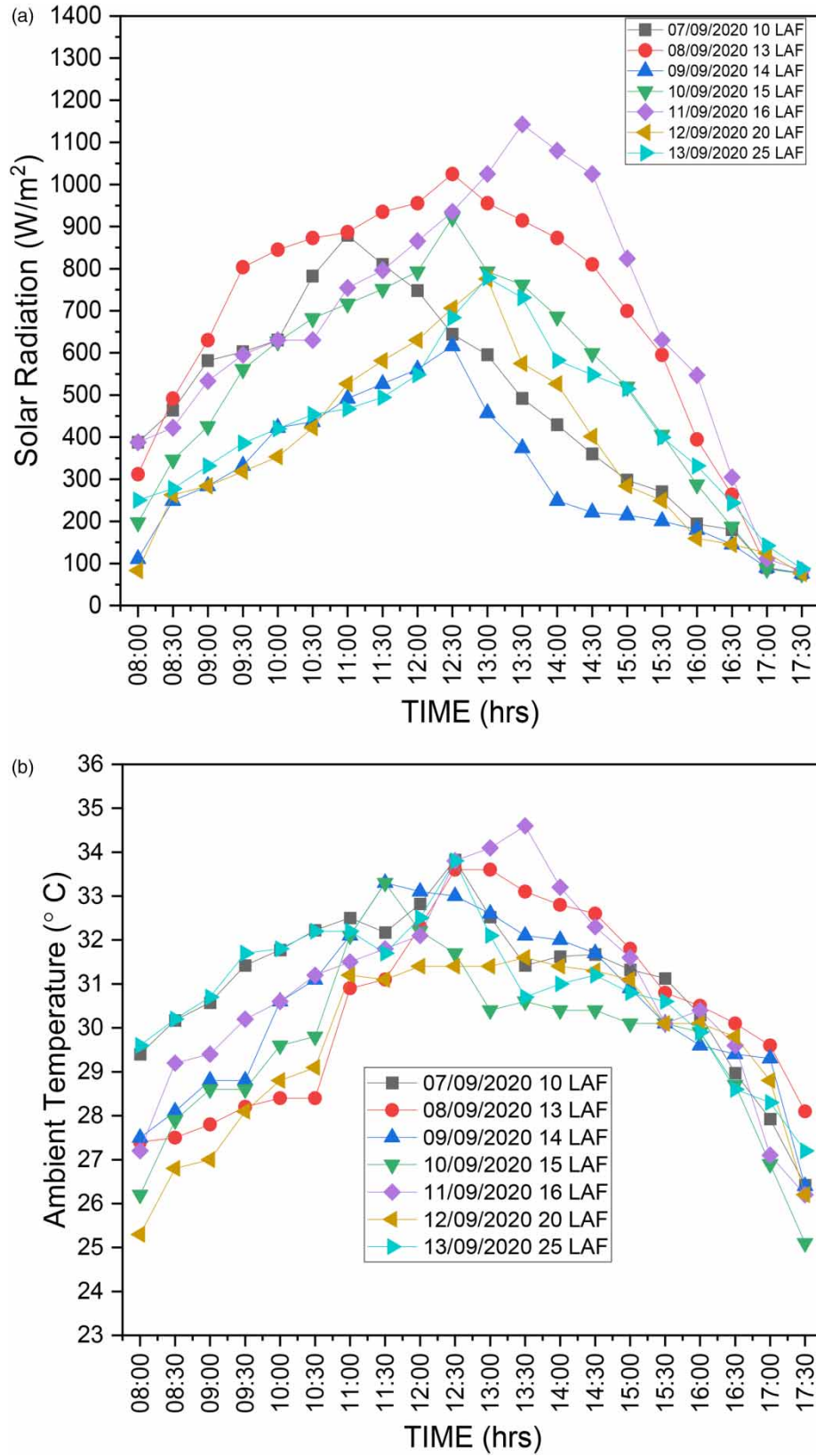
**Figure 2** | (a) Variation of solar radiation on testing days. (b) Variation of ambient temperatures on testing days.

temperature was fluctuating between 25 and 34 °C on all days. Also, it was found that the average ambient temperature on all the testing days was 30 °C. It was also noted that there were many variations in the ambient temperature from morning to evening during all the days of the experiments.

