PERFORMANCE ASSESSMENT OF SINGLE SLOPE SOLAR STILL INTEGRATED WITH HANGING COTTON WICK

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Abstract

Experimental investigation was conducted to evaluate and compare the performance of a conventional single-slope solar still (SCSS) and a modified configuration incorporating a hanging cotton wick to enhance the effective evaporative surface area. For this purpose, two identical conventional solar stills were fabricated to ensure a controlled comparative assessment of the effect of surface area augmentation on water evaporation and distillate yield. In the modified solar still (MCSS), the additional evaporative surface was arranged vertically and parallel to the galvanized iron (GI) sidewalls, supplementing the horizontal basin water surface and the system's sensible heat storage capacity. Outdoor experiments were conducted during May and June 2023 with a basin water depth of 10 cm. The cumulative distillate yield of the MCSS demonstrated a 39.51% enhancement compared to the SCSS. Moreover, the cost of distilled water production was reduced from ₹0.72/L for the SCSS to ₹0.51/L for the MCSS, indicating both performance and economic advantages of the proposed modification.

Keywords: *Solar still; Hanging wick; Evaporative surface enhancement; Distillate yield; Water desalination*

1. Introduction

Rapid population growth and industrialization have led to the depletion and contamination of natural water resources, resulting in a serious global challenge of water scarcity and stress [1]. Among various sustainable water purification methods, the solar still is considered one of the most economical and environmentally friendly systems for converting brackish or saline water into potable water [2]. Solar desalination is a simple, eco-friendly, and cost-effective technique that harnesses solar energy - a free and inexhaustible source available during daylight hours - to produce clean drinking water [3–6].

However, the conventional solar still (CSS) suffers from several limitations, such as low distillate yield and the requirement of a large surface area for effective operation. Consequently, researchers have continuously explored innovative methods to enhance its performance and overcome these shortcomings [7].

Extensive research has been conducted to improve CSS productivity through various design modifications and performance enhancement strategies. These include the integration of fins, phase change materials (PCMs), energy storage media, modified glass cover geometries, and multi-basin configurations [8–10]. Kabeel et al. reviewed several categories of solar stills, including semi-circular stills with baffles, multi-basin designs, wick-type and stepped-type stills, weir-type configurations, inclined cover glass designs, coupled solar stills, and integrated solar stills with external condensers [11].

Sodha et al. conducted experiments on a single-slope multi-wick solar still and achieved a maximum freshwater productivity of 2450 g/m² on sunny days [12]. Tiwari and Selim were the first to analyze a dual-slope multi-wick solar system (MWSS), which demonstrated higher productivity but required greater investment [13]. Pat et al. modified a dual-slope still by introducing multiple black jute wicks in a 2 m² basin with transparent walls, resulting in a yield of 9.012 L/m²/day [14]. Suraparaju et al. studied the effect of novel pond fibers placed on the basin water surface and observed a 126% increase in yield when the glass cover was cooled with water [15].

Yeh and Chen developed a theoretical model for wick-assisted solar stills, analyzing the influence of additives, fabrication design, operating conditions, and environmental factors on performance [16]. Bassam and Himzeh experimentally investigated the use of sponge cubes of varying sizes in the basin water, reporting an improvement in distillate yield of 18% to 273% [17]. Srivastava and Agrawal examined the use of blackened cotton rags as porous fins in a CSS with a glass cover inclined at 24°, and reported a 22.2% increase in distillate output when the basin water depth was reduced from 0.04 m to 0.03 m [18]. Velmurugan et al. incorporated stones, fins, and sponges into the basin to enhance evaporation, resulting in productivity increases of 40.2% and 45%, respectively, compared to the conventional still [19]. Similarly, Alaian et al. investigated a solar still integrated with pin-finned wicks and observed increases of 55% and 23% in distillate yield and thermal efficiency, respectively, over the conventional still [20]. Singh et al. also noted that employing improved wick materials enhances system efficiency and thermal performance [21].

For a conventional solar still with a basin area of 1 × 1 m² and a water depth of 10 cm, previous studies have shown that the distillate yield can be improved through various design and material modifications, though often at higher cost. Literature surveys consistently indicate that using wick materials as extended evaporative surfaces is an effective approach to significantly enhancing the thermal efficiency and productivity of solar stills.

