

Performance analysis of snail shell biomaterials in solar still for clean water production: nature-inspired innovation for sustainability

Ramasamy Dhivagar^a, Subbarama Kousik Suraparaju^{b,c,d}, Farruh Atamurotov^{e,f,g}, Kalimuthu Gopi Kannan^h, Serikzhan Opakhai^{i,*} and Adil A. M. Omar^{j,k}

^a Department of Mechanical Engineering, QIS College of Engineering and Technology, Ongole 523272, India

^b Solar Energy Laboratory, Department of Mechanical Engineering, Sri Vasavi Engineering College (A), Tadepalligudem, Andhra Pradesh 534101, India

^c Centre for Research in Advanced Fluid and Process, University Malaysia Pahang Al-Sultan Abdullah, Lebuhraya Tun Razak, Gambang, Kuantan 26300, Pahang, Malaysia

^d Faculty of Mechanical & Automotive Engineering Technology, University Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

^e New Uzbekistan University, Movarounnahr street 1, Tashkent 100000, Uzbekistan

^f Institute of Theoretical Physics, National University of Uzbekistan, Tashkent 100174, Uzbekistan

^g University of Tashkent for Applied Sciences, Str. Gavhar 1, Tashkent 100149, Uzbekistan

^h Department of Mechanical Engineering, Indian Institute of Technology (ISM) Dhanbad, Dhanbad 826 004, Jharkhand, India

ⁱ Faculty of Physics and Technical Sciences, L.N. Gumilyov Eurasian National University, Astana 010000, Kazakhstan

^j Department of Mechanical Engineering, Faculty of Engineering, University of Khartoum, 45Al-Nit Avenue, P.O. Box 321, Khartoum, Sudan

^k Department of Mechanical Engineering, Faculty of Engineering, Sudan University of Science and Technology, Khartoum, Sudan

*Corresponding author. E-mail: enu@enu.kz

ABSTRACT

In this current investigation, the experimental performance of a solar still basin was significantly enhanced by incorporating snail shell biomaterials. The outcomes of the snail shell-augmented solar still basin (SSSS) are compared with those of a conventional solar still (CSS). The utilization of snail shells proved to facilitate the reduction of saline water and enhance its temperature, thereby improving the productivity of the SSSS. Cumulatively, the SSSS productivity was improved by 4.3% over CSS. Furthermore, the SSSS outperformed in energy and exergy efficiency of CSS by 4.5 and 3.5%, respectively. Economically, the cost per liter of distillate (CPL) for the CSS was 3.4% higher than SSSS. Moreover, the SSSS showed a shorter estimated payback period (PBP) of 141 days which was 6 days less than CSS. Considering the environmental impact, the observed CO₂ emissions from the SSSS were approximately 14.6% higher than CSS over its 10-year lifespan. Notably, the SSSS exhibited a substantial increase in the estimated carbon credit earned (CCE) compared to the CSS. Ultimately, the research underscores the efficacy of incorporating snail shells into solar still basins as a commendable approach to organic waste management, offering economic benefits without compromising environmental considerations.

Key words: snail shells, biomaterial, carbon credit, desalination, organic waste management, solar still

HIGHLIGHTS

- The snail shell biomaterial is used in solar still for clean water production.
- The hourly productivity of SSSS is enhanced by 6.8% than CSS.
- The energy efficiency of SSSS and CSS is about 24.1% and 23%, respectively.
- The pay back period of SSSS is 141 days, whereas it is 147 days for CSS.

INTRODUCTION

The burgeoning global concern regarding the reduction of CO₂ emissions and the finite nature of fossil fuel resources has significantly propelled the industrial sector toward the adoption of solar energy. Besides energy, the widening gap between the limited supply of freshwater resources and the rising demand for water makes water scarcity a serious threat to sustainable development. The growing world population, fast urbanization, and industry have driven up the amount of water that is needed. Water scarcity is a global phenomenon that arises from the depletion of freshwater reservoirs due to various contributing factors, including population growth, poor water management practices, and climate change (Taner 2019; Reddy *et al.* 2022). Desalination has the promise of becoming the solution to this urgent problem. To make brackish or saltwater suitable

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

for agriculture and human consumption, contaminants and salt must be removed (Ebhota & Tabakov 2023). Desalination becomes a critical tactic as traditional freshwater sources are overused and eventually run out. Furqan *et al.* (2023) stated that thermal desalination is a crucial technique among the numerous desalination technologies since it uses heat to effectively separate salt and contaminants from water. Some advantages of desalination like increased freshwater supply, diversification of water sources, independent of climate conditions, technology advancements, addressing water scarcity, support for agriculture and industry and emergency water supply.

Despite these advantages, it's important to note that desalination also has some challenges and considerations, including high-energy requirements, environmental impacts, and the potential for brine disposal issues (Suraparaju *et al.* 2021). Balancing the benefits and drawbacks is essential in implementing sustainable desalination projects. Additionally, ongoing research and development focus on addressing these challenges and making desalination more efficient and environmentally friendly. In response to these challenges, there is a burgeoning interest in integrating renewable energy sources, particularly solar energy, into the desalination process to foster sustainability. Systems for desalinating water driven by renewable energy significantly lower greenhouse gas emissions, supporting international efforts to tackle climate change (sustainable development goal, SDG). Furthermore, by promoting ecosystem resilience and biodiversity preservation, this integration lessens the total environmental impact of desalination. Additionally, the cooperative relationship between desalination and renewable energy helps to build a more sustainable infrastructure for the provision of water and sanitation, thereby achieving the overarching goal of sustainable management for all (Selfa *et al.* 2024).

In order to reduce reliance on non-renewable energy sources, solar desalination uses the power of the sun to fuel the process (Abdullah *et al.* 2023a). Diverse solar-powered reverse osmosis systems, solar-assisted multi-effect distillation, and solar stills are examples of creative ways to deal with water scarcity in a sustainable way. Solar stills are ideal for the desalination process since they are low-tech and self-sufficient, requiring no regular maintenance from a trained professional (Panchal *et al.* 2021). To increase the efficiency of solar stills, many researchers have employed materials that undergo phase changes, energy storage materials, porous media, nanoparticles, reflectors, and fins (Mohd Shatar *et al.* 2022). Figure 1 illustrates the primary benefits, constraints, and research areas of solar still.

The solar still basin uses materials that store sensible heat to achieve higher productivity. As a result, the dry cow dung was used in solar still basin as biomaterial heat storage and increased the productivity by 35% than conventional solar still (CSS) (Panchal 2015). Samuel *et al.* (2016) reported that solar thermodynamic fluid in a plastic container yielded almost 66% more water than CSS. Bhargava & Yadav (2019) observed that jute fabric, bamboo cotton, and dry cotton enhanced productivity significantly. In this, bamboo cotton resulted in around 52% higher productivity than other materials. Similarly, the jute fabric

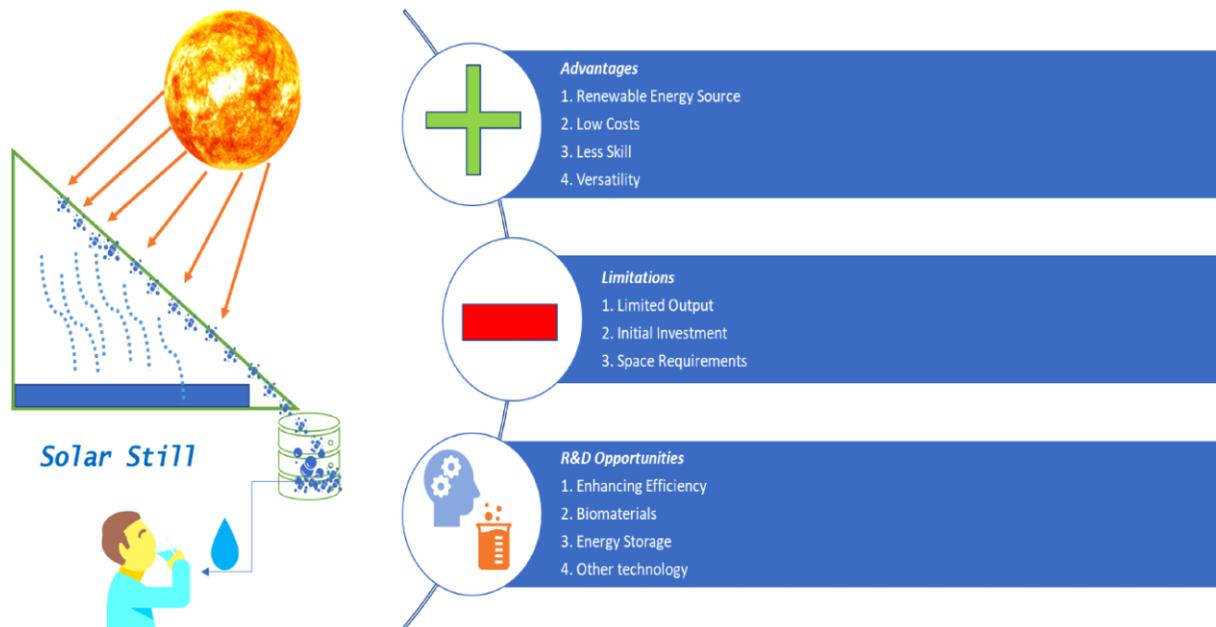


Figure 1 | Solar still and its primary benefits, constraints, and research areas of solar still.

and sand were utilized in the solar still basin and enhanced the productivity by 15% (Kabeel *et al.* 2018). In the same way, the sand-filled coal powder and cotton cylinders were incorporated in the solar still basin and achieved 31% higher productivity than CSS (Dumka *et al.* 2019). As a result, the overall system performance was greatly enhanced in cotton cylinders. In another work, the pumice stones were introduced in a solar still basin and increased the productivity by 28% than CSS (Bilal *et al.* 2019). As an external energy storage medium, the gravel coarse aggregate assisted in the solar still improved the cumulative productivity to 4.21 kg/m² (Dhivagar *et al.* 2021a).

Several researchers have found ways to enhance the energy efficiency of solar stills using various materials that store sensible heat. El-Sebaei *et al.* (2009) reported that the salts in solar still basin increased energy efficiency by 37.8%. Similarly, the estimated energy efficiency in black granite gravel-assisted solar still was around 52% greater than CSS (Sakthivel & Shanmugasundaram 2008). Results from this experiment show that granite stone considerably increased the system efficiency. The evaporation rate in V-type solar stills was significantly increased by floating charcoal in the basin (Kumar *et al.* 2008). The energy efficiency achieved in this trial was 30% higher than CSS. In addition, the heat produced at the charcoal surface accelerated the condensation. Similarly, the aluminium-coated sheets improved the energy efficiency of multi-effect solar still basin by 62% than CSS (Rahim 2003). In this experiment, the stored energy in the daytime was significantly utilized during nighttime to improve efficiency. Bilal *et al.* (2019) employed 10 kg of pumice stones in a solar still basin increasing overall energy efficiency to 28.8%.