Besides these, the temperatures of glass, water, absorber and LA fibre were also recorded. The recorded temperatures of both systems were graphically plotted with the variation of time from morning to evening in Figure 3(a)–3(d) respectively. It is observed from Figure 3(a) that the glass surface temperatures of the LA fibre solar still were lesser than the conventional one. This occurrence was due to the presence of porous structured LA fibres in the basin water, which minimized the inside free convection currents. The highest glass temperatures reported in SSLAF and CSS were 60.1 °C and 65.2 °C. However, the magnitude of the ambient temperature and insolation also directly affected the glass surface temperature. It is interpreted in Figure 3(b) that the water temperature in the SSLAF was greater than CSS during all days of the experiments. This is mainly due to the inclusion of LA fibres in the absorber basin containing seawater. The LA fibres, absorber and water received the solar radiation through the transparent glass. The energy storing capacity of water and absorber leads to the rise in the water temperature in the absorber. Besides this, the energy absorbed by the fibres in the basin having low heat-storing capacity
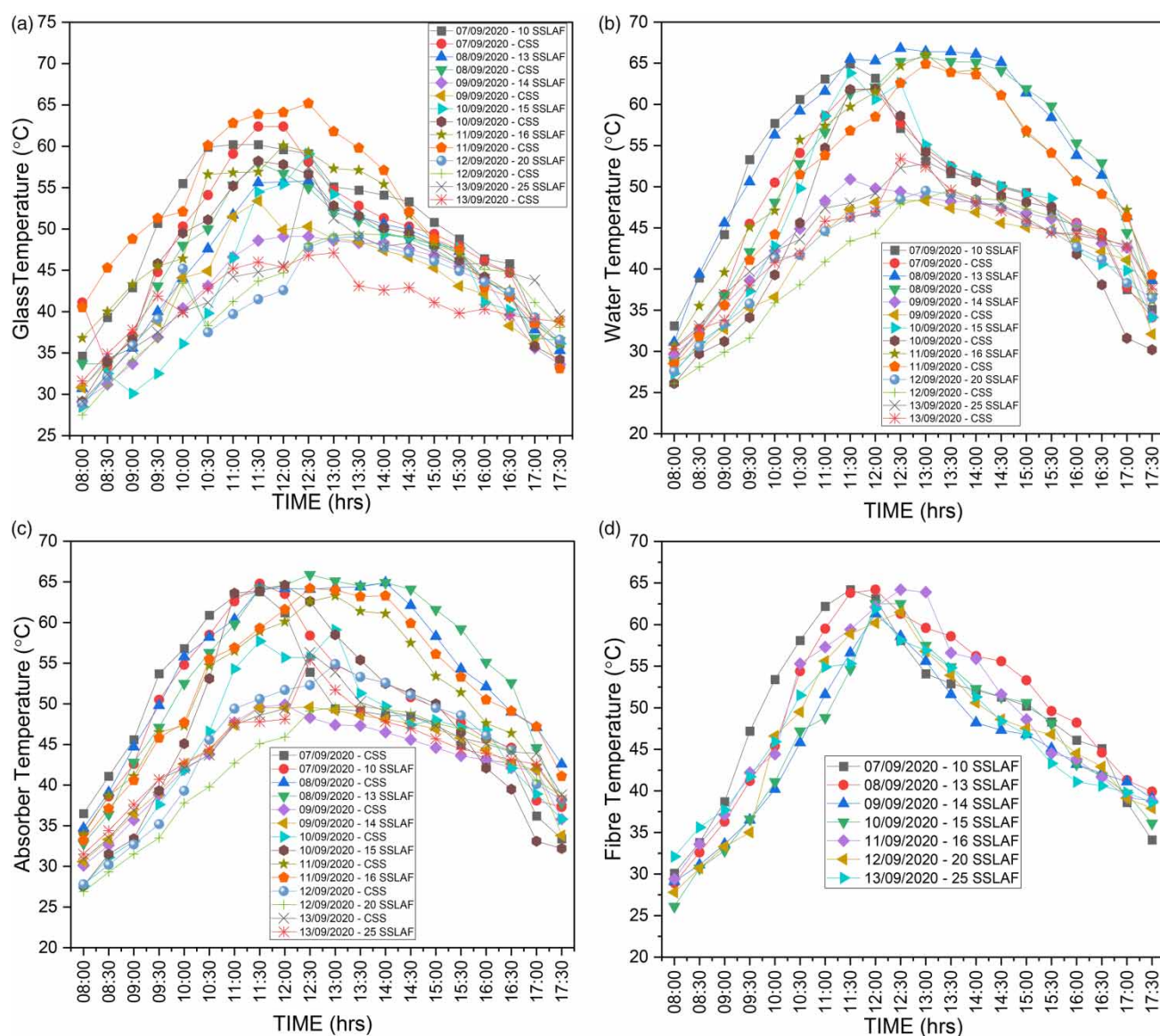