2. Methodology

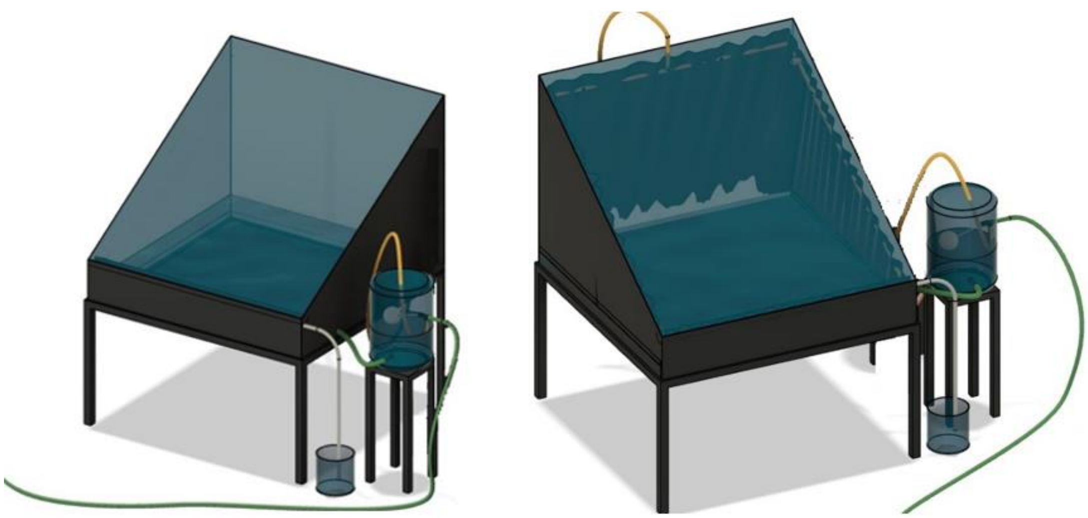
This section presents the design, fabrication, installation, monitoring, and calibration processes for the single-slope solar distillation system, with a novel modification that integrates a black, hanging cotton wick.

2.1 Experimental Setup

The primary objective of this experimental study was to evaluate the performance enhancement of a modified solar still incorporating a black hanging wick, compared to a conventional single-slope solar still (SCSS). For this purpose, two identical single-slope solar stills were fabricated, each with a basin area of 1 m² and a 5 mm thick transparent glass cover. Both stills were constructed using galvanized iron (GI) sheets to ensure structural durability and uniformity.

The inner bottom surface of each basin was coated with black paint to maximize solar energy absorption. The higher and lower vertical sides of the still measured 0.577 m and 0.160 m, respectively. The top of the still was sealed with a 5 mm-thick clear glass cover inclined at 30° to the horizontal, optimizing solar radiation capture and condensate flow.

To minimize heat losses, all vertical and bottom surfaces of the solar still were insulated with 50 mm thick thermocol sheets, effectively reducing convective heat transfer from the sidewalls. A rubber sealing strip was applied along the edges of the glass cover to prevent vapor leakage and maintain system integrity. The schematic arrangement of the conventional solar still (SCSS) is shown in Fig. 1(a).



(a) (b)

Figure 1. Schematic of experimental setup of SCSS and MCSS

In the modified conventional solar still (MCSS), four black cotton cloths—each having the same dimensions as the four vertical inner surfaces of the still—were used as hanging wicks. These cloths were suspended from a hollow distribution pipe through which water was supplied as required. The lower ends of the hanging black cloths were immersed in the saline water present in the basin. Due to capillary action and gravitational effects, the cloths remained continuously moist as water was drawn upward by surface tension and replenished through the hollow pipe.

During operation, solar radiation caused water to evaporate from the basin, gradually reducing its water level. To compensate, a control valve (cock valve) automatically opened, allowing saline water to flow through the hollow pipe at the top of the still, as illustrated in Fig. 1(b). The pipe was perforated with small, uniformly distributed holes along its length, ensuring even water distribution across all four vertical surfaces. As the water exited through these holes, a significant portion was absorbed by the hanging cloths, while the remaining water dripped back into the basin.