Many researchers estimated the exergy efficiency to assess the energy losses in the solar still system. Vaithilingam *et al.* (2022) investigated the exergy efficiency of solar stills with copper fins and found a higher efficiency than CSS. Dinesh *et al.* (2022) used the solar still basin made of black granite, colored glass balls, and white ball marbles to determine the highest exergy efficiency in CSS. Kateshia & Lakhera (2022) used lauric acid and pin fins in a solar still basin and estimated the exergy efficiency to be 2.23%. Similarly, Selimefendigil *et al.* (2022) used the CuO nanoparticles as an absorber coating and discovered a maximum exergy efficiency of about 2%. Dhivagar & Mohanraj (2021) estimated the exergy efficiency of 4.4% in the solar still basin using graphite plate fins in conjunction with magnets. Balachandran *et al.* (2021) used eggshells in a solar still basin which had the maximum exergy efficiency of about 2.36%.

Many studies have analyzed the cost-effectiveness of solar still employing sensible heat storage materials. Sellami *et al.* (2016) used Portland cement in the solar still basin and estimated the CPL of about 0.00103 USD. Similarly, Kabeel *et al.* (2019) found that the usage of composite materials in the solar still basin had a CPL of about 0.0013 USD. In addition, the overall estimated CPL of CSS without energy storage material was about 0.027 USD. Samuel *et al.* (2016) applied encapsulated salt to the CSS basin and attained a CPL of 0.0094 USD. Rufuss *et al.* (2018) discovered that the CPL of solar stills that utilized phase change materials and graphite oxide was about 0.12 USD. Dhivagar *et al.* (2021b) employed magnets as heat storage devices inside the solar still basin and estimated the CPL of around 0.213–0.216 USD.

Many researchers use enviro-economic analysis to demonstrate solar stills' environmental performance. Joshi & Tiwari (2018) estimated the environmental effect of an active solar still and found that it releases about 7.14 tons of CO₂ in a year. In another study, Piyush *et al.* (2018) found that the jute and cotton fabric solar stills released 7.82 and 8.69 tons of energy-based CO₂ emissions during the experimentation. Khanmohammadi & Khanmohammadi (2019) found that paraffin wax can release exergy-based CO₂ emissions by 0.139 tons/year. Bait (2019) analyzed that the CO₂ emission in active solar stills was about 4.42 tons. Similarly, Hassan *et al.* (2020) evaluated the exergy-based CO₂ emissions as 5.9 tons/year.

Some of the recent studies in the enhancement of solar still performance are done using natural source materials. Dhivagar *et al.* (2023) used the conch shell biomaterial as an energy storage medium and porous media in a solar still conch shell solar still (CSSS) and investigated its impact on water productivity and efficiency. Experiments demonstrated a notable enhancement in performance compared to CSS. The CSSS showcased a 10.8% increase in cumulative water productivity, along with superior energy and exergy efficiency by 10.3 and 9%, respectively. Furthermore, carbon footprint reduction and CO₂ emissions mitigation were significantly improved, highlighting the potential of this innovative approach for sustainable desalination. Similarly, Ramzy *et al.* (2023) aimed to optimize solar still performance by testing different absorbing materials in arid conditions. Two solar stills were constructed and compared using materials like black luffa and steel wool pads. Results from testing in Egypt showed steel wool pads yielded the highest productivity at 4.3 kg/m² and the highest thermal efficiency at 32.74%. Moreover, steel wool pads had the lowest CPL at 0.0034 USD/kg. This study suggests steel wool pads as a promising modification for improving solar still performance in addressing water scarcity. A study by Abdullah *et al.* (2023b) explored enhanced designs for spinning wick solar stills to address freshwater scarcity. Two designs were tested: one with a wick belt in an 'LC' shape path and the other in an 'L' shape path. Wick materials, rotation direction, and

timing were varied. Jute wicks outperformed cotton. Counterclockwise rotation yielded higher productivity. The best output was with 30 min off and 5 min on, achieving 17% more yield than the other design. With additional enhancements like reflectors, fans, and nanofluids, productivity increased by 28%, yielding freshwater at CPL of 0.016 USD.

Elsawy *et al.* (2023) conducted an experimental study aimed at enhancing freshwater production efficiency and reducing costs using minimal energy. They evaluated the performance of a hemispherical solar still under various configurations, employing charcoal from guava tree wood (CHL) and carbonized corncobs (CCC) as floating agricultural waste materials. Both materials underwent physical and chemical activation to improve their photothermal properties. Tests were carried out using seawater and lake water in Kafrelsheikh, Egypt. Results showed significant improvements in thermal and exergy efficiencies, daily output, and cost-effectiveness compared to conventional distillation methods. Abdullah *et al.* (2023c) address the escalating challenge of freshwater scarcity, proposing solar distillers as viable solutions for remote locales and small households. However, conventional models suffer from low efficiency. They examined two modified designs of rotating wick distillers: one with an 'L'-shaped path (l-RWSS) and another with an 'LC' shape (LC-RWSS). The study evaluated different wick materials, rotation directions, and intervals. Results indicate that jute wicks outperformed cotton. LC-RWSS, especially with counterclockwise rotation, exhibited superior productivity, enhanced further with graphene quantum dots nanofluid, offering a promising solution to freshwater scarcity at reduced costs. In recent research by Khalili *et al.* (2023), stepped solar stills' absorber surfaces were examined with a focus on enhancing their performance. Metal fins were introduced to augment radiant energy absorption. The study varied input factors such as inlet flow rate, number, angle, height, and material of fins. Results indicated a productivity increase with higher fin numbers and a decrease with rising inlet flow rates. Notably, copper fins outperformed others, with +30° angled fins proving the most effective. The optimal configuration yielded around 171% efficiency boost compared to fins-less designs.

SIGNIFICANCE OF THE CURRENT RESEARCH

In harnessing solar energy for sustainable water production, researchers have explored various sensible heat-storing materials in solar still basins. Among these, using snail shells as a biomaterial is a novel and eco-friendly approach which contributes to the broader objectives of SDG. Solar stills with snail shells in the absorber basin are a creative adaptation of traditional solar still technology. In this setup, snail shells are utilized as a means to enhance the efficiency of the still in collecting and purifying water. Here's a more precise breakdown:

- Design:** The solar still consists of a basin-like structure that collects water. Inside this basin, snail shells are placed as absorbers. These shells absorb solar radiation during the day, heating up the water inside the basin.
- Evaporation:** As the water in the basin heats up, it begins to evaporate. The evaporated water vapor rises and condenses on a transparent cover placed over the basin. This cover allows the condensed water to trickle down to a collection point, where it is gathered as potable water.
- Role of snail shells:** The snail shells act as absorbers of solar radiation, increasing the temperature of the water in the basin. This acceleration of heating helps in enhancing the evaporation process, thereby improving the overall efficiency of the solar still.
- Sustainability:** Snail shells are abundant and renewable, making them an eco-friendly alternative to synthetic materials.
- Cost-effectiveness:** Snail shells are inexpensive or even free, reducing the overall cost of the solar still.

Challenges associated with this setup:

- Shell availability:** One challenge is ensuring an adequate supply of snail shells. Depending on the location and scale of the project, sourcing a sufficient quantity of shells may be difficult.
- Shell preparation:** Preparing snail shells for use in the absorber basin can be labor-intensive and time-consuming, especially if large quantities are needed.
- Shell durability:** Snail shells may degrade over time due to exposure to water and sunlight, potentially reducing their effectiveness as condensation surfaces.
- Maintenance:** Like any component of solar still, the snail shells require regular maintenance. They may need cleaning to prevent the buildup of dirt or algae, which could reduce their effectiveness as absorbers. Keeping the absorber basin clean and free from biofouling or mineral buildup can be more challenging with snail shells present, requiring regular maintenance.

5. **Temperature regulation:** While the shells can help in heating the water, there might be challenges in regulating the temperature within the basin. If the water gets too hot, it could lead to excessive evaporation or even damage to the still components.
6. **Design optimization:** Designing the solar still with snail shells requires careful consideration of factors such as shell placement, spacing, and orientation to maximize their effectiveness. Optimization may involve experimentation and iterative improvements. Ensuring a consistent distribution of snail shells in the absorber basin can be challenging, impacting the overall performance of the solar still.
7. **Scalability:** Scaling up the technology to meet larger water demands may pose challenges in terms of cost-effectiveness and practicality. It's essential to assess scalability issues before implementing the technology on a larger scale.

Despite these challenges, solar stills with snail shells offer a promising approach to water purification, especially in regions with abundant sunlight and limited access to clean water sources. Therefore, the study seeks to enhance the productivity of solar stills by incorporating snail shells as a sensible heat storage material. By evaluating the increase in productivity under consistent climatic conditions, a comparative analysis is conducted between SSSS and CSS. The investigation explores multiple dimensions: energy, exergy, economics, and environment. This comprehensive analysis provides a holistic understanding of the implications of utilizing snail shells in solar stills compared to CSS. The evaluation not only scrutinizes the performance of snail shells but extends its purview to assess the economic viability and environmental impact and align the research with key pillars of SDG. Furthermore, snail shells are naturally recyclable which makes them a sustainable resource and a green way to produce freshwater. This feature is in perfect harmony with the SDG, especially the ones that deal with affordable, clean energy, clean water and sanitation, and responsible consumption and production. The incorporation of snail shells as a biomaterial in solar stills improves efficiency and is in line with international efforts for a more sustainable and just future. All things considered, this research is a testimony to innovation in sustainable technology. The study conclusions add to the current discussion on substitute materials for applications in renewable energy, highlighting the significance of comprehensive strategies that take environmental responsibility and technical advancement into account.

EXPERIMENTS

The experiment was conducted in Ongole which was located 15.5° north and 80.04° east of India. This research aimed to contribute to SDG by harnessing solar energy through two distinct solar stills called SSSS and CSS, respectively. [Figure 2](#) depicts the schematic and experimental views of SSSS and CSS. Both solar stills were made of stainless steel with a consistent thickness of 2 mm and had a surface area of 0.5 m². The solar still basins were painted black to improve heat transfer and absorption by encouraging the use of renewable resources. All sides of the solar stills were wrapped in 1 cm thick thermocol to reduce heat loss and provide insulation for increasing energy efficiency. The top of the solar stills had a 3 mm thick glass cover that was angled at 15° below the latitude of the location. This design option connects with SDG by embracing new solutions for sustainable energy production. In addition, the use of silicon rubbers was to prevent the vapor from escaping into the environment and complies with SDG by increasing resource efficiency and minimizing waste.

