

Performance Enhancement of an Inverted Pyramid Solar Still Using Pebble Stones, Coir Fiber, and Sugarcane Bagasse

Karthik Jayanarasimhan¹, Navin Kumar Balasubramanian¹, Nagaraj M^{*2}, S. Mayakannan³, Giridharan.M.R⁴

¹Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai-600124.

^{2*}Institute of Agricultural Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India-602 105.

³Department of Mechanical Engineering Rathinam Technical Campus, Coimbatore - 641021.

⁴Department of Mechanical Engineering Meenakshi College Of Engineering Chennai-600078

*Corresponding Author Email: nagaraj.mech786@gmail.com

ABSTRACT

This work is first systematic assessment of combined thermal performance of different natural materials incorporated in geometry-optimized inverted pyramid made of aluminum. A comprehensive framework, which incorporates energy, exergy, and environmental parameters is used to assess the study. It also presents a new solar still design that utilizes such materials. Interrelations between the incorporation of the pebble stones with the coir fiber and sugarcane bagasse on heat transfer relationship, behavior of the evaporation, and efficiency of the entire system have never been studied previously, particularly in an optimized basin shape. In order to develop a viable and economical desalination system, the present idea combines both the geometrical solar intensification and material-enhanced thermal betterment. The experiment results proved the integrated arrangement to be the most effective one of all the scenarios taken into consideration: To regulate the temperature, pebble stones were used as thermal storage, coir fiber stimulated evaporation of thin-film using capillaries and sugarcane bagasse with its porous structure, facilitated even distribution of water in addition to restricting the thermal losses. The inverted pyramid structure enhanced thermal use by minimizing convection heat losses and enhancing solar energy concentration. The optimal construction produced 32.9% better than the reference still given a similar operating protocol and attained a peak yield of 3.16 kg/day of distillate per m². The increase in efficiency was identified as 36.3% with a rise in efficiency to 26.6 to 41.8% in terms of heat transfer in embodied energy respectively. This result offers viability to the logic that a sustainable and effective solution to distributed solar desalination is the addition of multifunctional natural materials on an ideal basin.

Keywords: Solar still, Heat transfer, Solar density, Thermal storage, Pebble stones.

1. Introduction

According to the increasing demand of clean energy and freshwater, a lot of interests have been created in solar thermal technologies like solar air heaters, solar stills and solar desalination systems. The current studies are aimed at the enhancement of the system and comprehensive energy-exergy-economic and environmental examinations to achieve

efficiency, productivity, and sustainability. The experimental and numerical studies of two pyramid-shaped solar stills, which differ in geometry of the glass covers were compared to increase freshwater productivity. The inverted pyramid with an M-shaped glass cover was modified and the resulting pyramid had 22 times more output of distilled water as compared to the conventional design [1]. A single-slope solar still that is passive and includes an integrated finned condenser was tested experimentally to enhance productivity and the condensing process. The new system almost doubled thermal efficiency and updated fresh water production cost by a large margin than that of the traditional stills [2]. An inexpensive sensible heat storage material using box type solar cookers were used to increase thermal performance. The optimized cooker had 59.1% efficiency, low boiling time and 3.51-year payback period and could be used in low-income households [3]. The development of an economical sensible heat storage material and its application to a solar air heater was done to use it in space heating and drying. The optimized model demonstrated great advancement in exhaust temperature, efficiency, and hot-air supply time unlike the conventional designs [4]. Jute fibre, coconut fibre matrix and cellulose pad were used as the packing materials in a solar HDH desalination system that was experimentally evaluated. Cellulose pad provided the best freshwater yield and efficiency also coconut and jute fibre provided alternatives that are cost-effective and sustainable [5]. A salt-resistant solar interfacial evaporator strategy has been suggested using a peak-shaving and valley-filling strategy. The high-performance 3D coconut-fiber-based evaporator was shown to have stable high evaporation rates even with high salinity and concentrated solar irradiation [6].

This paper discussed the use of natural wood absorbers made of charcoal in plain solar desalination plants to enhance evaporation and efficiency. The best performance was observed with Gamal wood charcoal which gave higher distillate yield and efficiency compared to other materials used [7]. A Janus-structured solar evaporator made of pomelo peel and MXene was made to effectively evaporate salt without being salt-contaminated. The system exhibited great solar-to-thermal performance, stability, anti-bacterial activity, and possible wastewater treatment [8]. An experimental research implemented a 4E analysis on a comprehensive tubular solar still, which was modified with absorber geometry, wicks, and thermal storage. The hybrid corrugated-absorber system had great productivity, efficiency, cost-effectiveness, and reduction of CO₂[9]. An experimental study conducted with three incremental changes to a conventional pyramid distiller evaluated by using corrugated absorbers, wick materials, and CuO nanofluid. The hybrid system was productive in freshwater as 73% higher and the lowest cost per liter [10].

Although studies regarding solar stills with single natural materials have been carried out, no research has been done thoroughly to check the thermal impact of pebble stones, cotton fibers, and sugarcane bagasse used as an inverted pyramid in an aluminum basin. Sugarcane bagasse enhances the water circulation and reduces heat loss; coir fibers promote the evaporation through capillary in the presence of thin films; and pebble stones serve as thermal storage. In particular, within a geometrically optimized basin, very little is known of the interaction of these two factors with each other and their influence on the dynamical processes of heat transfer, evaporation, and overall efficiency of entire system. Moreover, no past study reviewed this arrangement through an in-depth approach. To address these gaps, this paper tests and evaluates passive solar still which has been improved multifunctional natural resources and pyramid shaped aluminum basin. The idea has been supported by a thorough research and can provide a novel, relatively cheap, and energy-efficient desalination technique, combining geometric solar by material-based thermal optimization.

2. Experimental methods

2.1. Construction and design aspects

An experiment was conducted to find how the natural materials affect the solar still efficiency. The main component of the system was a black-coated, inverted shaped aluminum basin with 1 mm thick and designed to absorb solar radiation. A wooden box with dimensions of $78 \times 78 \times 50 \text{ cm}^3$ provided structural support for basin, which have dimensions of $70 \times 70 \times 21 \text{ cm}^3 \times H$. To reduce heat loss to the ambient, 3 cm of glass wool with a thermal conductivity of $0.033 \text{ W/m} \cdot ^\circ\text{C}$ was cover outside of basin. The pyramid shaped glass covers were 3 mm thick with an angle of 50° to optimize solar energy capture. To make the most possible use of the available solar energy, the basin was angled at a 31° angle which is the same as the latitude of the test location. Four thermocouples were inserted at strategic locations that would monitor the temperatures of the glass cover; each sensor on the slanted four surfaces of the glass pyramid. In order to ensure that, the data is a true reflection of the thermal nature of the cover, four values were recorded at once and average them to come up with the representative temperature.

The selection of the materials was also an important element of the design. The aluminum construction of the basin was to enable the basin to transfer heat to the salt water efficiently and rapidly absorb heat through the high thermal conductivity rates of the metal. The initial case study involved the 5 L of working salt water that ensured the constant level of water in the basin at the level of approximately 11 cm. A composition saline water tank were employed to maintain constant water levels and a constant thermal condition required when thermal efficiency is being measured and the performance accurately assessed.

Between July and August 2025, the experiment was monitoring key operational and environmental variables, including the water temperature, air temperature, solar radiation, the temperature of the glass cover, and the speed of wind in real-time. Distillate yield was recorded on an hourly basis to determine performance of various mechanism structures.