The wetted hanging cotton cloths provided an extended evaporative surface, thereby enhancing overall evaporation rate by increasing the area exposed to solar radiation. Fig. 1(b) shows the schematic of the black hanging cloths and their arrangement along the inner vertical walls of the still. As the evaporation rate increased, the chamber's internal vapor pressure rose, potentially reducing condensation on the cover glass due to a higher local saturation temperature.

Temperature monitoring was carried out using a digital data acquisition system. A solar pyranometer was used to measure the incident solar radiation during the experimental period. In total, seven K-type thermocouples were installed in the SCSS and nine in the MCSS to measure the temperatures at critical locations, including the basin bottom, basin water, inner and outer glass surfaces, internal air, inlet water, and collected distillate, as shown in Fig. 2. Additional thermocouples were positioned to record the temperature of the condensed water collected from the inner glass surface.

Figure 2. Experimental set up of SCSS and MCSS

Throughout the experiments, it is assumed that the pressure inside the solar still remains constant at 1 atm, and the principles of psychrometrics are therefore applicable.

2.2 Experimental and Monitoring Procedure

To evaluate the performance enhancement of the modified conventional solar still (MCSS) over the single-slope conventional solar still (SCSS), experiments were conducted during May and June 2023. The tests were performed under varying weather conditions; however, data collected on clear sky days were selected for performance comparison to ensure consistency. Both solar stills were operated simultaneously under identical environmental and operating conditions at the same location.

Each experiment commenced at 09:00 AM. To minimize vapor leakage, the freshwater collection chamber was initially filled with 100 mL of water. This reference volume ensured that the PVC collection pipe remained submerged, thereby preventing vapor escape, which could occur if the collection chamber were completely dry. Observations were recorded hourly from 09:00 AM to 06:00 PM.

Outdoor trials of both the SCSS and MCSS are shown schematically in Fig. 2. Hourly data were collected between 09:00 AM and 06:00 PM, and the key observations and performance characteristics were analyzed based on these experimental readings.

2.3 Uncertainty analysis

Experimental uncertainty is the degree of dispersion associated with measured values and reflects the reliability of the data. The uncertainties of the instruments used during the experimental observations are summarized in Tab. 1. These uncertainties were taken into account when evaluating the accuracy and consistency of the recorded results.

Table 1. Experimental uncertainty errors

Measurement Devices	Accuracy	Error in %	Capacity Range
Thermocouple	±1 ºC	0.25	0-100 ºC
Digital Hygrometer	± 5%	2	10-99 %
Anemometer	±0.1 m/s	10	0-15 m/s
Solarimeter	±1 W/m^2	0.25	0-5000 W/m^2
Graduated flash	±5 ml	5	0-10000 ml

2.4 Cost analysis

The economic viability of any modification is a key parameter in determining the overall success of an experimental study. Tab. 2 presents the detailed cost breakdown of all materials, components, and utilities used in the fabrication of both systems.

For estimating the cost of distilled water, the operational lifespan of both setups was assumed to be 10 years, with an average of 300 sunshine days per year. The cost of land required for system installation has been excluded from the analysis.

Based on the experimental observations recorded on 12th May 2023, the distillate yield of the modified conventional solar still (MCSS) increased from 2.91 L/m^2/day to 4.06 L/m^2/day, representing a significant improvement over the single-slope conventional solar still (SCSS). Consequently, the cost of freshwater production was reduced from ₹0.72/L for the SCSS to ₹0.51/L for the MCSS, highlighting both performance and economic advantages of the modification.

Table 2. Cost of fabrication of both solar stills

Items	Cost for SCSS (Rs.)	Cost for MCSS (Rs.)
GI Sheet	4200	4200
Cover Glass	680	680
Paint	220	80
Insulation	120	120
MS Stand	800	800
Rubber tape	60	60
Silicon	40	40
Tubes & connector	70	70
Others	100	100
Black Wick	-	80
Total (Fixed Cost), INR	**6290**	**6230**
Total (Fixed Cost), US$	**69.89**	**69.22**

3. Results and Discussion

Both the single-slope conventional solar still (SCSS) and the modified conventional solar still (MCSS) were tested under identical environmental conditions at the same location. The basin water depth was maintained at 10 cm in both systems. Hourly variations in temperature and distillate output were recorded on 12th May 2023.