Preparation of snail shells

Snail shells provide a novel and sustainable method for SSSS that could have an impact on SDG. Snail shells which are mainly made of calcium carbonate ([Hou et al. 2004](#)) are collected from riverbeds and carefully cleaned by hand to ensure purity. The reproducibility of the experiment is enhanced by the standardized size of the snail shells which measure roughly 3.5 cm in length and 3 cm in height, indicating a consistent technique. To comply with SDG, the snail shells are sun-dried for 2 days, not just to eliminate any remaining smells but also to bring out the ecologically beneficial component of the research. The use of dried snail shells ([Figure 3](#)) in the solar still basin is a deliberate strategy to increase heat absorption and improve efficient heat transfer.

In material analysis, the researchers employed the Scanning Electron Method (SEM), a cutting-edge technique involving a concentrated stream of high-energy electrons. This technique has revealed the crystalline structure and surface roughness of the snail shells, as seen in [Figure 3](#) at different magnification levels. The results from SEM reveal a porous surface on the snail shell which was the crucial finding that holds significant promise for SDG. A key revelation from the SEM analysis is that the porous nature of the snail shell's surface enhances its capacity to absorb solar radiation. This novel insight contributes to developing eco-friendly technologies, aligning with SDG by harnessing solar energy efficiently.

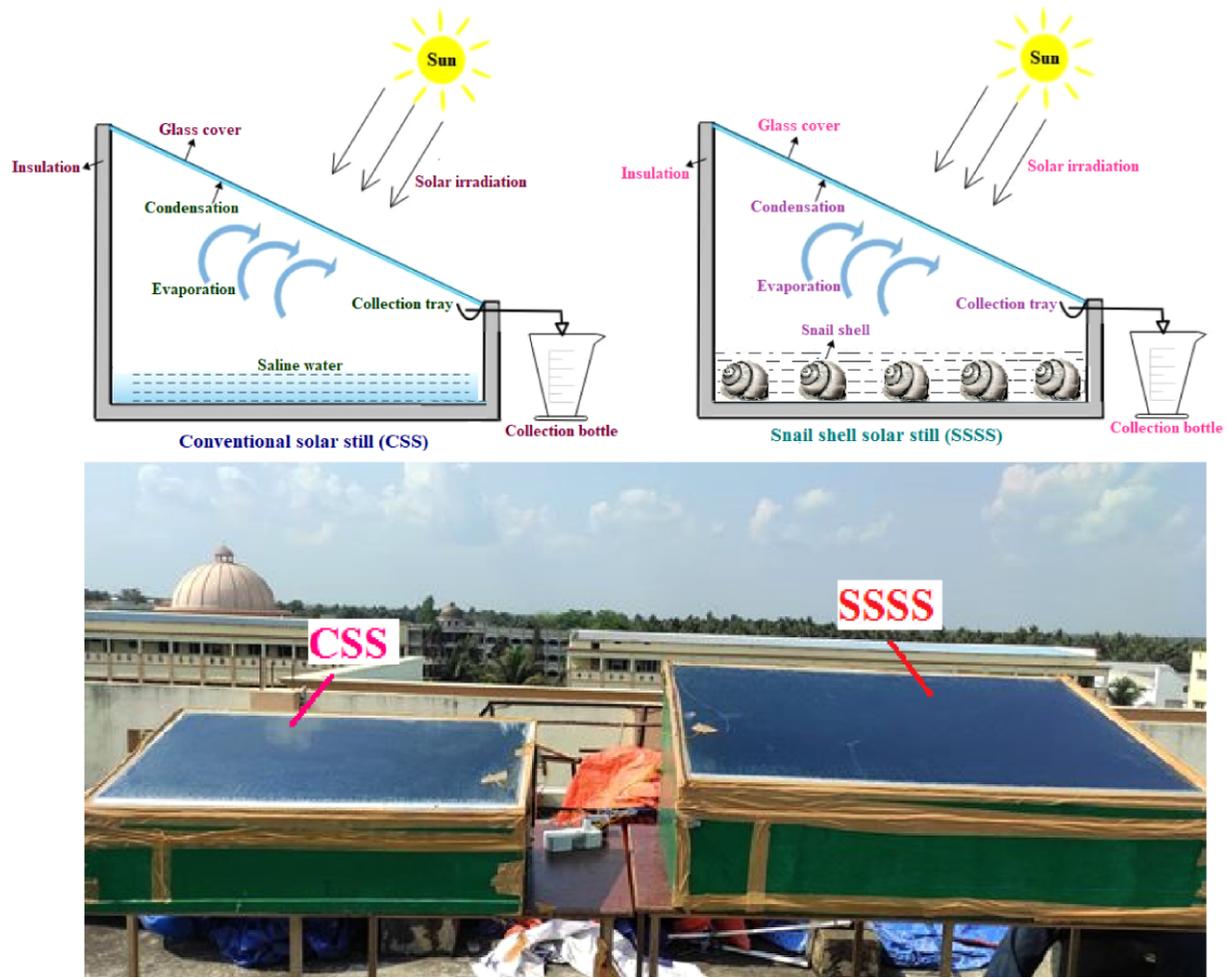


Figure 2 | Schematic and experiment view of SSSS and CSS.

The experiment included performing a porosity test on ten different weights of snail shells, each of which had a different size. To determine porosity, the dry weight of each sample was meticulously assessed using a cutting-edge digital scale. The method was used which required soaking the samples in hot water for an hour to saturation. The detailed list of properties of the snail shells used in this innovative investigation is summarized in Table 1. In basin, the saline water warms with the heat stored in snail shells and evaporates. The dissipated vapor condenses on the inside surface of the glass cover finally.

Measurements with uncertainty analysis

The experiments were conducted with 20 snail shells in the absorber basin and the temperatures such as glass cover, water, snail shell ambient temperatures and incoming solar radiation were analyzed for the water productivity in the solar still. The water productivity is measured using a measuring jar for each solar still and the productivity is measured for every 1 h. During experimentation, the K-type thermocouples are employed in solar stills to detect saline water, snail shells, glass cover, and ambient temperatures with ± 0.2 °C accuracy. A solarimeter monitors solar irradiation with a precision of ± 5 W/m². An anemometer is used to measure wind speed with an accuracy of ± 0.1 m/s. The basin water level was kept at a depth of 2 cm. Finally, the distillate was measured using a beaker with an accuracy of ± 5 mL. The average errors observed in thermocouples, solarimeter, anemometer and measuring beaker were about 2, 0.1, 0.3, and 0.2%, respectively. Experimental study considers the inaccuracy and uncertainty of measured quantities. The uncertainty δ of calculated result F, such as solar still

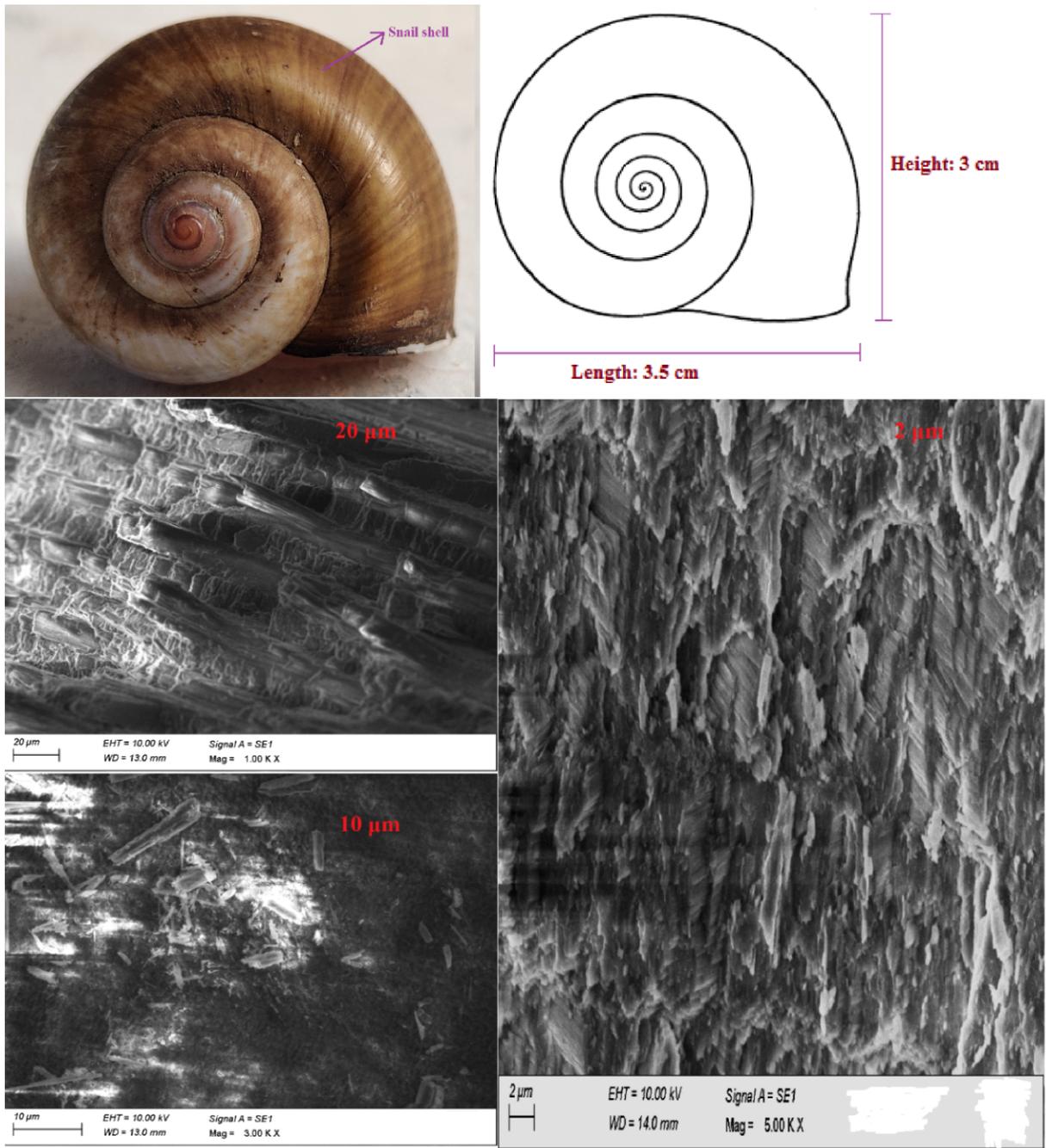


Figure 3 | Actual, schematic view with dimension and SEM image of porous structure of snail shell.

efficiencies, are computed using the following relation (Kateshia & Lakhera 2022):

$$\delta = \sqrt{\left(\frac{\partial F}{\partial x}\right)^2 \delta_x^2 + \left(\frac{\partial F}{\partial y}\right)^2 \delta_y^2} \quad (1)$$

Here, δx and δy are denote the uncertainty of x and y . As a result, the margins of error for the energy and exergy efficiency are 2.1 and 0.7%, respectively.