2.2. Studied cases

This research aims at investigating the efficiency of inverted shaped solar still with natural materials, like pebble stones, coir fiber, and sugarcane bagasse. The first one is Reference Solar Still (RSS), second one is the Pebble stones (PS-SS), the third is the Coir fiber (CF-SS), the fourth is the Sugarcane bagasse (SB-SS), the fifth is the combination of the Pebble stones and Coir fiber (PSC-SS), the 6th is the combination of the Pebble stones and Sugarcane bagasse (PSSB-SS) and the 7th is the combination of the Pebble stones and Coir fiber + Sugarcane bagasse (CS). These seven examples were done with three independent factors, which were pebble stones, coir fiber, and sugarcane bagasse, each factor present or absent, based on a full factorial design structure. These 23 factorial structures are systematically used to evaluate the solar still thermal and exergy performance, taking into consideration the main effects, as well as the interaction effects. By so doing, we will know that our experiments are thorough, that have kept the bias to the bare minimum, and that will be able to distinguish between the additive and the synergistic effects of the factors of enhancement.

To ensure the maximum heat transport and energy storage in the aluminum basin, the experimental environment was carefully designed. Components of thermal energy storage of natural pebble stones were necessary to ensure the evaporation process and help with heat retention. At the base of the basin, a rock-based thermal layer was created with 2 kg of pebble

stones which were evenly distributed; the layer captured and gradually released heat facilitating the maintenance of temperature and increasing the time of evaporation. Capillary action also increased the area of effective evaporation and consequently, increased contact with the solar radiations and even distribution of water. This was added by natural fibers like sugarcane bagasse and coir fiber. An increased evaporative surface area, which was occasioned by increased water absorption and porosity was obtained as a result of the natural sugarcane bagasse incorporated within the basin. The black coating enhanced the absorption and emissivity of the fibers. Due to their abundance, low cost, eco-friendliness, and low processing requirement, these fibers have been chosen. Also, the sides of the basin were lined with cloth to improve movement of water across the sides.

With a factorial design, we had chance to investigate systematically the interaction between capillary-driven evaporation (Coir fiber and Sugarcane bagasse) and heat storage (pebble stones) with an aim of maximising thermal efficiency and production. A sustainable and economically viable solution to enhancing production of freshwater in regions with limited water supply is to incorporate such natural minerals.

2.3. Experimental procedure

The quality of data and its reliability was ensured because a consistent preparation methodology was used on a daily basis. Prior to commencing the testing the water level in basin were adjusted to required level and any leaks or structural problems were located and corrected where necessary. To guarantee that the measurements were correct, the following instruments were calibrated prior to the commencement of each trial: a data logger, a type of vane anemometer, solar power meter, and Type K thermocouples. To minimize heat loss and ensure that the system is as thermal efficient as possible, it was ensured that thermal insulation was applied to all the parts. The nature of the trials being outside, it became essential to schedule each test on the days when the weather was similar because it was essential to assure reliability. Operational data were recorded on an hourly basis and included temperature of salt water and heat exchanger basin liner, inner and outer sides of glass, the air surrounding it and any organic pollutants. In order to have accurate observation of distillate yield, the freshwater output was observed at a particular hour with a calibrated volumetric flask. The glass was washed on a daily basis to maintain the solar transmittance value at high value, insulation was strengthened.

2.5. Measurements and uncertainty analysis

The measurements was taken every day between 9:00 AM and 5:00 PM, and information was observed every hour. Use of Type K thermocouples allowed for the recording of temperature changes in a variety of media, including salt water, the liner of the basin, the inner and outer surfaces of glass, the surrounding environment, and the natural materials themselves. In order to record and examine the temporal changes, a data logger was employed. A data-logging solar meter was used to monitor strength of the solar radiation, and a Vane-type anemometer to record the speed of the wind. A precision-calibrated flask was used to measure volume of distilled water hourly. An uncertainty analysis were conducted by Holman's approach to guarantee the dependability of the data. Table 1 summarizes the expected uncertainties of the measuring devices:

Table 1 Characteristics of the measurement instrument

| Instrument | Unit | Precision | Value | | Error (%) |
|------------|------|-----------|-------|----|-----------|
| | | | From | To | |
| | | | | | |

| | | | | | |
|-------------------------|-------------------|-------|---|------|-----|
| K-type thermocouples | °C | ± 0.1 | 0 | 100 | 1.3 |
| Graded flask | mL | ± 1 | 0 | 2000 | 2 |
| Datalogging solarimeter | W/ m ² | ± 1 | 0 | 5000 | 1.5 |

The experimental results were highly reliable and accurate, with an overall uncertainty of ±1.4% in daily productivity and ±2.5% in daily efficiency calculations.

A formula for uncertainty propagation was used:

$$W_R = \sqrt{\left(\frac{\partial R}{\partial x_1} W_1\right)^2 + \left(\frac{\partial R}{\partial x_2} W_2\right)^2 + \dots + \left(\frac{\partial R}{\partial x_n} W_n\right)^2} \quad (1)$$

Each independent variable's uncertainty (W1, W2, W3,..., Wn) contributes to the total uncertainty (WR). In particular, the uncertainty in productivity is indicated by the equation: hourly water production vs basin saltwater depth m = f(h).

$$W_m = \sqrt{\left(\frac{\partial m}{\partial h} W_h\right)^2} \quad (2)$$

Furthermore, the following equation can be used to ascertain the degree of uncertainty in thermal efficiency ($W_{\eta_{th}}$):

$$W_{\eta_{th}} = \sqrt{\left(\frac{\partial \eta_{th}}{\partial m} W_m\right)^2 + \left(\frac{\partial \eta_{th}}{\partial I_R} W_{I_{(r)}}\right)^2} \quad (3)$$

2.6.Theoretical analysis

One important measure of a solar still's capacity to extract potable water from the sun is its thermal efficiency. In passive solar stills, the evaporation-condensation process is primarily driven by solar light. When the condensing cover reaches solar still, it absorbs some of incident radiation and lets rest flow through to the water layer and basin liner.

2.6.1. Thermodynamic analysis

One way to express the rate of convective heat transfer from surface of water to inside surface of glass is as follows[11]:

$$\dot{q}_{cw} = h_{cw} \times (T_w - T_{ci}) \quad (4)$$

This formula can be used to compute the heat transfer coefficient (h_{cw}) among water surface and inner surface of transparent cover:

$$h_{cw} = 0.886 \times \left((T_w - T_{ci}) + \frac{(P_w - P_{ci})(T_w + 273.15)}{[268900 - P_w]} \right)^{\frac{1}{3}} \quad (5)$$

$$P_w = e^{\left(25.317 - \frac{5144}{T_w + 273}\right)} \quad (6)$$

$$P_{ci} = e^{\left(25.317 - \frac{5144}{T_d + 273}\right)} \quad (7)$$

With use of hcw, the hew can be assessed as :

$$h_{ew} = 0.016273 \times h_{cw} \times \frac{P_w - P_{ci}}{T_w - T_{ci}} \quad (8)$$

Hew can be used to evaluate the theoretical distillation output (\dot{m}_{ew}) as stated in :

$$\dot{m}_{ew} = \frac{h_{ew} \times (T_w - T_{ci}) \times 3600}{L} \quad (9)$$

where L were latent heat of vaporization, which may determined by following formula:

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

$$\dot{q}_{rw} = h_{rw} \times (T_w - T_{ci}) \quad (11)$$

where hrw were radiative heat transfer rate coefficient:

$$h_{rw} = \varepsilon_{eff} \times \sigma \times ((T_w + 273.15)^2 + (T_{ci} + 273.15)^2) \times (T_w + T_{ci} + 546.2) \quad (12)$$

$$\frac{1}{\varepsilon_{eff}} = \frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_{ci}} - 1 \quad (13)$$

When convective, evaporative and radiative heat transfer coefficients are added together, total heat transfer coefficient were calculated as follows :

$$h_{1w} = h_{cw} + h_{ew} + h_{rw} \quad (14)$$

The addition of sugarcane bagasse and coir fiber to the modified solar still changes the mass transfer behavior and local heat through capillary and porous effects. Instead than reformulating the governing equations, these effects were integrated by effective modifications to the properties. Due to the increased capillary-driven transport and film-wise evaporation generated by Coir fiber and Sugarcane bagasse layers, effective thermal conductivity, evaporative surface area, and permeability factor was adjusted accordingly.