**Figure 3** | (a) Variation of glass temperatures in two solar stills on testing days. (b) Variation of water temperatures in two solar stills on testing days. (c) Variation of absorber temperatures in two solar stills on testing days. (d) Variation of fibre temperatures on testing days.

dissipates the absorbed energy to the water very rapidly. The dissipated energy from the fibres leads to an increase in the temperature and thus the water temperatures in the SSLAF were recorded as high when compared to CSS during all days of experiments. The highest water temperatures reported in SSLAF and CSS were 66.8 °C and 65.8 °C.

In addition to this, the absorber basin temperatures of the solar still with LA fibres were higher than the conventional solar still. This difference in temperatures can be witnessed in Figure 3(c). As a result of the inclusion of dried LA fibres in the absorber basin in all the considered cases, the temperature of the absorber basin in SSLAF increased when compared to the conventional still. The highest absorber basin temperatures reported in SSLAF and CSS were 65.9 °C and 64.9 °C respectively. From Figure 3(d), it is inferred that the maximum surface temperature of the LA fibres was observed as 64.2 °C. The surface temperature of LA fibres varied with the number of LA fibres. It was also observed that the maximum fibre temperatures on all testing days were ranging from 61.3 to 64.2 °C. The increased surface temperature of the LA fibre led to an increase in the evaporation rate from the porous structured LA fibres. The LA fibres were almost similar to the water temperatures in the absorber basin on all testing days. From Figure 3(d) it is also apparent that the temperature of the LA fibres increased from 8.00 am to 12.30 pm and then started decreasing to the lowest value.