Table 1 | Properties of snail shells (Haoze *et al.* 2015)

| Properties | Value |
|---------------------------------------|------------------------|
| Specific heat capacity of snail shell | 0.32–0.36 kJ/kg-K |
| Density of snail shell | 2.55 g/cm ³ |
| Mass of snail shell | 18 g |
| Porosity of snail shell | 48% |
| Thermal conductivity of snail shell | 4.8 W/m ² K |

THERMODYNAMIC ANALYSIS

The study examined the energy and exergy efficiency of SSSS and CSS systems, evaluating their individual contributions to the system's overall thermodynamic performance. This comprehensive study attempted to bring out the complex details of each system's performance, taking into account both energy and exergy factors.

Energy efficiency

The relationship between the evaporation rate and the amount of net solar energy was examined in order to evaluate the efficiency of the solar still.

The latent heat of vaporization is determined as follows (Elango *et al.* 2015):

$$L = 2.4935 \times 10^6 \times [1 - 9.4779 \times 10^{-4} T_w + 1.3132 \times 10^{-7} \times T_w^2 - 4.794 \times 10^{-9} \times T_w^3] \quad (2)$$

In this case, L refers to the latent heat of water, which is measured in kilojoules per kilogram, and saline water has a temperature that is denoted in degrees Celsius and is denoted by T_w :

The energy efficiency of solar is still as follows (Elango *et al.* 2015):

$$\eta = \frac{\sum m_w \times L}{A_{ss} \times \sum I_s \times 3,600} \quad (3)$$

Here, η stands for energy efficiency (in %), m_w shows distillate mass (in kg), L stands for the latent heat of water (in kJ/kg), A_{ss} is known for (in m²) and I_s stands for solar irradiation (in W/m²).

Exergy efficiency

By applying the second law of thermodynamics to energy analysis, the exergy analysis was estimated as mentioned below. The rate of evaporation is expressed as a percentage of total solar energy gained.

The exergy efficiency of solar still (Elango *et al.* 2015):

$$\gamma = \frac{Ex_{out}}{Ex_{in}} = \frac{\sum m_w \times L \times \left(1 - \frac{T_a + 273}{T_w + 273}\right)}{3,600 \times \left[1 - \frac{4}{3} \times \left(\frac{T_a + 273}{T_s}\right) + \frac{1}{3} \times \left(\frac{T_a + 273}{T_s}\right)^4\right]} \quad (4)$$

Here, γ stands for exergy efficiency (in %), Ex_{out} is known for exergy output (in W/m²), m_w shows distillate mass (in kg), L stands for the latent heat of water (in kJ/kg), T_a and T_w are known for the temperature of the atmosphere and saline water (in K). Here, Ex_{in} stands for exergy input (in W/m²), A_{ss} is known for (in m²) and I_s stands for solar irradiation (in W/m²); T_a and T_s are known for the temperature of the atmosphere and sun (6,000 °C) in K.

Economic analysis

Solar stills efficiently produce distillate and have a quicker payback time. The relations listed below are used to examine it (Parsa *et al.* 2020):

The capital recovery factor and the initial capital cost are the two components which collectively make up the fixed annual cost. In this situation, the capital recovery factor for a solar still with a lifespan of 10 years is 12%.

$$FAC = CRF \times CC \quad (5)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (6)$$

The annual salvage value is estimated using the sinking fund factor, and 20% of the capital cost is the salvage value in this:

$$ASV = SSF \times S \quad (7)$$

$$S = 0.2 \times CC \quad (8)$$

$$SSF = \frac{i}{(1+i)^n - 1} \quad (9)$$

According to the calculations, the annual maintenance cost equals 15% of the fixed annual cost.

$$AMC = 0.15 \times FAC \quad (10)$$

$$AC = FAC + AMC - ASV \quad (11)$$

Calculations are done to determine the payback period and the cost per liter of distillate.

$$CPL = \frac{AC}{P_d} \quad (12)$$

$$PBP = \frac{\text{Investments}}{\text{Net earnings}} \quad (13)$$

The annual productivity can be considered (picked 270 days) on clear sunny days (Dhivagar *et al.* 2022).

Profit cost ratio

A method for solar still cost evaluation is known as the profit cost ratio (PCR), and it is estimated by (Shoeibi *et al.* 2021):

$$PCR = \frac{UAB}{AC} \quad (14)$$

In this case, UAB stands for cost-benefit and AC for annual cost:

$$UAB = m_w \times POW \quad (15)$$

Here, POW stands for the price of water in units of 0.1 USD/kg, while m_w is the annual productivity in kg. Therefore, the PCR needs to be higher than one for the investment to be effective.

Enviro-economic analysis

The environmental and economic analysis shows how much carbon dioxide (CO₂), a solar still emits over its lifetime and how much carbon credits it generates. Conventional power stations that burn fossil fuels release an estimated 1.58 kg/kWh of carbon dioxide, as taken in the present study (Dwivedi & Tiwari 2012):

The annual energy output is estimated by:

$$E_{\text{out}} = \frac{m_w \times L}{3,600} \quad (16)$$

Here, E_{out} stands for embodied output energy (in kWh), m_w shows distillate mass (in kg), and L represents the latent heat of water (in kJ/kg).

The CO₂ emission is evaluated by:

$$N_{CO_2} = \frac{(E_{out} \times LT - E_{in}) \times 1.58}{1,000} \quad (17)$$

Here, N_{CO_2} stands for CO₂ emission (in kg), E_{in} and E_{out} are known for the embodied input and output energies in kWh, and LT represents the lifetime of solar still (in years).

The market price and net CO₂ emission are used to calculate the carbon credit earned (CCE):

$$CCE = N_{CO_2} \times R_{CO_2} \quad (18)$$

Here, R_{CO_2} represents the cost of CO₂ emissions (in USD). Figure 4 shows the flow chart for the experimentation and evaluation analysis.

RESULTS AND DISCUSSION

This section explores the findings of the SSSS and CSS experiments under similar weather conditions which were conducted in Ongole City, India.

Experimental analysis during days of work

The research findings depicted in Figure 5 illustrate the dynamic relationship between solar irradiation, wind velocity, and temperature within the experimental framework. Notably, solar irradiation exhibited its peak intensity during the morning and afternoon hours, registering at approximately 945.2 W/m², whereas it decreased to its lowest point of 46.1 W/m² in the evening. Despite the continuous availability of solar energy over a span of 12 h, the practical utilization window remained confined to 8 to 10 h during the experiment (Dhivagar *et al.* 2024). Observations revealed a progressive escalation in wind velocity over time, correlating with a consequent decline in the temperature of the glass cover. This phenomenon notably

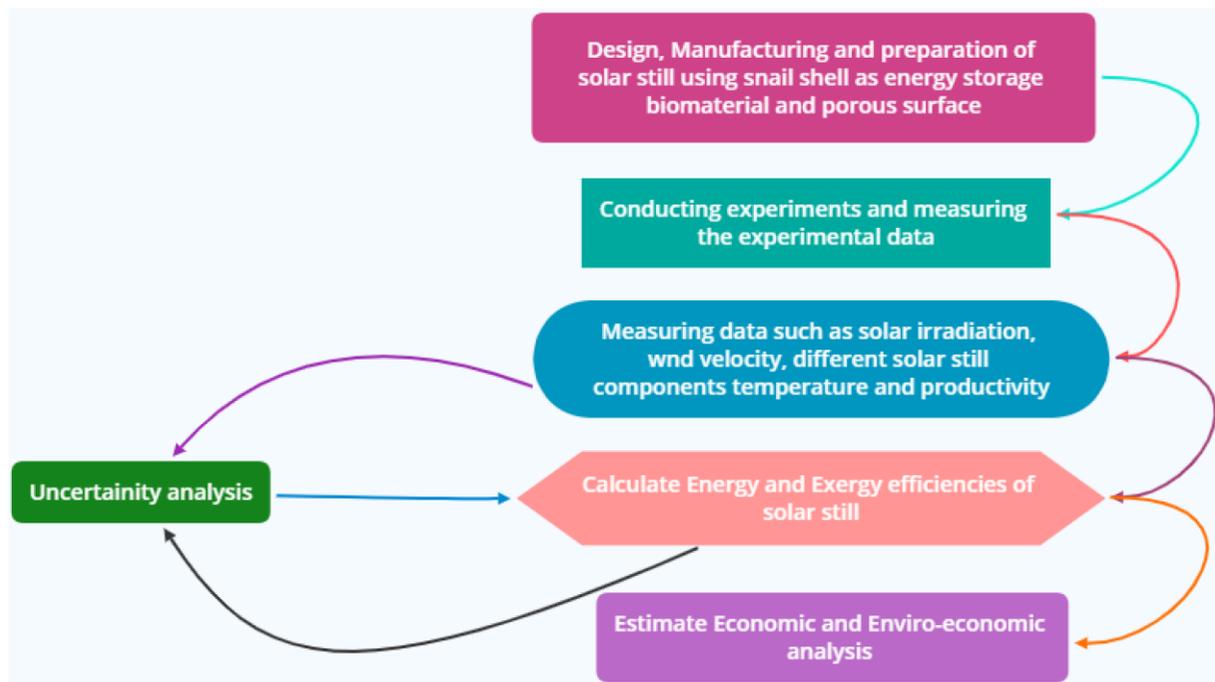


Figure 4 | Flow chart for experimentation and evaluation process.