2.7. Energy analysis

Using first law of thermodynamics as basis, an energy analysis were conducted to assess how well solar still can use solar radiation to produce freshwater. The system's performance and operational feasibility are determined by how efficiently this energy conversion is carried out .

Therefore, the mathematical evaluation of still's internal efficiency is as follows[12]:

$$\eta_i = \frac{\dot{m}_{ew} \times L}{A_s \times I(t) \times 3600} \quad (15)$$

$$\text{nenergy} = \frac{\sum \dot{m}_{ew} \times L}{\sum A_s \times I(t) \times 3600} \quad (16)$$

Latent heat of vaporization (L), hourly distillate output (m³ ew), and anticipated area of still (A) are all variables in this context.

Various solar still designs can be directly compared using this equation. An rise in water output and an improvement in energy consumption are both indicated by higher efficiency numbers. Improvements in energy conversion can be found through the analysis by modifying designs and optimizing materials.

2.8. Exergy analysis

By taking irreversibility and losses into account, exergy analysis evaluates energy conversion. Exergy of an object is its greatest work potential before it returns to its resting state in relation to its external environment. The equation for exergy balance of closed system were given by [13]:

$$\sum \dot{E}_{x, in} - \sum \dot{E}_{x, out} = \sum \dot{E}_{x, dest} \quad (17)$$

Here is the formula for determining input exergy from solar radiation:

$$\sum \dot{E}_{x, in} = \sum \dot{E}_{x, sun} = A_5 \times I(t) \times \left[1 - \frac{4}{3} \left(\frac{T_a + 273}{T_s} \right) + \frac{1}{3} \left(\frac{T_a + 273}{T_s} \right)^4 \right] \quad (18)$$

As stated in the exergy yield of deionized water is:

$$\sum \dot{E}_{x, out} = \sum \dot{E}_{x, evap} = \frac{\dot{m}_{ew} \times L}{3600} \times \left(1 - \left(\frac{T_a + 273}{T_w + 273} \right) \right) \quad (19)$$

$$n_{exergy} = \frac{\sum \dot{E}_{x, out}}{\sum \dot{E}_{x, in}} \quad (20)$$

In order to optimize energy utilization and decrease losses, this study can be used to find inefficiencies.

2.9. Energy payback period analysis

2.9.1. Embodied energy

A well-known indicator for environmental evaluation, embodied energy (EE) provides a solid basis for contrasting the long-term viability of various products and systems. It measures the overall amount of energy used during the whole material or component's life cycle, which includes everything from extracting resources to processing, manufacturing and transportation [14]. In order to choose alternatives with less environmental effect and better energy efficiency, this metric is crucial for determining which materials have high energy demands.

When it comes to solar stills, EE is a key sustainability metric, especially when comparing designs with different materials. However, research and data sources may differ in their challenges in identifying consistent system boundaries, which might impact the accuracy of EE assessments. EE values used at investigation was obtained from well-known sources in the literature, guaranteeing that they are comparable to other, more reliable environmental performance assessments. This ensures that the analysis is consistent.

According to the following equation, overall EE of solar still mechanism was estimated.

$$E_{in} = \sum (\text{Energy density of all component} \times \text{Mass of each component}) \quad (21)$$

The total embodied energy of the system is significantly reduced with the incorporation of natural materials, specifically Pebble stones, Coir fiber, and Sugarcane bagasse. Because of their biodegradability, local availability, and low processing needs, these materials have small energy footprints by definition. Natural materials not only reduce energy efficiency (EE), but they also improve energy recovery and increase the lifespan of the system, both of which are important for sustainability in the long run. Their use is in line with the principles of renewable energy technology's low-impact material consumption and helps with ecologically responsible desalination.

2.9.2. Energy payback time

Energy payback time is the amount of time needed for solar still to generate equal amounts of energy as it consumed during its construction. One sign of a energy-efficient and sustainable system is a shorter EPBT.

Two methods exist for evaluating EPBT, as described below : one is energy streams, and the other is exergy streams.

$$(\text{EPBT})_{en} = \frac{E_{in}}{E_{en,out}} \quad (22)$$

$$(\text{EPBT})_{ex} = \frac{E_{in}}{E_{ex,out}} \quad (23)$$

2.10. Environmental analysis

The continued reliance on fossil fuels to generate power is a leading cause of global warming, making solar-powered desalination systems an environmentally preferable option. In order to the desalination system work for the environment, this study looks at how well it may reduce CO₂ emissions. For coal-based power in India, point-of-production CO₂ emission is around 0.628 kg CO₂/kWh. Total T&D losses are estimated to be between 10% and 20%, with more recent estimates getting close to 20%, according to national and international energy statistics. The effective emission is around 0.785 kg CO₂/kWh provided when this loss factor is applied multiplicatively.

The worldwide average for CO₂ emissions per kilowatt-hour (kWh) from coal-fired power plants is around 980 g .

$$\varphi_{CO_2} = EF \times \frac{E_{en,out} \times n}{1000} \quad (24)$$

Despite its usefulness as a worldwide standard, the absolute CO₂ intensity would probably be lower if we used an Egyptian grid-mix factor that represents the region's energy mix, which is mainly hydro, solar, and natural gas. The improved solar still's relative performance improvement over the reference system, however, would stand.

Using the following formula , we can determine the exergo environmental parameter and use it to evaluate the environmental effect from an exergy standpoint:

$$\varphi_{ex,CO_2} = EF \times \frac{E_{ex, out} \times n}{1000} \quad (25)$$

$E_{ex, out}$ stands for the solar still's annual exergy output, while χ_{ex,CO_2} denotes CO₂ mitigation in tons according to the exergy technique.

2.11. Enviro-economic analysis

An alternate method for calculating the system's environmental and economic advantages is the exergo-enviroeconomic parameter. It takes into account both the energy and exergy outputs, which stand for maximum amount of work that system is capable of doing. This is the definition of the exergo-enviroeconomic parameter given by:

$$\zeta_{CO_2} = \varphi_{CO_2} \times z_{CO_2} \$ \quad (26)$$

3. Results and discussion

A thorough evaluation of effects of using natural materials in solar still efficiency was provided in this section. Performance metrics such as energy payback time, exergy, enviroeconomic, and exergoeconomic factors are used to conduct the evaluation.