## Productivities of the solar stills

This inclusion of LA fibres into the absorber basin augmented the freshwater yield of the solar still. Thus, the presence of *Luffa acutangula* fibres enhanced the evaporation rate from the basin water by adsorbing the salts from the seawater as the LA fibre is having adsorption as its attribute. Also, it absorbed the seawater by its porous nature and made the evaporation process very easy and rapid. The increased number of fibre samples in the system decreased the evaporation rate by absorbing more water into the fibres. Also, the greater number of fibres in the basin hindered the incoming solar radiation, which reduced the intensity of basin water heating. However, for all the considered cases of the number of LA fibres in the absorber basin, the productivity of the SSLAF was high compared to the CSS. The difference in temperatures augmented the evaporation rate for all considered cases, and in turn, the yield of the solar still to a maximum value of 25.23% when compared to CSS. The cumulative yield in both solar stills from 8.00 am to 05.30 pm was plotted in Figure 4. The enhancement in the freshwater productivity of SSLAF compared to CSS was plotted as a histogram in Figure 5. In Figure 4, it was noticed that the cumulative yield started and increased from 10.00 am. The maximum quantity of the freshwater output was observed between 11.00 pm and 16.00 pm and slowly decreased till minimum freshwater yield was obtained. It was well noticed that from Figure 5, for the 15 numbers of LA fibres, the difference between the freshwater yield in CSS and SSLAF was maximum and it was 25.23% higher compared to CSS, whereas for the SSLAF with 10, 13, 14, 16, 20 and 25 numbers, the difference between the freshwater yield in CSS and SSLAF was 12.27, 17.45, 22.04, 22.69, 14.64, and 4.09% respectively. From Figure 5,
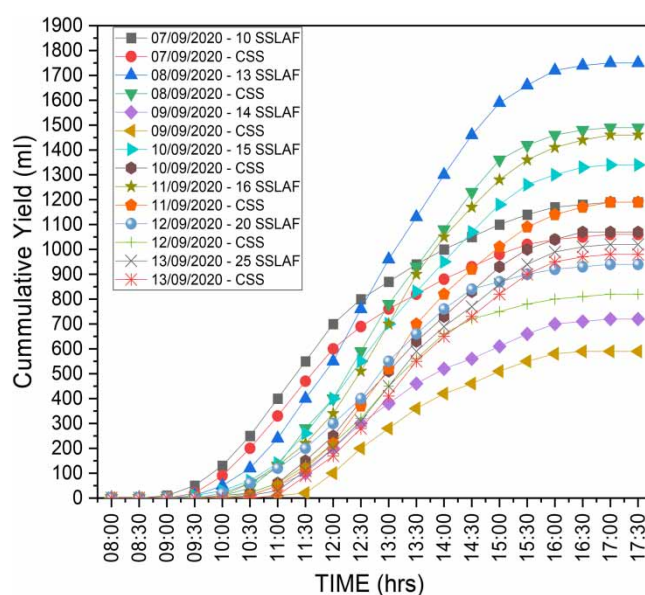


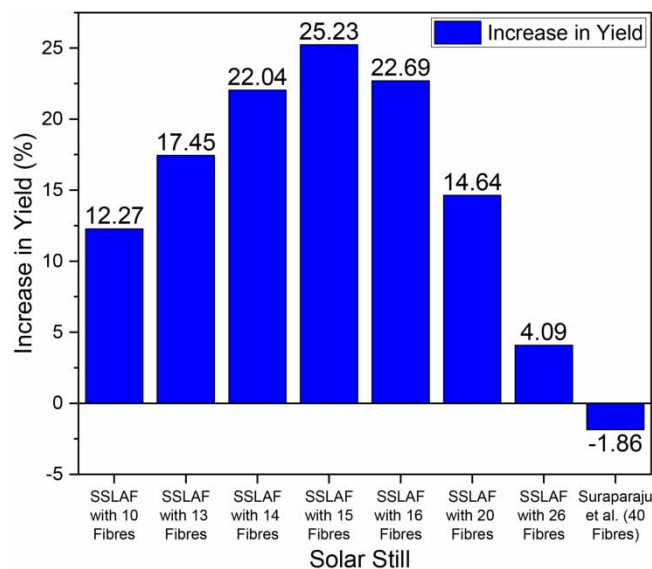**Figure 4** | Cumulative yields of two solar stills on testing days.

**Figure 5** | Comparison of increase in the yield with the varying number of fibres.

it was observed that the freshwater productivity was increased from 10 fibres to 15 fibres and then decreased to the minimum percentage of enhanced yield in the solar still with 20 fibres. However, from the literature (Suraparaju & Natarajan 2020), it was seen that the solar still with 40 number LA fibres decreased the productivity when compared to the conventional one due to more absorption of water in the basin and hindrance to the incoming solar radiation. From Figures 4 and 5, it can be concluded that the use of a minimum number of LA fibres in the solar still for improving the freshwater yield exhibited noteworthy results. The increase in the number of LA fibres in the solar still was leading to a decreasing yield due to greater water absorption and obstruction of the evaporation rate of water. The SSLAF with 15 fibres can be concluded as the optimum number for improved yield for the selected configuration of solar still with LA fibres.