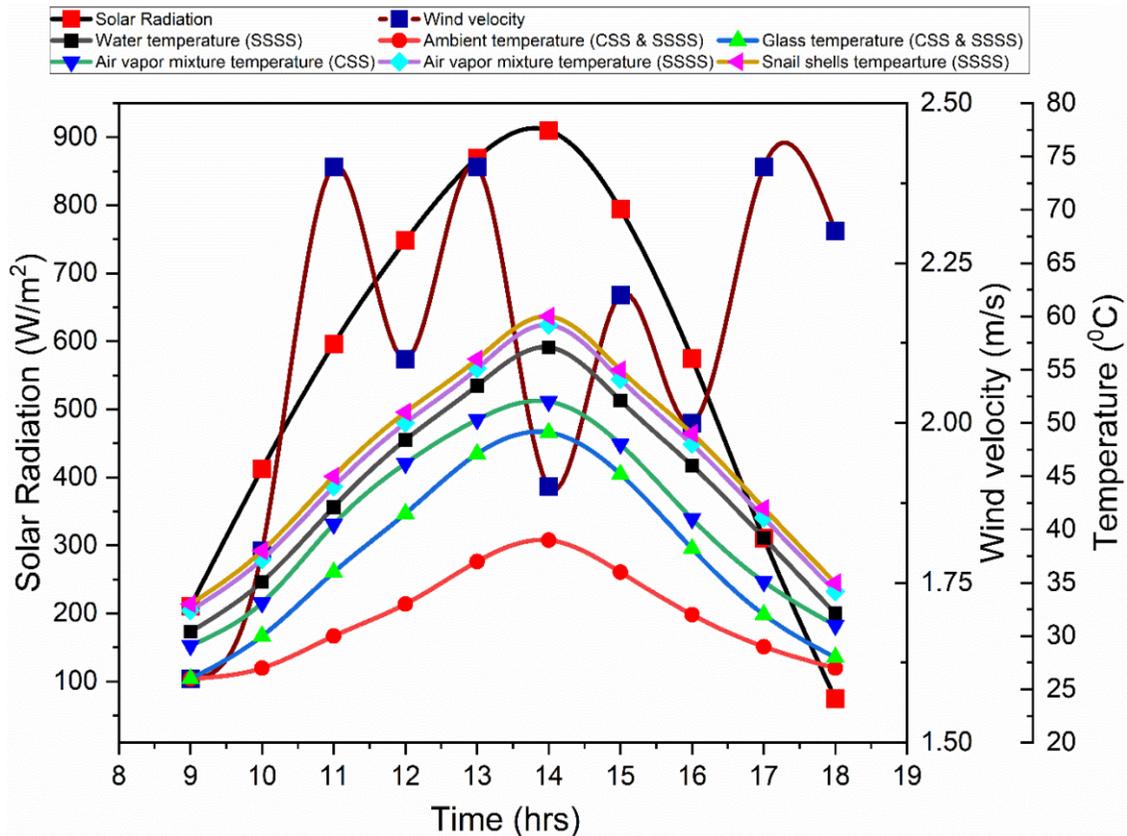


Figure 5 | Fluctuations of solar irradiation and wind velocity with temperature.

amplified condensation levels, particularly evident as wind velocity peaked at 2.3 m/s around 18:00 h, manifesting their maximum influence. An average wind velocity range of 1.4–2.4 m/s emerged as a pivotal factor significantly impacting productivity rates. Temperature dynamics exhibited distinctive patterns throughout the day, with ambient temperatures reaching their zenith of approximately 39.1 °C by 14:00 h, only to taper down to around 26 °C as solar irradiation waned toward evening. The glass cover atop the still apparatus proved most efficacious, capitalizing on intense solar irradiation to facilitate the facile evaporation of saline water. At its peak, the glass cover temperature soared to about 49.1 °C by midday before gradually receding to approximately 32 °C come evening. Similarly, the temperature of the snail shell exhibited a notable variation, peaking at 60.3 °C around 14:00 h and subsiding to 35.1 °C by 18:00 h. In CSS and snail shell solar still (SSSS) setups, the temperature differentials in the air–vapor mixture were evident, with the latter recording higher temperatures of about 52 and 59.1 °C, respectively. This temperature differential of 12.01% between SSSS and CSS underscores the accelerated evaporation facilitated by the incorporation of snail shells, thus augmenting the air–vapor temperature within the SSSS configuration. Furthermore, the highest recorded temperatures of the saline water within CSS and SSSS configurations were approximately 51.3 and 57.1 °C, respectively. Notably, the SSSS arrangement demonstrated a superior capacity for heat retention attributed to the enhanced absorption of energy under higher solar irradiation levels, resulting in a 10.1% elevation in water temperature compared to CSS. In summation, the integration of snail shells in the SSSS configuration emerges as a promising avenue for bolstering thermal efficiency and augmenting water temperatures, thus underscoring its potential for enhancing solar desalination processes.

Productivity analysis

Figure 6 depicts the hourly and cumulative productivities of two solar still designs. It is evident that both stills exhibit higher productivity levels during the midday hours (13:00–15:00) and lower productivity in the evening, reflecting the fluctuations in solar irradiation. At 14:00 h, the hourly productivity in the SSSS and CSS stands at approximately 0.44 and 0.41 kg,

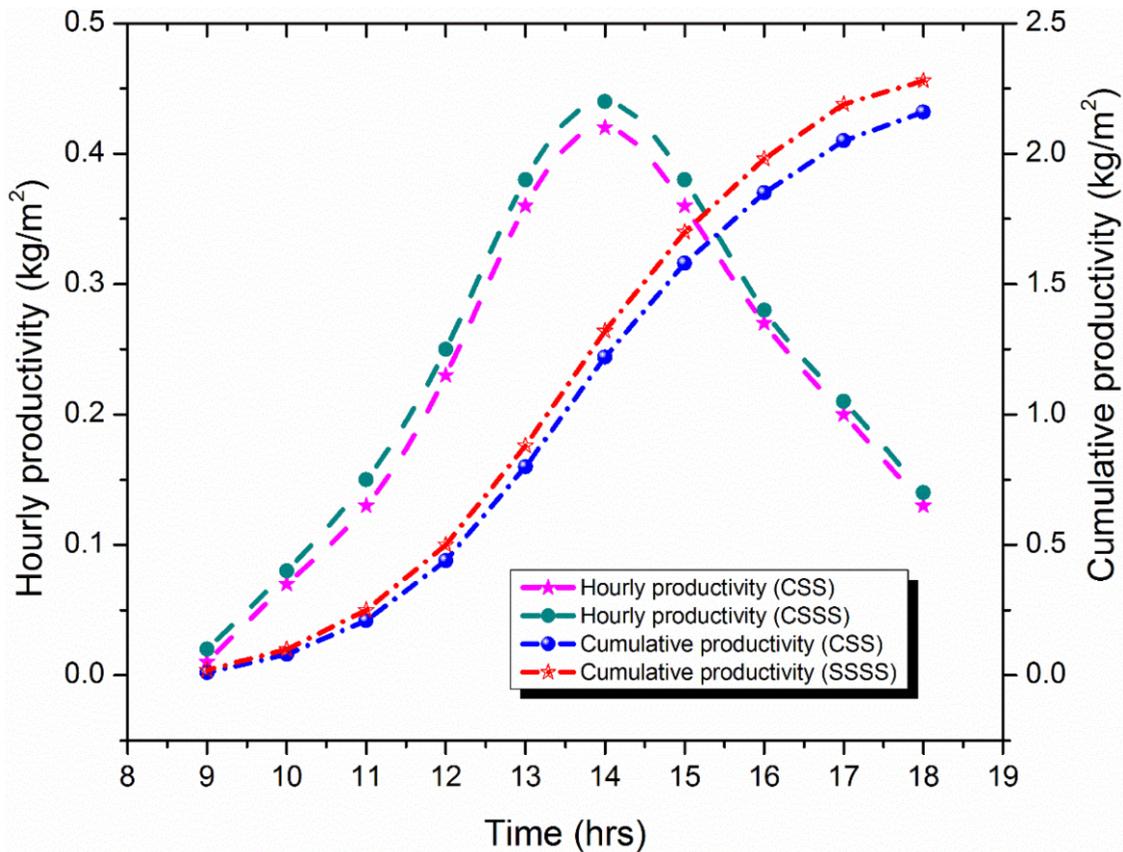


Figure 6 | Variations of hourly and cumulative productivities.

respectively, with SSSS showing a notable 6.8% increase compared to CSS. This enhancement in productivity can be attributed to the utilization of snail shells, which effectively store sensible heat and facilitate rapid heat transfer within the SSSS basin due to their porous structure. The cumulative productivity observed in SSSS and CSS is around 2.28 and 2.18 kg/m², respectively, with SSSS exhibiting around 4.3% higher cumulative productivity than CSS. This difference underscores the advantageous impact of incorporating biomaterials like snail shells into solar still designs. Such innovative approaches not only enhance productivity but also contribute to SDGs. Moreover, the comparative analysis presented in Table 2 offers a comprehensive evaluation of the overall productivity of the solar stills, shedding light on the influence of various energy storage techniques and biomaterial choices. This research highlights the potential of biomaterial integration in solar technology to improve efficiency and sustainability.

Thermodynamic performance

Energy efficiency is an essential factor in accomplishing the SDG. The thermal performance of snail shells which capture solar irradiation and transform it into perceived heat is a major factor in this regard. As part of the effort to save energy,

Table 2 | Comparison of productivity of various energy storage and biomaterials used in solar still by various researchers

| Authors Name | Materials used for energy storage | Productivity improvement (kg/m ²) |
|-----------------------------------|-----------------------------------|---|
| Faegh & Shafii (2017) | Square sponge | 2.6 |
| Mousa & Gujarathi (2016) | Paraffin | 2.1 |
| Balachandran <i>et al.</i> (2021) | Egg shells | 2.46 |
| Dhivagar <i>et al.</i> (2023) | Conch shells | 2.35 |
| Present study | Snail shells | 2.28 |

Mohanraj *et al.* (2021) emphasize the importance of solar irradiation and the way it affects energy and energy waste. Figure 7 illustrates the fluctuations in energy and exergy efficiencies, offering valuable insights into the performance of SSSS and CSS. At 14:00 h, SSSS demonstrated an impressive energy efficiency of approximately 24.1%, marking a notable 4.5% improvement over CSS, which had an estimated energy efficiency of 23%. This disparity favoring SSSS signifies a significant advancement in solar energy harnessing, aligning well with Sustainable Development Goals (SDGs). Delving deeper into exergy efficiency, both systems exhibit distinct performances at the same hour. SSSS boasts an exergy efficiency of 2.8%, while CSS trails slightly behind at 2.7%. This meticulous examination highlights SSSS's superior exergy efficiency, showcasing around a 3.5% advantage over CSS. In summary, the findings underscore the promising potential of SSSS in enhancing both energy and exergy efficiencies compared to conventional CSS, thereby contributing positively toward sustainable energy utilization and the broader SDG agenda.