3.1. Solar still temperatures

Thermal behavior of solar stills is affected by the fluctuation in solar energy throughout the day. The glass cover temperature rises at midday due to peak intensity of the solar radiation, which slows the condensation rate. The result is that there is an imbalance in rates of condensation and evaporation, leading to higher temperatures at air-vapor interface among glass cover and water surface. Improvements to the system should aim to do three things: temperature rise of water at basin, decrease buildup of heat on glass cover, and maximize the efficiency of evaporation while minimizing thermal losses. Because of their inexpensive price, abundant availability, and beneficial thermal storage qualities, pebble stones were chosen. During peak solar exposure, these materials can quickly raise temperatures while efficiently releasing heat at night since they have lower heat capacities than water and air. They also reduce heat loss through the still's base and walls due to their poor thermal conductivity.

The 5 liter of water is used in the experimental setup, which makes use of inverted basin solar still that is combined with natural pebble stones, coir fiber, and sugarcane bagasse. Solar radiation at 912.2W/m² midday and then declines to 452.2W/m² at sunset, according to hourly temperature and radiation profiles measured from 9:00 to 17:00. When compared to the RSS, water temperature profiles improved significantly after using natural materials; thermal storage reduced temperature swings and maintained high temperatures after sunset. Fig. 1 shown that RSS reached peak water temperature of 74.2 °C at noon, and then it dropped to 52.2 °C by 17:00. The configurations that were altered using natural materials, such as CF-SS, SB-SS (natural Sugarcane bagasse), and PS-SS (natural pebble stone), showed peaks of 70 °C, 47 °C, and 56 °C at 13:00. These arrangements maintained maximum temperatures of 37 °C, 45 °C, and 52.2 °C until 17:00. Direct solar radiation absorption caused the NS-SS combination to reach its highest peak temperature; nevertheless, it cooled down quickly after sunset. As a result of their better heat storage capabilities, SB-SS and CF-SS arrangements kept temperatures higher for longer periods of time.

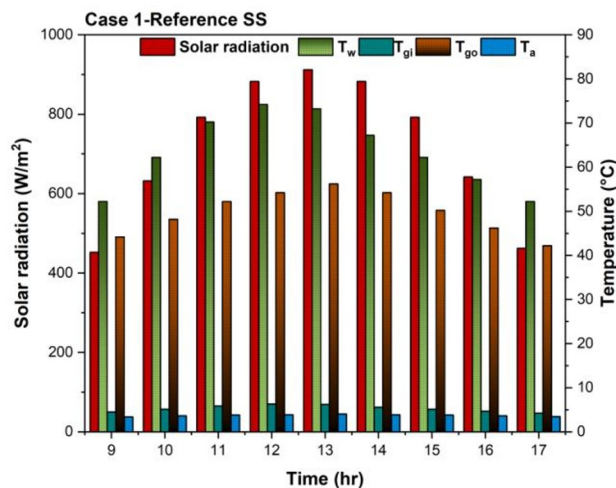


Fig. 1. Thermal behavior of the baseline solar still

The temperature changes of internal glass cover (T_{gi}) are shown at Fig. 2a-c. At noon, T_{gi} at RSS reached $72.2\text{ }^{\circ}\text{C}$, and by 17:00, it had dropped to $50.2\text{ }^{\circ}\text{C}$. At 13:30, CF-SS, SB-SS, and PS-SS reached their highest temperatures of $77.2\text{ }^{\circ}\text{C}$, $58.2\text{ }^{\circ}\text{C}$, $72.2\text{ }^{\circ}\text{C}$. By 17:00, the temperatures had dropped to $67.2\text{ }^{\circ}\text{C}$, $60.2\text{ }^{\circ}\text{C}$, and $50.2\text{ }^{\circ}\text{C}$. These results show that compared to using only pebble stones, the changes based on sugarcane bagasse and coir fiber improved heat retention significantly.

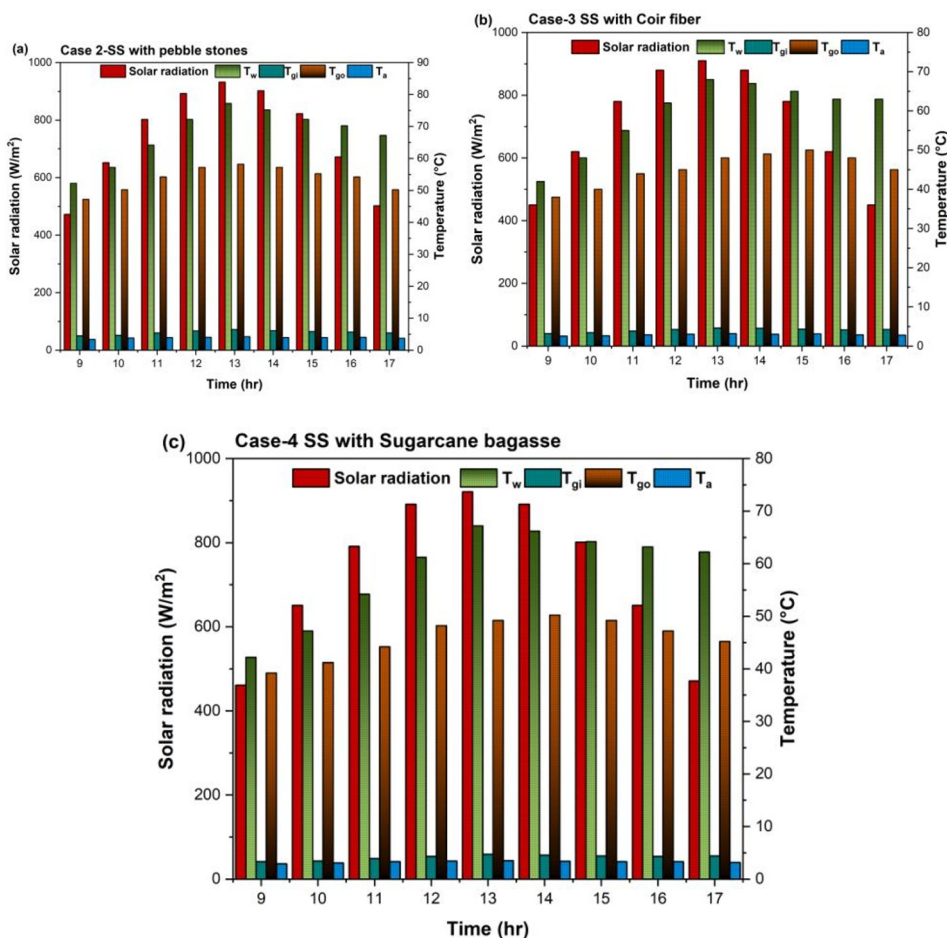


Fig. 2. (a) Temperatures with pebble stone, (b) Temperatures with coir fiber, (c) Temperatures with sugarcane bagasse.

Figure 3 shows the temperature distributions for several natural material configurations. Water temperatures reached their highest points at 14hours, 15hours, and 16 hours, respectively, reaching 70.2°C, 67.2°C, 69.2°C for PSC-SS, PSSB-SS, and PSCSB-SS configurations. By 17:00, the temperature had dropped to 66.2°C, 62.2°C and 63.2°C. At 57.2°C, 56.2°C, and 59.2°C, the corresponding T_{gi} values were at their highest, and then they dropped to 51.2 °C, 52.2 °C, and 54.2 °C. It appears from findings that a combination of various natural materials increases the capacity to store heat and allows evaporation to continue into the night.

The testing results indicate that, the solar stills are better when they are made of natural materials to enhance their thermal management. The reason is that it enhances efficiency of energy storage, reduces heat losses and enables evaporation to proceed even after sunset. As it can be seen in the figures 1 and 2, such factors as pebble stones, coir fiber, and sugarcane bagasse influence significantly the thermal dynamics of the system. Even though the properties of various materials to retain heat vary, a combination of various materials will enhance effective temperature management owing to individual synergistic advantages. The relevance of thermal energy storage methods enhancing sustainability and efficiency of solar desalination is revealed by the fact that it directly results in increased production of freshwater due to its thermal storage capabilities.