### Enhancement of evaporation rate and productivity using LA fibres

The freshwater productivity of the solar still was significantly augmented by the luffa acutangular fibres in the absorber basin. The porous natural fibres absorbed the water by the action of capillary rise and the wet surface area for evaporation was increased in the absorber basin. The incoming solar radiation raised the temperature of water in the absorber as well as the fibre temperatures. Due to the better heat transfer coefficient of LA fibres, the temperature of water in the fibres also increased. The porous nature of the fibre led to the rapid evaporation of basin water from the enhanced surface area in the absorber. It was observed that porosity, capillary rise, absorbency and the heat transfer coefficient of the fibres led to an increase in the water temperatures which further led to an increase in the productivity from SSLAF relative to CSS. It was also observed that the absorber with more fibres had a lower evaporation rate compared to the absorber basin having the optimum number of fibres. It was mainly due to the over absorption of water into fibres that it took more time for heating the water and fibres. Also, the greater surface area occupied by the fibres in the absorber obstructed the incoming radiation, which further reduced the temperature rise of the water. Hence, it was reported that the optimum number of fibres in the absorber basin enhanced the evaporation rate comparatively better than the more number of fibres on the absorber. From the above inferences, it was concluded that the inclusion of fibres in the absorber basin increased the evaporation rate and productivity of SSLAF when compared to CSS. Also, it was observed that the inclusion of the optimum number of fibres enhanced the potable water yield to a greater extent relative to other configurations.

### Thermo-exergo-economic analysis

The instantaneous thermal efficiency of each solar still was evaluated from Equation (1) and the average thermal efficiency of each considered case was plotted as a histogram. The variation of average thermal energy efficiency with the number of LA fibres is shown in Figure 6. Also, the increase in efficiency was plotted as a line diagram in the same graph (Figure 6). It can be noticed from the histogram, all the average thermal efficiencies of the SSLAF system were more than 20%. The inclusion of
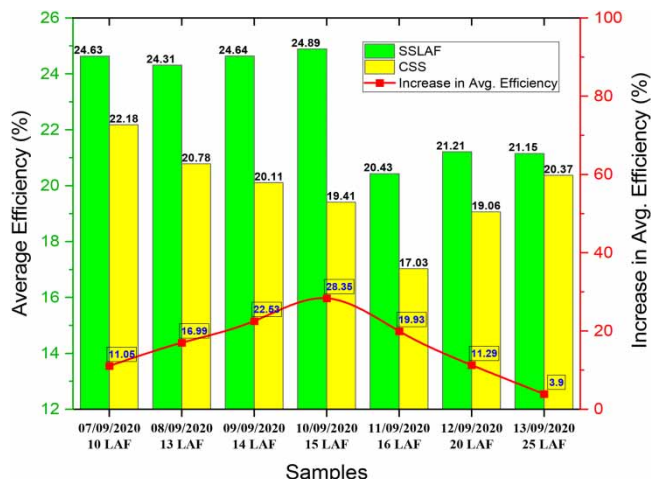
**Figure 6** | Comparison of average energy efficiency and an increase in efficiency with the varying number of fibres.

LA fibres into the absorber basin of the solar still effectively improved the thermal performance, as shown in the histogram. In comparison with the efficiency of CSS, the efficiency of SSLAF was greater in all the cases considered for experimental investigation.The effective increase in the efficiency of SSLAF concerning CSS is shown in Figure 6, as a line diagram. It was observed that the increase in average thermal efficiency with fifteen numbers of LA fibres was 28.35% whereas, for 10,13,14,16,20 and 25 number of LA fibres, the increase in the average thermal efficiency was observed as 11.05%, 16.99%, 22.53%, 19.93%, 11.29% and 3.9% respectively compared with CSS. It can be concluded from the above information that the SSLAF with 15 LA fibres was the optimum with the selected configuration for better yield. The exergy efficiency of the solar stills in all considered cases was evaluated using the exergy analysis mentioned in section 3.2. The average exergy efficiency of each solar still is plotted in Figure 7 as a histogram. It was noticed that all the exergy efficiency was almost less than 2% in all considered cases. This was mainly due to the high temperature of the sun (5,777 K) in the evaporative input and the nominal temperatures at the output of the setup that tend to lesser exergy efficiencies. It was also observed that energy utilization was greater in all SSLAF systems compared to the conventional system. Thus, it can be concluded that the inclusion of fibres in the SSLAF augmented the exergy efficiency compared to CSS.