Influence of snail shells on the performance of solar stills

The integration of snail shells into the basin of solar still markedly increased the production of clean water in the SSSS compared to the CSS. The primary factor contributing to this enhancement is the increased basin water temperatures and the expanded wet surface area, attributable to the inherent porosity of the snail shells. These shells, when included in the absorber basin, significantly improved the absorption of solar radiation, thereby elevating the overall system temperatures. The porous nature of the snail shells and their capacity for water absorption increased the wet surface area within the basin, which in turn enhanced the evaporation rate. Additionally, the heat-retaining properties of the snail shells contributed to higher water and absorber temperatures in the SSSS. The empirical data clearly indicate that the temperatures of both the water and the absorber in the SSSS were significantly higher than those in the CSS. This increase in basin water temperature in the SSSS facilitated a greater evaporation rate within the absorber basin, thereby resulting in higher water productivity. Consequently, the improved system temperatures and the increased wet surface area in the absorber basin of the SSSS led to a substantial

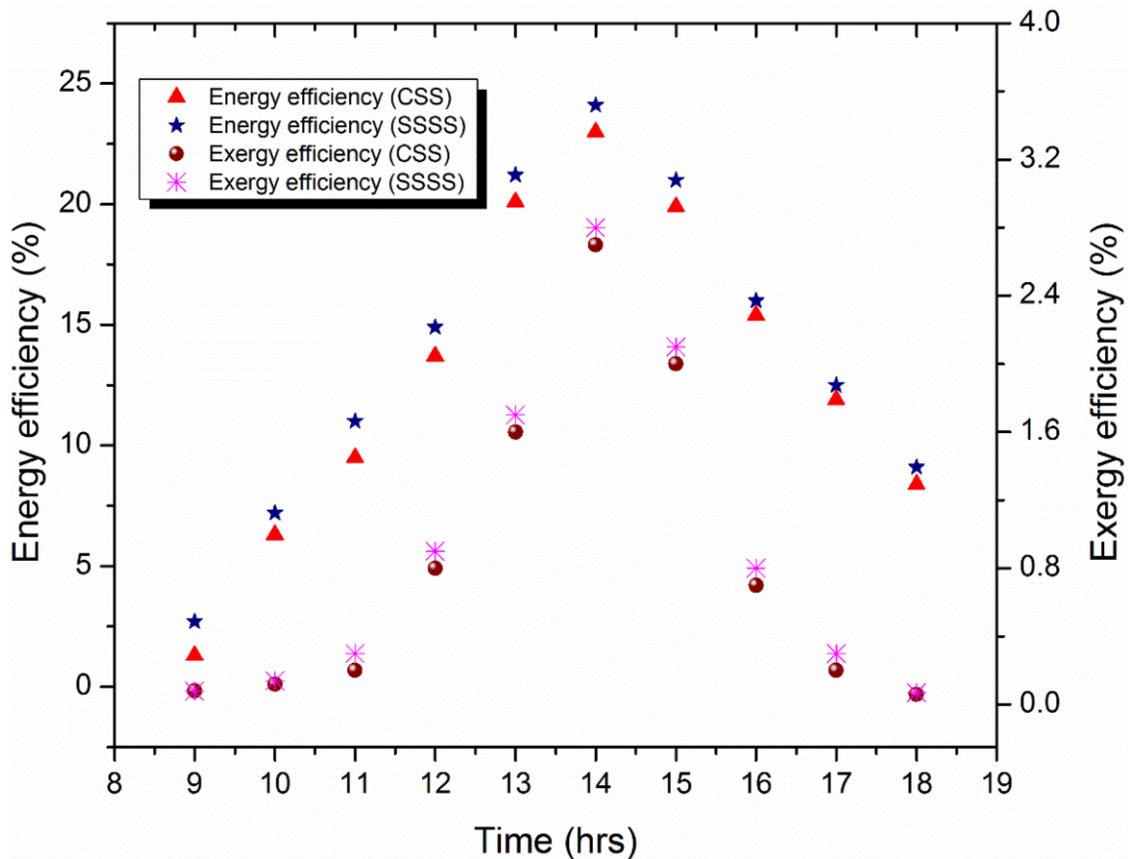


Figure 7 | Variations of energy efficiency and exergy efficiencies.

improvement in productivity when compared to the CSS. In conclusion, the strategic inclusion of snail shells in the absorber basin not only augmented the absorption of solar radiation but also enhanced the heat storage and water evaporation processes. These modifications significantly boosted the performance and productivity of the SSSS relative to the CSS, underscoring the effectiveness of this innovative approach.

Economic results

The economic viability of sustainable alternatives is demonstrated by the results reported in Table 3 which compares the financial metrics of SSSS and CSS. Notably, the capital costs of SSSS and CSS are considered similar because snail shells are free and widely available. Within this framework, Table 3 provides a detailed perspective which demonstrates that SSSS has a small cost-effectiveness advantage over CSS. When it comes to productivity, the CPL stands out as a key statistic. According to the estimates in Table 3, SSSS has a CPL of around 0.028 USD, while CSS has a little higher CPL of 0.029 USD. This leads to a 3.4% cost advantage for SSSS against CSS which suggests the economic usage of snail shells. These findings are significant in the context of environmental sustainability when the scope is expanded to include the SDG. This study is supplemented by a visual representation in Figure 8 which depicts the PBP for SSSS and CSS. The PBP for SSSS was roughly 141 days whereas CSS was somewhat behind at approximately 147 days. The disparity strengthens SSSS economic efficiency, as a shorter PBP means faster returns on investment.

Table 3 | The economic analysis of SSSS and CSS

| Parameters | CC | AMC | AC | P_d | CPL | PBP |
|------------|-----------|----------|-----------|----------|-----------|----------|
| SSSS | 90.33 USD | 2.39 USD | 17.36 USD | 615.6 kg | 0.028 USD | 141 days |
| CSS | 90.33 USD | 2.39 USD | 17.36 USD | 588.6 kg | 0.029 USD | 147 days |

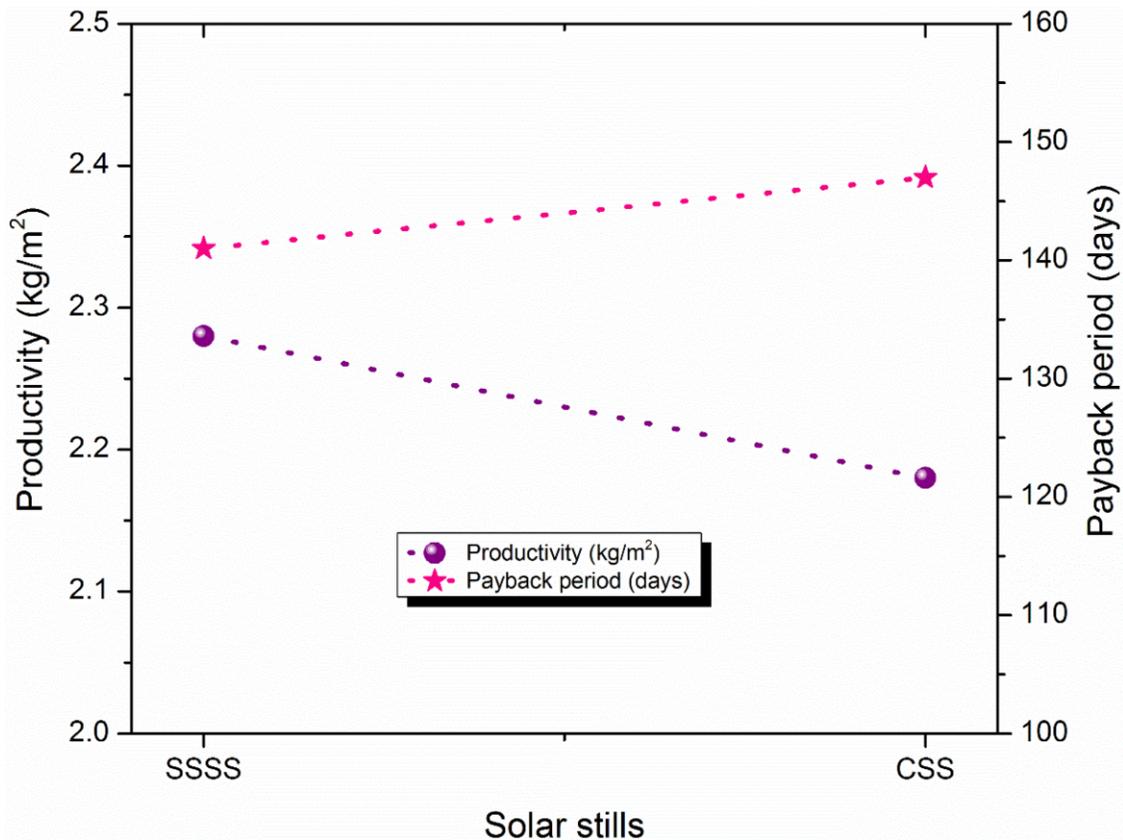


Figure 8 | Variations of PBP with solar still productivity.

Table 4 shows the PCR for SSSS and CSS which provides perspective into their financial estimation. A detailed examination reveals a significant difference in SSSS which is 5.7% higher than CSS. These financial measurements take on added significance in the context of the SDG. In Figure 9, the PCR greater than one indicates that the entities earn more revenues than their associated costs which provides the foundation for long-term operations.

Enviro-economic results

The investigation of the embodied energy in various components of solar stills was highlighted as an important feature of SDG (Rahul *et al.* 2023). Snail shells are the natural biomaterial which contributes the ecological benefit to SSSS. Here, SSSS and CSS had a total embodied energy of 239 kWh. By supporting renewable resources and limiting the ecological influence, conforms with sustainability ideals and addresses the SDG. When the carbon dioxide (CO₂) emissions from SSSS and CSS are examined over a decade, it is clear that such systems play a critical role. According to the estimates, the SSSS and CSS will generate around 7.5 and 6.4 tons of CO₂, respectively, during their lifetime of 10 years. With SSSS producing 14.6% more CO₂ than CSS, the noticeable difference raises concerns about optimizing the design and manufacturing processes of solar still components to reduce environmental effects. This reduction in CO₂ emissions is essential for attaining SDG and highlights the importance of implementing sustainable technologies. Furthermore, the predicted CCE for SSSS and CSS are around USD 180 and USD 153.6, respectively (as shown in Table 5) and provide an actual economic perspective on the environmental impact. This economic value emphasizes the significance of sustainable activities which matches with

Table 4 | Profit cost ratio of SSSS and CSS

| Solar stills | <i>n</i> | <i>i</i> (%) | AC (USD) | POW (USD) | <i>m_w</i> (kg/year) | UAB (USD) | PCR |
|--------------|----------|--------------|----------|-----------|--------------------------------|-----------|-----|
| SSSS | 10 | 12 | 17.36 | 0.1 | 615.6 | 61.5 | 3.5 |
| CSS | 10 | 12 | 17.36 | 0.1 | 588.6 | 58.8 | 3.3 |