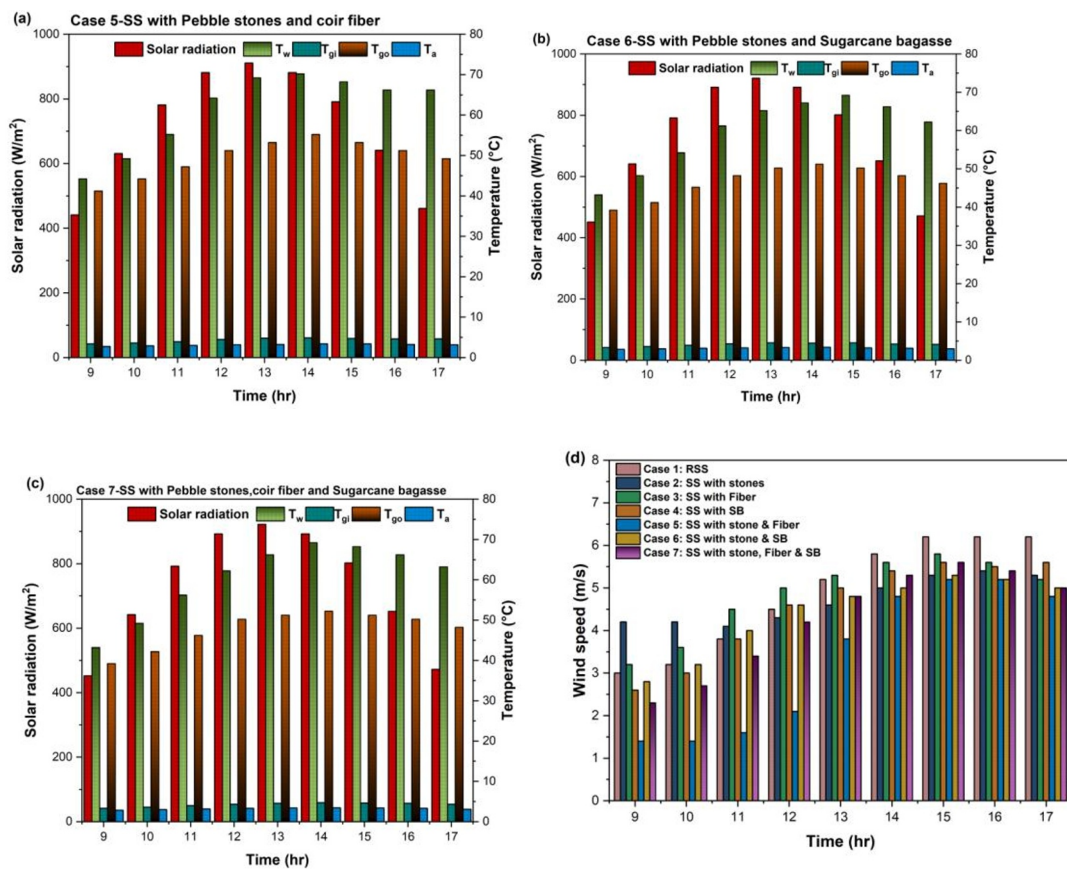


Fig. 3. (a) Temperatures with pebble–coir combination, (b) Temperatures with pebble–bagasse combination, (c) Temperatures with hybrid natural materials, (d) Wind speed variations during experiments

3.2. Effect of Natural Materials on Temperature Regulation

Including natural materials like pebble stones Coir fibers and sugarcane bagasse increases thermal performance of solar stills as shown in Figure 1 and Figure 2. These substances augment heat intake, retention and distribution. Comparing it with reference solar still, it is possible to observe that such changes enhance the management of heat and, consequently, yield fresh water and evaporation efficiency.

At noon, the RSS had increased to an extreme of 72°C. The heat-retention was low; temperatures fell 30% to 52°C at 17:00. The highest temperature was 76 °C at 13:00 when pebble stones were introduced as they are direct sources of heat. However, at 17:00 the temperature fell to 17 Georges, indicating that there was minimal heat storage in the long term and cooling rate were only fifteen percent slower than RSS. Conversely, the structure involved in Coir fibers cooled slower, to 73°C at 13:00 but remaining at 67°C at 17:00, a fall of 35%. It is due to the increased heat dispersion that can be achieved through the large surface area of the Coir fiber and its capillary properties of the fiber that the fiber achieves such amazing heat retention. The system made of sugarcane bagasse cooled down 36 % slower than the RSS at 13:00, and even worse still, at 17:00 with a high temperature of 74°C and an even better heat retention of 70°C. The insulating property and the ability of the sugarcane bagasse to trap heat on its surface has enabled this improvement.

As can be seen in figure 2, the layouts that make use of a large number of natural materials achieve even superior thermal regulation. The PSC-SS arrangement had 30 percent higher heat retention than the RSS, and peak temperature 70 °C at 14: 00 constant temperature until 17: 00. The PSSb-SS stone/sugarcane bagasse system reached its top temperature of 62 C 15:00 and held 73 C until sunset, higher sustained heat holding time than RSS. Having highest temperature 73 C at 14: 00, and lowest cooling rate, 45-50 C 17: 00, most thermally stable combination, PSCSB-SS performed half better in heat retention than the RSS.

The impact of material configurations on the efficiency of solar stills is summarized in Table 2. Pebble stones are great for absorbing and storing heat directly, and coir fibers are great for distributing heat and reducing the impact of temperature swings. Because it floats, sugarcane bagasse keeps its heat for a long time by floating on the water's surface. The most balanced thermal performance was shown by the PSCSB-SS design, which could maintain higher temperatures for longer durations, increase the possibility of evaporation throughout the night, and improve distillate yield.

Table.2 Performance effect of natural materials.

| Natural Material | Peak Water Temperature | Important Advantage | Impact |
|--------------------------------|-----------------------------|-------------------------------------|------------------------------|
| Natural material configuration | Peak water temperature (°C) | Sustained temperature at 17:00 (°C) | Key benefit |
| No material (RSS) | 74.2 | 52.2 | Baseline case |
| Pebble stone (PS-SS) | 76.0–77.2 | 37.0–40.0 | Thermal storage |
| Coir fiber (CF-SS) | 73.0–75.0 | 60.0–67.0 | Capillary-driven evaporation |
| Sugarcane bagasse (SB-SS) | 72.0–74.0 | 70.0–74.0 | Insulating floating layer |

| | | | |
|--|------|-----------|-----------------------------------|
| Pebble stone + Coir fiber (PSC-SS) | 70.2 | 66.2 | Synergistic evaporation + storage |
| Pebble stone + Sugarcane bagasse (PSSB-SS) | 67.2 | 62.2–73.0 | Balanced storage and insulation |

The internal glass temperature trends (T_{gi}) were also very similar to the water temperature fluctuations with the only difference that the peaks were much lower. The natural materials added to the process enhanced condensation efficiency and production of water because they moderated T_{gi} .

Use of natural materials enhances thermal performance, increases production of desalination, and extends evaporation beyond the daylight hours, which are the results of the trial. This study forms the foundation of the further solar still constructions that utilize the free thermal features of materials to enhance energy efficiency and fresh water yield in sun desalination.