The CPL and payback period for both the CSS and SSLAF systems were evaluated from the economic analysis in section 3.3. The initial investment price was according to the Indian retail value. The assumptions made for cost analysis were that
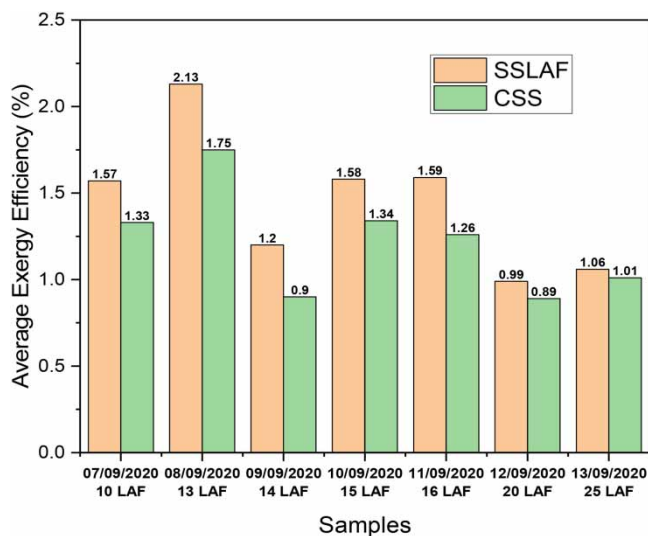


**Figure 7** | Comparison of average exergy efficiency and an increase in efficiency with the varying number of fibres.

the rate of interest was 15% and the salvage was taken as 20% of the fixed cost. The life span of the system was taken as 10 years and the number of working days was taken as 280 days per annum. The operation and maintenance prices were taken as 15% of the fixed costs (Suraparaju & Natarajan 2021a). The yield for economic analysis was considered as the average yield of the solar still on seven testing days. The considered parameters and the outcomes of the cost analysis were tabulated under Table 2. From the table, it was apparent that the cost per litre of freshwater produced for SSLAF was about ₹2.31 (INR) whereas the cost per litre of freshwater produced for a conventional still was about ₹2.83 (INR). The payback periods of SSLAF and CSS were 5.12 months and 6.0 months respectively. The outcomes of the economic analysis of both systems are plotted in Figure 8 for a better comparison between CSS and SSLAF. It can be concluded that the SSLAF has an improved economic performance with the inclusion of LA fibres. Also, the outcomes of the current investigation are compared with the available literature and the comparison is tabulated in Table 3.

## WATER QUALITY ANALYSIS

The samples of saline water and potable water from the CSS and SSLAF were collected and the water quality parameters tested. The results are tabulated in Table 4. The observed values were compared with the BIS requirements. It was observed that the distillate parameters were in the acceptable range given by BIS.

**Table 2** | Parameters and outcomes of the economic analysis

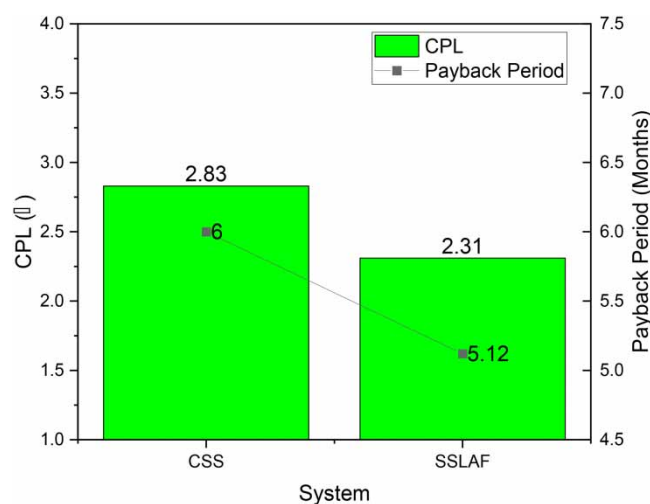| Parameter | SSLAF | CSS |
|---|---|---|
| l | 10 years | 10 years |
| r | 0.15 | 0.15 |
| I | ₹9,200 | ₹9,000 |
| C | 0.2 | 0.2 |
| F | 1,840 | 1,800 |
| A | 90.62 | 88.8 |
| $A_m$ | 276 | 270 |
| $A_C$ | 2,025.4 | 1,981.2 |
| $P_l$ | 840 | 700 |
| CPL | ₹2.31 | ₹2.83 |
| Market value of one litre of water = ₹20 | | |
| Payback period | 5.12 months | 6 months |