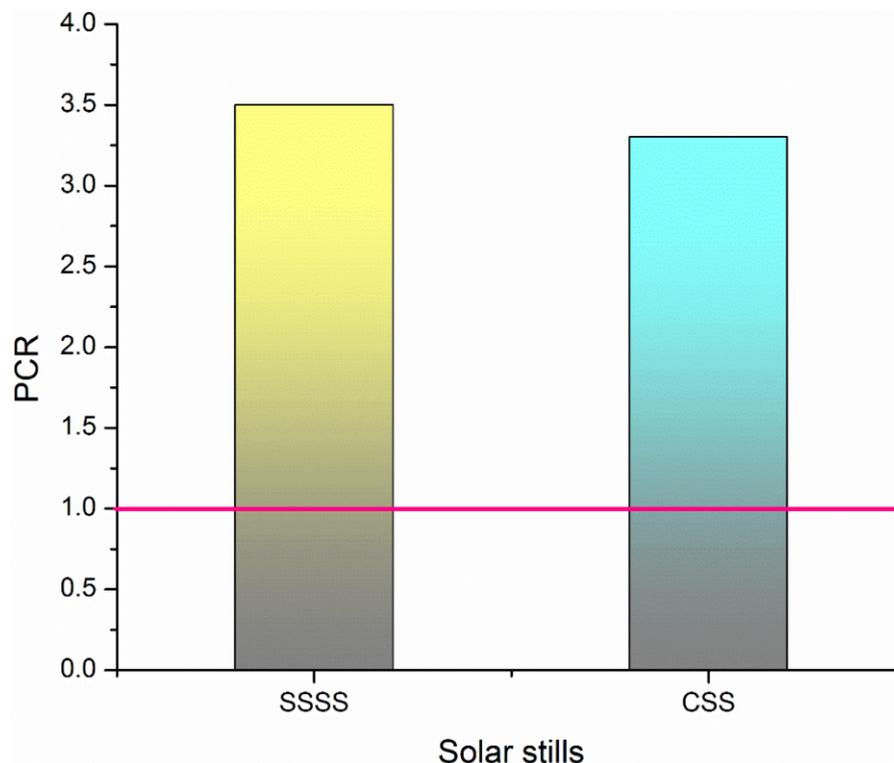
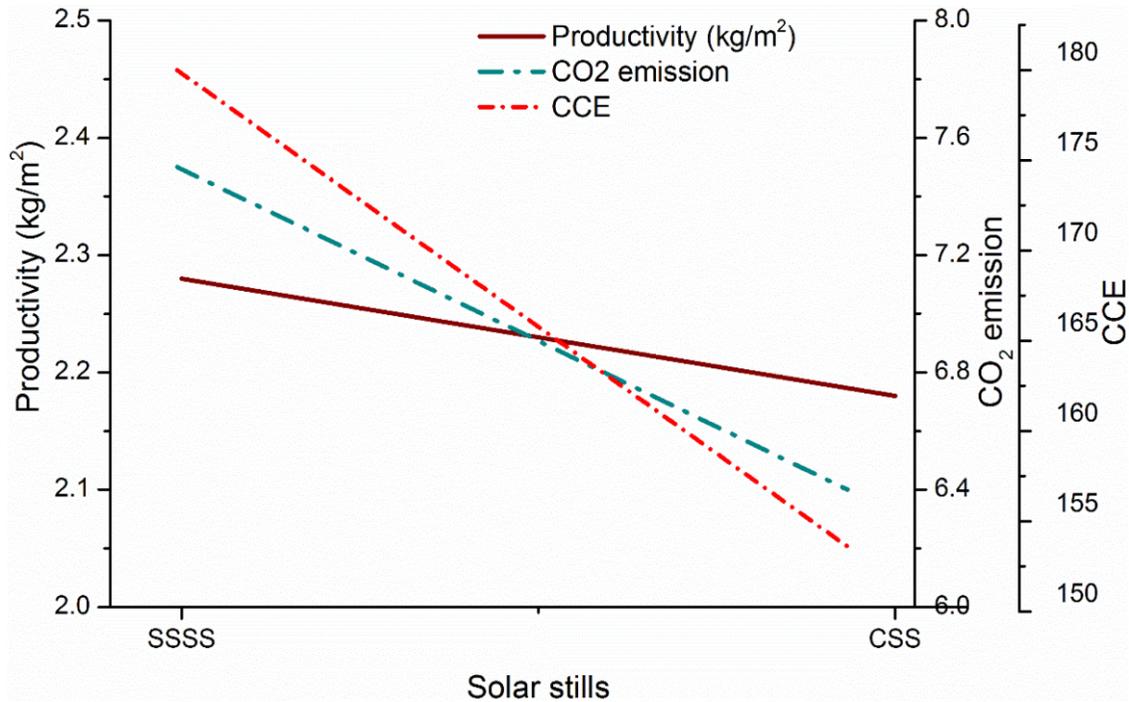


Figure 9 | Variations of PCR with solar still productivity.

Table 5 | Variations of CO₂ emission in SSSS and CSS

| Solar stills | Productivity (kg) | E_{in} (kWh) | E_{out} (kWh) | CO ₂ emission (tons) | CCE (USD) |
|--------------|-------------------|----------------|-----------------|---------------------------------|-----------|
| SSSS | 615.6 | 239 | 504.3 | 7.5 | 180 |
| CSS | 588.6 | 239 | 429.4 | 6.4 | 153.6 |

**Figure 10** | Variations of productivity with CO₂ emissions and CCE.

SDG (Shoeibi *et al.* 2022). As illustrated in Figure 10, the findings demonstrate a clear correlation: heightened productivity corresponds with elevated levels of both carbon dioxide (CO₂) emissions and cumulative carbon emissions (CCE) throughout the lifespan of the study. This suggests a direct relationship between increased output and environmental impact, indicating that as productivity rises, so too does the ecological footprint in terms of greenhouse gas emissions.

It is observed that the outcomes from the snail shell based solar still are significant and are in line with the previous studies such as solar still with sand troughs (Nagaraju *et al.* 2022), PCMs (Sahu *et al.* 2023; Suraparaju & Natarajan 2023; Suraparaju *et al.* 2024a), photothermal absorbers similar to snail shells and natural fibers (Suraparaju *et al.* 2024b). Therefore, the current small scale prototype SSSS can be scaled up for industrial use and sustainable drinking water uses in rural and coastal areas.

CONCLUSIONS

In this comprehensive study, the performance of SSSS and CSS were analyzed under the same climatic conditions. The SSSS proved to be a more effective system which slightly increased the productivity due to the use of snail shells inside the basin to absorb and store sensible heat.

- The SSSS hourly productivity increased by 6.8% when compared to CSS. Although both systems produced around the same cumulative productivity averaging 2.28 kg/m² for SSSS and 2.18 kg/m² for CSS, the hourly increases highlighted the better performance in SSSS.

- Energy efficiency is an important metric and is preferred the SSSS with a rate of 24.1% which was slightly higher than the CSS with a rate of 23%. Additionally, the system's capacity to generate work was measured as exergy efficiency and showed a little but significant lead in SSSS at 2.8% and in CSS at 2.7%.
- The CPL for the SSSS and CSS were estimated to be around 0.028 USD and 0.029 USD, respectively. Moreover, the PBP of the CSS and SSSS were calculated to be around 147 days and 141 days, respectively, which demonstrates the system's economic feasibility and the SSSS had a slightly faster return on investment.
- The environmental impact and emissions of both systems were evaluated. The estimated CO₂ emissions from the SSSS and CSS during a 10-year period were 7.5 and 6.4 tons, respectively. Simultaneously, the CCE of both SSSS and CSS have resulted in around 180 USD and 153.6 USD, respectively, which demonstrates the financial impact of carbon mitigation initiatives.

The research results indicate that the SSSS is a feasible and environmentally conscious replacement for CSS, which is particularly relevant to SDG. To sum up, the SSSS demonstrates its effectiveness in raising output and reducing energy consumption. It is a concrete step in the direction of sustainable development, combining social effect, environmental responsibility, and economic viability in a harmonious way.

FUNDING

There is no funding support for this research work.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

- Abdullah, A. S., Hitesh, P., Wissam, H. A. & Omara, Z. M. 2023a [Methods used to improve solar still performance with generated turbulence for water desalination- detailed review](#). *Results in Engineering* **19**, 101251.
- Abdullah, A. S., Hadj-Taieb, L., Aljaghtham, M., Omara, Z. M. & Essa, F. A. 2023b [Enhancing rotating wick solar still performance with various porous breathable belt designs and nanofluid](#). *Case Studies in Thermal Engineering* **49**, 103205.
- Abdullah, A. S., Alqsair, U., Aljaghtham, M. S., Kabeel, A. E., Omara, Z. M. & Essa, F. A. 2023c [Productivity augmentation of rotating wick solar still using different designs of porous breathable belt and quantum dots nanofluid](#). *Ain Shams Engineering Journal* **14**, 102248.
- Bait, O. 2019 [Exergy, environ-economic and economic analyses of tubular solar water heater assisted solar still](#). *Journal of Cleaner Production* **212**, 630–646.
- Balachandran, G. B., David, P. W. & Rajendran, G. 2021 [Investigation of performance enhancement of solar still incorporated with Gallus gallus domesticus cascara as sensible heat storage material](#). *Environmental Science and Pollution Research* **28**, 611–624.
- Bhargava, M. & Yadav, A. 2019 [Experimental investigation of single slope solar still using different wick materials: A comparative study](#). *Journal of Physics: Conference Series* **1276**, 012042.
- Bilal, A., Jamil, B., Haque, N. U. & Ansari, M. A. 2019 [Investigating the effect of pumice stones sensible heat storage on the performance of a solar still](#). *Groundwater for Sustainable Development* **9**, 100228.
- Dhivagar, R. & Mohanraj, M. 2021 [Performance improvements of single slope solar still using graphite plate fins and magnets](#). *Environmental Science and Pollution Research* **28**, 20499–20516.
- Dhivagar, R., Mohanraj, M., Hidouri, K. & Belyayev, Y. 2021a [Energy, exergy, economic and enviro-economic \(4E\) analysis of gravel coarse aggregate sensible heat storage-assisted single-slope solar still](#). *Journal of Thermal Analysis and Calorimetry* **145**, 475–494.
- Dhivagar, R., Mohanraj, M., Deepanraj, B. & Murugan, V. S. 2021b [Assessment of single slope solar still using block and disc magnets via productivity, economic, and enviro-economic perspectives: A comparative study](#). *Environmental Science and Pollution Research* **29**, 50951–50959.
- Dhivagar, R., Shoeibi, S., Kargarsharifabad, H., Ahmadi, M. H. & Sharifpur, M. 2022 [Performance enhancement of a solar still using magnetic powder as an energy storage medium-exergy and environmental analysis](#). *Energy Science and Engineering* **10**, 3154–3166.
- Dhivagar, R., Shoeibi, S., Parsa, S. M., Hoseinzadeh, S., Kargarsharifabad, H. & Khiadani, M. 2023 [Performance evaluation of solar still using energy storage biomaterial with porous surface: An experimental study and environmental analysis](#). *Renewable Energy* **206**, 879–889.
- Dhivagar, R., Shoeibi, S., Kargarsharifabad, H., Sadi, M., Arabkoohsar, A. & Khiadani, M. 2024 [Performance analysis of solar desalination using crushed granite stone as an energy storage material and the integration of solar district heating](#). *Energy Sources, Part A* **46**, 1370–1388.