3.3. Heat transfer analysis

Figure 4 shows the time-dependent changes in total, convective, radiative, and evaporative heat transfer. The pebble stones set on the bottom of the basin soak up the sun's rays, causing them to gradually release the heat they have stored. The capillary-driven heat transmission is improved by coir fibers covering the basin surface, and evaporation and condensation are affected by the insulating layer of sugarcane bagasse floating on the water surface.

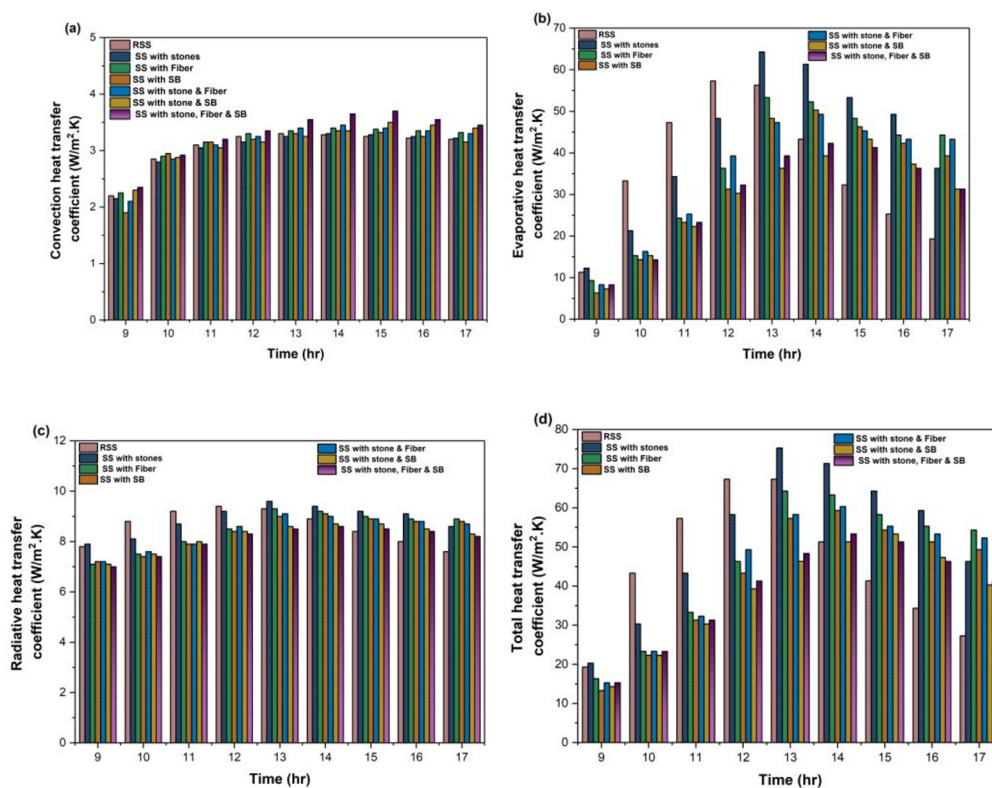


Fig. 4. (a) Convective heat transfer coefficient, (b) Evaporative heat transfer coefficient, (c) Radiative heat transfer coefficient, (d) Total heat transfer coefficient.

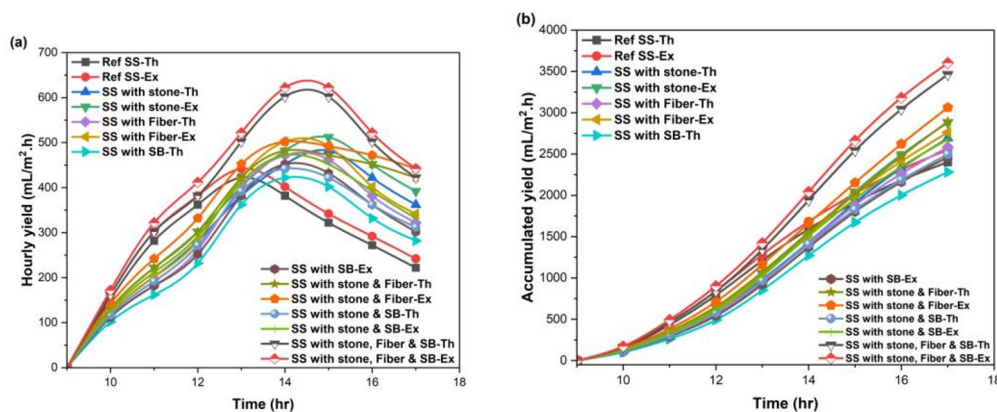
Different arrangements have different heat transfer coefficients. At thirteen minutes, the configuration with only pebble stones reaches its maximal radiative, evaporative, and heat transfer of $3.3 \text{ W/m}^2\cdot\text{K}$, $56.3 \text{ W/m}^2\cdot\text{K}$, and $9.3 \text{ W/m}^2\cdot\text{K}$, in that order. Seventeen minutes, these coefficients have decreased to $3.2 \text{ W/m}^2\cdot\text{K}$, $19.3 \text{ W/m}^2\cdot\text{K}$, $7.6 \text{ W/m}^2\cdot\text{K}$, and $27.3 \text{ W/m}^2\cdot\text{K}$, in that order. This precipitous drop shows that pebble stones alone can not keep up with evaporation. The PSCSB-SS configuration, which includes pebble stones, coir fiber, and sugarcane bagasse, has lower peak values at 14:00, $3.65 \text{ W/m}^2\cdot\text{K}$, and $42.3 \text{ W/m}^2\cdot\text{K}$, in that order. However, it holds heat more effectively, and the decrease is slower, reaching 3.45 , 31.3 , 8.2 and $41.3 \text{ W/m}^2\cdot\text{K}$, in that order on 17 hours. By enhancing energy absorption and redistribution, the mix of materials promotes thermal retention.

Because of differences in material arrangement and energy retention, convective heat transfer displays unique behavior. The heat-storing materials are in direct touch with the water, PSCSB-SS arrangement attains maximum convective heat transfer coefficient, reaching a peak of $3.7 \text{ W/m}^2\cdot\text{K}$ on 15 hours. Combination of Coir fibers and Sugarcane bagasse greatly boosts surface area accessible for heat exchange, lowers unexpected thermal losses. When used in solar stills, the increased wet area exposed to sunlight is a result of the fibers' porous structure. Especially when used to thin-film evaporation processes, this layout speeds up water evaporation and boosts desalination efficiency.

The significance of material distribution and selection in maximizing solar still heat transfer is underscored by these results. Multiple natural material configurations guarantee ongoing evaporation beyond peak sunlight hours due to their more gradual thermal drop. This increased freshwater yield is directly attributed to the modified material configurations' positive impact on thermal efficiency, which in turn improves solar desalination efficiency.

4.4. Freshwater yield

Over course of an 8-hour observation period, Figure 5 shows fluctuations at hourly, cumulative, and midnight distillate productivity for configurations. The setup that produced the most freshwater was the one that used pebble stones, coir fiber, and sugarcane bagasse, which is called PSCSB-SS. After sunset, the PSCSB-SS setup maintained larger temperature differential among interior glass (T_{gi}) and ambient air (T_{go}), despite a little delayed initial caused by heat storage capacity. Hourly productivity was 622 mL/m^2 , overnight production was 912.3 mL/m^2 , and the total yield was 3602 mL/m^2 because of prolonged heat gradient that increased condensation rates.