**Figure 8** | Representation of outcomes of economic analysis.

**Table 3** | Comparison of viability with the available literature

| References | Solar still | Enhancement (%) | CPL (₹) | Payback period |
|---|---|---|---|---|
| Current research | Solar still with Luffa fibres | 25.23 | 2.31 | 5.12 months |
| Modi & Modi (2019) | Solar still with jute cloth as wick material | 21.46 | 2.4 | 15 months |
| Ramalingam *et al.* (2021) | Solar still with coconut coir | 69.5 | – | 4 months |
| Hansen *et al.* (2015) | Solar still with polystyrene sponge | 25.6 | – | – |

**Table 4** | Water quality parameters

| Parameters/Solar still | Saline water | CSS | SSLAF | BIS |
|---|---|---|---|---|
| pH | 8.9 | 7.6 | 7.6 | 6.5–8.5 |
| TDS | 33,000 ppm | 125 | 125 | 50–250 |

## CONCLUSIONS

In the current investigation, the effect of *Luffa acutangula* fibres on the productivity of a single slope solar still was evaluated at the National Institute of Technology Puducherry, Karaikal, India. The solar stills considered for experimental evaluation were as follows; (i) Conventional Solar Still (CSS) and (ii) Solar Still with *Luffa acutangula* Fibre (SSLAF). The effect of the number of *Luffa acutangula* fibres such as 10, 13, 14, 15, 16, 20 and 25 were estimated for better productivity of the solar still. The important conclusions made from this research are as follows:

1. The comparative analysis with a varying number of *Luffa acutangula* fibre samples in the solar still concluded that the basin with 15 fibre samples attained better efficiency when compared to other numbers of fibres in the absorber basin.
2. It was also observed that the optimum percentage occupancy of fibres in the absorber basin was about 25% for better productivity compared to 45, 35, 20 and 10% occupancy in the absorber basin. It was observed that the solar still with 25 LA fibre samples (45% occupancy) led to more water absorption and less evaporation rate. Therefore, introducing more fibres into the absorber led to a decrease in freshwater productivity.
3. The increase in the yield of the SSLAF with 15 LA fibre samples was 25.23% higher compared to CSS; whereas, for the SSLAF with 10, 13, 14, 16, 20 and 25 fibers, the increase in the freshwater yield was 12.27, 17.45, 22.04, 22.69, 14.64, and 4.09% respectively compared to CSS.
4. The average thermal efficiency of the SSLAF with 15 LA fibres was increased by 28.35%; whereas, for 10,13,14,16,20 and 25 LA fibres, the increase in the average thermal efficiency was observed as 11.05, 16.99, 22.53, 19.93, 11.29 and 3.9% respectively compared with CSS.
5. It was noticed that energy utilization was greater in all considered SSLAF systems compared to CSS. Thus, it can be concluded that the inclusion of fibres into the SSLAF augmented the exergy efficiency compared to CSS.
6. The economic analysis of both solar stills reported that the cost per litre production of freshwater was about ₹2.31 and ₹2.83 for SSLAF and CSS respectively. The payback periods of the solar stills were 5.12 months and 6 months, respectively. Thus, the inclusion of *Luffa acutangula* fibres in the solar still is a better choice not only on the energy and exergy performance but also from the economic point of view.
7. It is concluded that the solar still with 15 *Luffa acutangula* fibres with 25% occupancy in the absorber basin provided a better thermo-exergo-economic performance compared to others due to appropriate enhancement in the evaporation from the basin.

## DATA AVAILABILITY STATEMENT

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

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