- Dinesh, M., Panchal, H., Ahmadein, M., Zayed, M. E., Alsaleh, N. A., Djuansjah, J., Moustafa, E. B., Elsheikh, A. H. & Kishor Kumar, S. 2022 Investigation and performance analysis of solar still with energy storage materials: An energy- exergy efficiency analysis. *Case Studies in Thermal Engineering* **29**, 101687.
- Dumka, P., Sharma, A., Kushwah, Y., Raghav, A. S. & Mishra, D. R. 2019 Performance evaluation of single slope solar still augmented with sand-filled cotton bags. *Journal of Energy Storage* **25**, 100888.
- Dwivedi, V. K. & Tiwari, G. N. 2012 Thermal modeling and carbon credit earned of a double slope passive solar still. *Desalination and Water Treatment* **13**, 400–410.
- Ebhota, W. S. & Tabakov, P. 2023 Facilitating photovoltaic cells performance improvement through the deployment of engineered organic nanomaterials. *Renewable Energy Research and Applications*. In press.
- Elango, C., Gunasekaran, N. & Sampathkumar, K. 2015 Thermal models of solar still – A comprehensive review. *Renewable and Sustainable Energy Reviews* **47**, 856–911.
- Elsawy, I. M., Hamoda, A., Sharshir, S. W. & Khalil, A. 2023 Experimental study on optimized using activated agricultural wastes at hemispherical solar still for different types of water. *Process Safety and Environmental Protection* **177**, 246–257.
- El-Sebaï, A. A., Yaghmour, S. J., Al-Hazmi, F. S., Faidah, A. S., Al-Marzouki, F. M. & Al-Ghamdi, A. A. 2009 Active single basin solar still with a sensible storage medium. *Desalination* **249**, 699–706.
- Faegh, M. & Shafii, M. B. 2017 Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes. *Desalination* **409**, 128–135.
- Furqan, J., Faisal, H., Shahin, S. & Mehdi, K. 2023 Application of advanced energy storage materials in direct solar desalination: A state of art review. *Renewable and Sustainable Energy Reviews* **186**, 113663.
- Haoze, L., Dalai, J., Rui, L. & Xiaodong, L. 2015 Structural and mechanical characterization of thermally treated snail shells. *Journal of the Minerals, Metals & Materials Society* **67**, 720–725.
- Hassan, H., Yousef, M. S., Fathy, M. & Salem Ahmed, M. 2020 Assessment of parabolic trough solar collector assisted solar still at various saline water mediums via energy, exergy, exergoeconomic, and enviroeconomic approaches. *Renewable Energy* **155**, 604–616.
- Hou, D. F., Zhou, G. S. & Zheng, M. 2004 Snail shell structure and its effect on mechanical behaviors. *Biomaterials* **25**, 751–756.
- Joshi, P. & Tiwari, G. N. 2018 Energy matrices, exergo-economic and enviro-economic analysis of an active single slope solar still integrated with a heat exchanger: A comparative study. *Desalination* **443**, 85–98.
- Kabeel, A. E., El-Agouz, S. A., Sathyamurthy, R. & Arunkumar, T. 2018 Augmenting the productivity of solar still using jute cloth knitted with sand heat energy storage. *Desalination* **443**, 122–129.
- Kabeel, A. E., Abdelaziz, G. B. & El-said, E. M. S. 2019 Experimental investigation of a solar still with composite material heat storage: Energy, exergy and economic analysis. *Journal of Cleaner Production* **231**, 21–34.
- Kateshia, J. & Lakhera, V. 2022 A comparative study of various fatty acids as phase change material to enhance the freshwater productivity of solar still. *Journal of Energy Storage* **48**, 103947.
- Khalili, M., Taheri, M. & Nourali, A. 2023 Metal fins efficacy on stepped solar still performance: An experimental study. *Desalination* **563**, 116706.
- Khanmohammadi, S. & Khanmohammadi, S. 2019 Energy, exergy and exergo-environment analyses, and tri-objective optimization of a solar still desalination with different insulations. *Energy* **187**, 115988.
- Kumar, B. S., Kumar, S. & Jayaprakash, R. 2008 Performance analysis of a 'V' type solar still using a charcoal absorber and a boosting mirror. *Desalination* **229**, 217–230.
- Mohanraj, M., Karthick, L. & Dhivagar, R. 2021 Performance and economic analysis of a heat pump water heater assisted regenerative solar still using latent heat storage. *Applied Thermal Engineering* **196**, 117263.
- Mohd Shatar, N., Mohd Faiz, M. S., Mohd Hanafi, A. & Mohd Faizul, M. S. 2022 Mix wettability surface on solar still cover for freshwater productivity enhancement. *Desalination* **534**, 115797.
- Mousa, H. & Gujarathi, A. M. 2016 Modeling and analysis the productivity of solar desalination units with phase change materials. *Renewable Energy* **95**, 225–233.
- Nagaraju, V., Murali, G., Bewoor, A. K., Kumar, R., Sharifpur, M., Assad, M. E. H. & Awad, M. M. 2022 Experimental study on performance of single slope solar still integrated with sand troughs. *Sustainable Energy Technologies and Assessments* **50**, 101884.
- Panchal, H. 2015 Performance analysis of solar still with cow dung cakes and blue metal stones. *Frontiers in Energy* **9**, 180–186.
- Panchal, H., Kishore Kumar, S., Alim Al Ayub, A., Hishan, S. S., Mohammad Hossein, D., Fadl Abdelmonem, E., Shanmugan, S. & Mohammad, K. 2021 Graphite powder mixed with black paint on the absorber plate of the solar still to enhance yield: An experimental investigation. *Desalination* **520**, 115349.
- Parsa, S. M., Rahbar, A., Davoud Javadi, Y., Koleini, M. H., Afrand, M. & Amidpour, M. 2020 Energy-matrices, exergy, economic, environmental, exergoeconomic, enviroeconomic and heat transfer (6E/HT) analysis of two passive/active solar still water desalination nearly 4000m: Altitude concept. *Journal of Cleaner Production* **261**, 121243.
- Piyush, P., Rahul, D., Dhananjay, S. & Amimul, A. 2018 Energy matrices, exergoeconomic and enviroeconomic analysis of modified multi-wick basin type double slope solar still. *Desalination* **447**, 55–73.
- Rahim, N. H. A. 2003 New method to store heat energy in horizontal solar desalination still. *Renewable Energy* **28**, 419–433.
- Rahul, P., Ramanathan, S., Dhivagar, R., Karthi, P. & Manivel, M. 2023 A review on solar desalination techniques using vacuum technology. *Proceedings of the Institution of Mechanical Engineers, Part C* **237**, 3086–3102.

- Ramzy, K., Abdelgaleel, M., Kabeel, A. E. & Mosalam, H. 2023 Performance of a single slope solar still using different porous absorbing materials: An experimental approach. *Environmental Science and Pollution Research* **30**, 72398–72414.
- Reddy, J., Jagadish, Negi, S., Das, B., Ali Ehyaei, M. & Assad, M. E. H. 2022 Energy and exergy analysis of a trapezoidal absorber plate-based solar air collector. *Energy Science & Engineering* **10**, 1067–1082.
- Rufuss, D. D. W., Suganthi, L., Iniyar, S. & Davies, P. A. 2018 Effects of nanoparticle-enhanced phase change material (NPCM) on solar still productivity. *Journal of Cleaner Production* **192**, 9–29.
- Sahu, S. K., Natarajan, S. K., K, A. S. & Suraparaju, S. K. 2023 Experimental investigation of a solar still combined with phase change material (RT58) in southern India climatic conditions. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **237**, 2635–2646.
- Sakthivel, M. & Shanmugasundaram, S. 2008 Effect of energy storage medium (black granite gravel) on the performance of a solar still. *International Journal of Energy Research* **32**, 68–82.
- Samuel, D. G. H., Nagarajan, P. K., Sathyamurthy, R., El-agouz, S. A. & Kannan, E. 2016 Improving the yield of fresh water in conventional solar still using low cost energy storage material. *Energy Conversion and Management* **112**, 125–134.
- Selfa, J. Z., Nanchen, N. C., Peter, M. K. & Pahalsan, C. D. 2024 Energy management for a random outage grid-tied hybrid photo-voltaic solar-thermal energy system for health center applications. *Renewable Energy Research and Applications* **5**, 131–145.
- Selimefendigil, F., Sirin, C. & Oztop, H. F. 2022 Experimental analysis of combined utilization of CuO nanoparticles in latent heat storage unit and absorber coating in a single-slope solar desalination system. *Solar Energy* **233**, 278–286.
- Sellami, M. H., Touahir, R., Guemari, S. & Loudiyi, K. 2016 Use of Portland cement as heat storage medium in solar desalination. *Desalination* **398**, 180–188.
- Shoeibi, S., Rahbar, N., Esfahlani, A. A. & Kargarsharifabad, H. 2021 A comprehensive review of enviro-exergo-economic analysis of solar stills. *Renewable and Sustainable Energy Reviews* **149**, 111404.
- Shoeibi, S., Mirjalily, S. S. A., Kargarsharifabad, H., Panchal, H. & Dhivagar, R. 2022 Comparative study of double-slope solar still, hemispherical solar still, and tubular solar still using Al₂O₃/water film cooling: A numerical study and CO₂ mitigation analysis. *Environmental Science and Pollution Research* **29**, 65353–65359.
- Suraparaju, S. K. & Natarajan, S. K. 2023 Development of thermal energy storage material from blends of Jatropha biodiesel and paraffin wax for augmenting freshwater generation capacity in a solar desalination system. *Journal of Energy Resources Technology* **145**, 121401.
- Suraparaju, S. K., Ragupathy, D. & Sendhil Kumar, N. 2021 Performance evaluation of single slope solar still with novel pond fibres. *Process Safety and Environmental Protection* **154**, 142–154.
- Suraparaju, S. K., Samykano, M., Dhivagar, R., Natarajan, S. K. & Ghazali, M. F. 2024a Synergizing environmental and technological advances: Discarded transmission oil and paraffin wax as a phase change material for energy storage in solar distillation as a step towards sustainability. *Journal of Energy Storage* **85**, 111046.
- Suraparaju, S. K., Samykano, M. & Natarajan, S. K. 2024b Effect of natural kenaf fiber on the augmentation of condensation rates in solar desalination: A sustainable approach to clean water production. *Journal of Thermal Analysis and Calorimetry*. In press.
- Taner, T. 2019 A feasibility study of solar energy-techno economic analysis from Aksaray city, Turkey. *Journal of Thermal Engineering* **3**, 1–1.
- Vaithilingam, S., Muthu, V. & Athikesavan, M. M. 2022 Energy and exergy analysis of conventional acrylic solar still with and without copper fins. *Environmental Science and Pollution Research* **29**, 6194–6204.

First received 18 April 2024; accepted in revised form 25 May 2024. Available online 7 June 2024