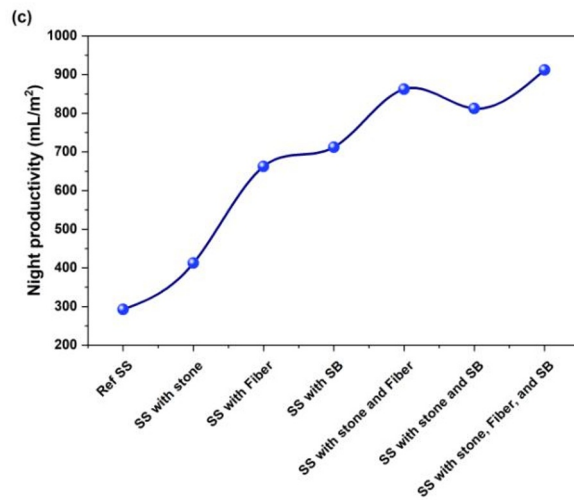


Fig. 5. Hourly and accumulated yield variations

Hourly, nightly, and cumulative provides of 292.3 mL/m², 152 mL/m², and 2923 mL/m² correspondingly were recorded by reference solar still, devoid of any natural materials, resulting in lowest productivity. For constant basin area 0.5 m². In another study, three modified pyramid distillers incorporating corrugated basins, wicks, nanofluids, and enhanced PCM were evaluated thermodynamically and economically. The best configuration improved yield by 76.9% and reduced freshwater cost by nearly 30% [15].

3.5. Energy and exergy efficiency

Solar still performance can be greatly enhanced by conducting an exergy study. Exergy output (W) varies hourly at all seven configurations (Fig. 6), revealing how changes like pebble stones, coir fibers, and sugarcane bagasse affect the performance under the same conditions.

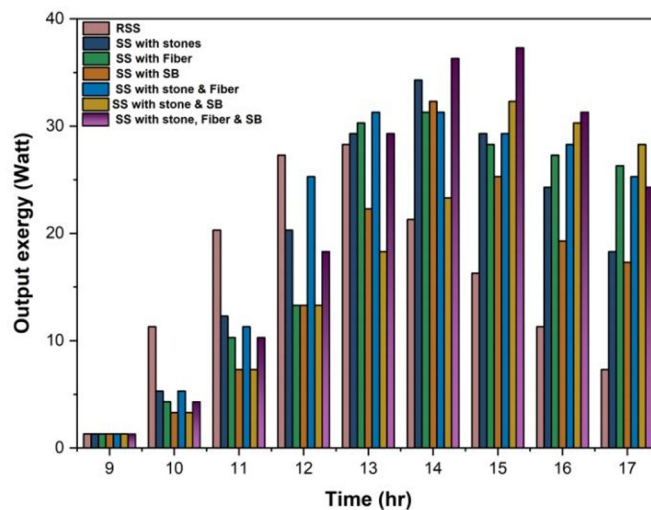


Fig. 6. Hourly output exergy variations.

According to Figure 7, the RSS had the worst energy efficiency at about 20% and the worst exergy efficiency at about 1.3%. Energy efficiency increased by 18% and exergy efficiency by 2 % after the addition of pebble stones. The pebble stones' ability to store heat during periods of high solar intensity and then release it slowly, so extending the time it takes for water to evaporate, is responsible for this improvement.

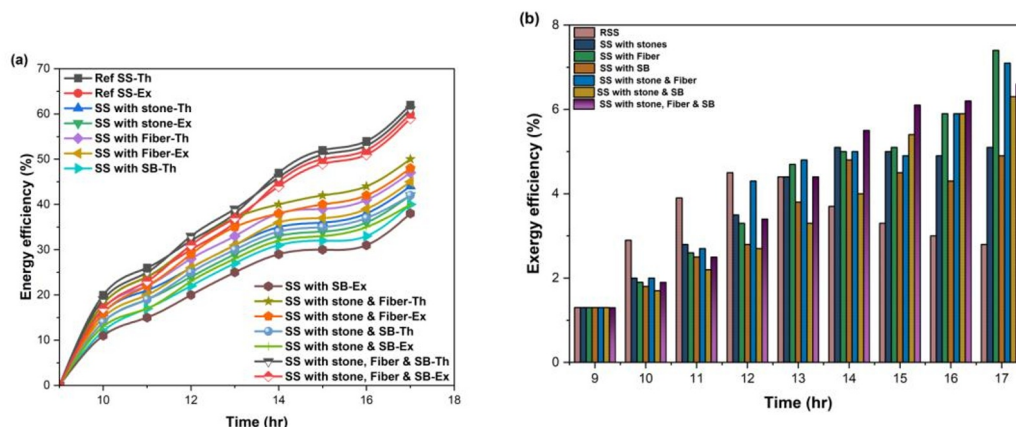


Fig. 7. Energy–exergy efficiency variations.

It was further increased to 45% exergy efficiency and energy efficiency of 4.8% using Coir fiber. The increased capillary action that the Coir fiber provided also enhanced rate of evaporation and heat transfer as water spread uniformly all over the surface. This set up showed that the Coir fiber played a vital role in realizing the optimal thermal performance, and it was higher than the ones made of SS and the pebble stones setups alone. The maximum exergy production of fibrous sugarcane bagasse was approximately 34 W and comparable to Coir fiber structure. It increased the amount of heat absorbed and water evaporation by raising evaporative surface area. The differences in heat conduction and water holding properties were likely to be the reason why its performance was slightly low as compared to the Coir fiber.

Pebble stones and coir fibers interacted to form a combined effect, which had the high exergy output 37 W on 1:30 PM. The thermal storing properties of pebble stones and capillary action of Coir fiber contributed a lot to the rate of evaporation. The pebble stone-sugarcane bagasse combination attained peak power of 36 W at 1:00 PM, which were quite similar to that of pebble stone-Coir fiber system, although slightly low in performance due to the difference in heat retention. By the best combination of the materials, the optimal combination of Pebble stones, Coir fibers, and Sugarcane bagasse, the maximum exergy output was reached at 1:30 PM, and was 39 W.

These outcomes are indicative of advantages of including different upgrades in solar stills. The results were superior heat absorption, storage, and evaporation due to the use of a great deal of materials instead of a single one. All the configurations had different cooling speeds, but they all reached their peak exergy output at the period 1:30 to 1:00. The constructions made of pebble stones proved to be better thermal storage that served them to excrete longer durations of time. PSCSB-SS setting recorded maximum overall efficiency with a peak energy and exergy efficiency of 55% and 6.0 respectively. This demonstrates the fact that maximizing the surface area, thermal storage and water distribution factors are synergistic to maximize solar stills efficiency.

The findings of the research on energy and exergy efficiency were rather important. First of all, configurations with many improvements were always more energy and exergy efficient than the ones with a single change. Also, it is worth mentioning that the energy efficiencies in the solar still systems have always been higher than the exergy efficiencies, which can be explained by the generation of entropy and irreversible losses. In some cases, exergy efficiency (better reflecting the real available work of the system) higher than energy efficiency, particularly with irreversible systems. Third thermal storage media of pebble stones played significant role at minimizing the efficiency decrease once the solar intensity peaked and raising the performance peaks. Finally, a solar still that utilized the best of the pebble stones, coir fibers and sugarcane bagasse performed the best.

4.6. Natural materials performance impact

Incorporating natural materials into distillate manufacturing processes optimizes heat retention, increases evaporation, and boosts thermal efficiency generally. The freshwater yield recorded for all setup were follows: Pebble stones (PS-SS) have an RSS of 3.14 kg/m² per day. 4.32 kg/m² day for PSSB-SS -3.4 kg/m²·day for CF-SS, 3.16 kg/m² day for PSCSB, 3.85 kg/m²·day for PSSB-SS, 3.53 kg/m²·day for PSC-SS, and 3.14 kg/m²·day for SB-SS (natural Sugarcane bagasse). By combining different organic materials to maximize solar energy use, PSCSB-SS configuration had maximum productivity, providing 32.9% more freshwater than RSS.

Figure 8a shows the efficiency which are proportional to the amount of solar radiation that was successfully transformed into distilled water. Following are thermal efficiencies that were measured for the different configurations: PS-SS –29.2%, RSS – 26.6%, SB-SS – 30.5%, CF-SS – 32.6%, PSSB-SS - 33.6%, PSCSB-SS - 41.8%. With a 36.3%, and PSC-SS – 38.3% improvement over the RSS, the PSCSB-SS combination had the best efficiency. The natural pebble stones, coir fiber, and sugarcane bagasse work together to increase water yield by raising heat absorption, storage, and evaporation efficiency. Each improved solar still's relative productivity improvement from the RSS is quantified in Fig. 8b. 46.8%, 60.2%, 10.85%, 25.4 %, 16.2 %, 45.7%. These findings highlight the significant improvements in performance that may be found when natural materials are used in solar still designs.

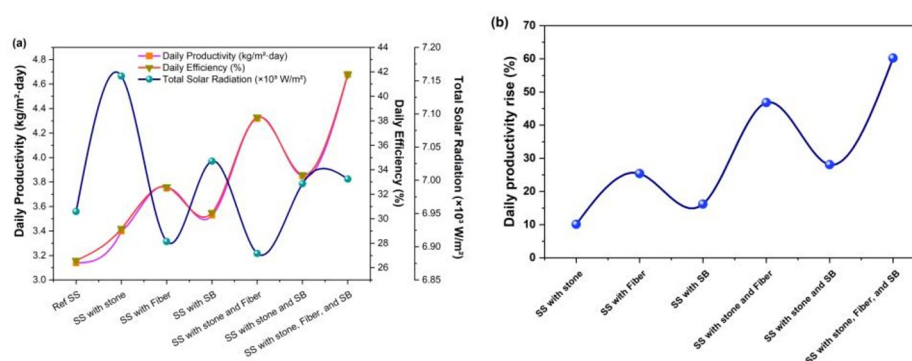


Fig. 8. Productivity–efficiency versus radiation & Daily productivity enhancement

3.7. Energy payback and embodiment

3.7.1. Embodied energy

To find out whether solar still systems are economically and energetically viable, it is essential to evaluate their embodied energy. Table.3 displays EERanges for each of solar architectures that were considered.

Table 3 Embodied energy analysis.

| Component | Materials | Embodied energy | Mass | Total embodied energy |
|-------------------------------|---|-----------------|----------|-----------------------|
| Insulation (m ³) | Glass wool | | 3 | |
| Glass cover (m ³) | Tempered glass | 18339.8 | 1.088889 | 235.73 |
| Basin coating | Black paint | 26 | 2 | 26 |
| Body and basin | Aluminium | 48.22 | 5.05 | 192.24 |
| Natural materials | Pebble stone, Coir fiber, and Sugarcane bagasse | - | - | - |
| Total embodied energy (kWh) | - | - | - | 454.17 |

Among the cases that were examined, 454.17 kWh were found to be the total embodied energy. These cases included reference solar still, solar still with pebble stone, solar still with Coir fiber, solar still with sugarcane bagasse, solar still with pebble stone and Coir fiber, solar still with pebble stone and Sugarcane bagasse, and solar still with pebble stone and Coir fiber as well as Sugarcane bagasse. Minimal gains in embodied energy are achieved through the use of natural elements such as pebble stone, coir fiber, and sugarcane bagasse, which reduce the requirement for processed materials that are energy intensive. The sustainability benefits of all three natural materials are further emphasized by the fact that they boost energy recovery and increase the longevity of the system when combined.

3.7.2. Energy payback time (EPBT)

The time takes forenergy system to produce energy that is equivalent to its embodied energy were known as its Energy Payback Time, and it is an important measure for assessing sustainability of energy systems. A practical and energy-efficient system is one with a lower EPBT. The results of this investigation are reported in Table 4, which assesses EPBT by both exergy and energy-based approaches.

Table 4 EPBT of natural-material still.

| Parameter | Ref SS | SS with pebble stone | SS with Coir fiber | SS with Sugarcane bagasse | SS with pebble stone&Coir fiber | SS with pebble stone&Sugarcane bagasse | SS with pebble stone&Coir fiber&Sugarcane bagasse |
|-------------------|--------|----------------------|--------------------|---------------------------|---------------------------------|--|---|
| Annual yield (kg) | 902.6 | 991 | 1110 | 1035.2 | 1303.8 | 1144 | 1426.2 |
| EPBT en | 5 | 5 | 5 | 5 | 5 | 5 | 5 |

| | | | | | | | |
|-----------------|--------|--------|--------|--------|--------|--------|--------|
| EPBT ex | 5.753 | 5.686 | 5.612 | 5.656 | 5.52 | 5.594 | 5.476 |
| Ex, out annual | 37.51 | 40.71 | 40.71 | 42.31 | 52.04 | 46.25 | 56.48 |
| En, out annual | 606.38 | 665.63 | 745.34 | 695.22 | 875.18 | 768.12 | 957.1 |
| Embodied energy | 458.16 | 458.16 | 458.16 | 458.16 | 458.16 | 458.16 | 458.16 |

We estimate the yearly freshwater yield by taking into consideration efficiency of solar stills and accounting fluctuations at solar intensity throughout the year. Summertime seems solar intensities of up to 1060 W/m² while wintertime sees them drop to 650 W/m², with minimums of 220W/m² and 55W/m² correspondingly. A complete years' worth of freshwater production can be estimated using this data.

4. Conclusion

The systematic study of the synergistic effect of the natural components like pebble stones, coir fiber, and sugarcane bagasse was carried out on an altered solar still with inverted pyramid-shaped aluminum basin to obtain the maximum thermal gain and yield of freshwater. The research is the first to combine multiple passive components to enhance temperature trapping, water dispersion, and capillary-based evaporation of thin-films simultaneously, unlike the past literature which focused on the effects of single materials. The inverted pyramid shape results in a thermally enhanced system, which enhances the absorption of solar flux and reduces the amount of convective losses. The hybrid optimum design had high daily distillate output, which was higher by far compared to the reference solar still, growing to 3.16 kg/m². This tremendous improvement evidences the value of multifunctional passive augmentation in comparison to more traditional designs and changes that utilize one material.

The exergy efficiency increase and thermal efficiency increase between the combined system were thermodynamically 36.3%, and 36.3% (between 26.6% and 41.8%); respectively. This important element is overlooked in the solar still optimization research and it has been demonstrated that the energy that is available is being utilized better to produce vapour and that larger portion of the available energy is being transformed into usable labor.

The enhanced solar still was superior following an in-depth analysis that involved both energy and exergy parameters. This work makes a contribution to the field by demonstrating how multifunctional natural materials and geometrical optimization can create a thermal performance and give sustainable, scalable solution to desalination. Specifically, it has been demonstrated in its findings that utilizing synergies of thermal processes can be used to help overcome the limitations of traditional sun stills, which can inform the design of passive solar desalination plants. This method may significantly help to increase decentralized freshwater at off-grid or resource-constrained, water-scarce regions, which can be seen as an alternative to enhance renewable desalination technology.

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