Fig. 3 illustrates the hourly variation of the chamber (air) temperature for both stills. It was observed that the average internal air temperature in the MCSS was consistently higher than that of the SCSS from the beginning of the experiment. The temperature difference between the two systems gradually decreased and became nearly equal at around 3:00 PM. The maximum chamber temperature recorded for the MCSS was 61°C, compared to 59°C for the SCSS. After 3:00 PM, the MCSS chamber temperature was slightly lower than that of the SCSS, possibly due to the higher moisture content and specific heat of the humid air inside the modified still.

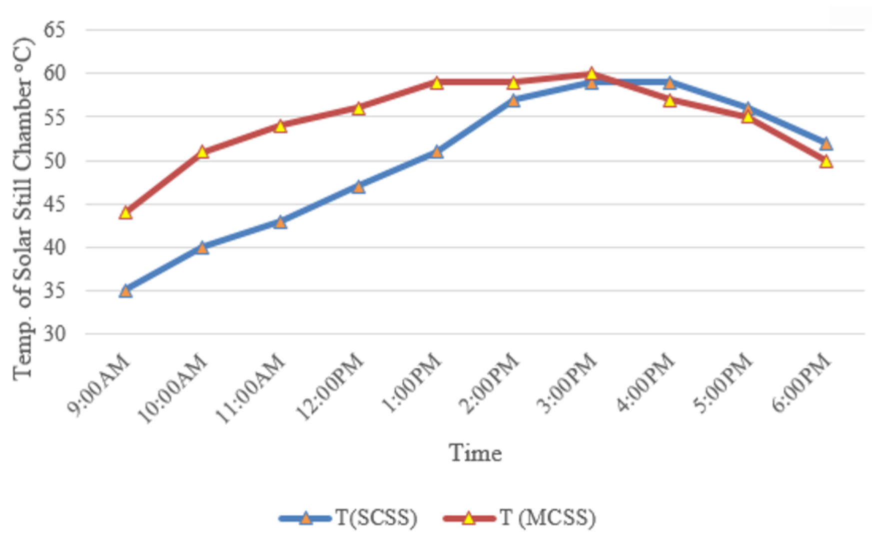


Figure 3. Hourly variation of still temperature

Fig. 4 shows the hourly variation of the basin water temperature for both stills. From the start of the experiment, the basin water temperature in the MCSS was higher than in the SCSS. This enhancement can be attributed to the preheating of water through the wet hanging black cloths, which absorb additional solar radiation. Based on the recorded data, the maximum basin water temperature in the SCSS reached 54°C, while the MCSS consistently maintained higher temperatures throughout the observation period.

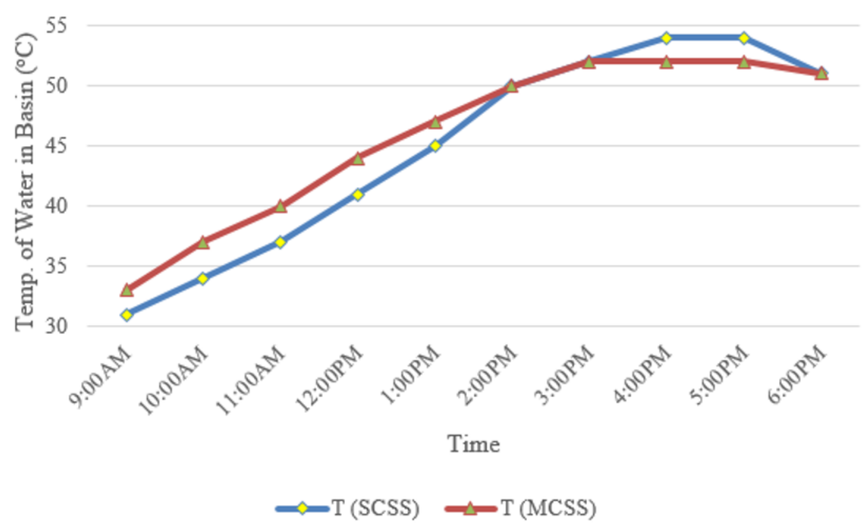


Figure 4. Variation of temperature of water in basin for SCSS and MCSS

The variation in the outer glass surface temperature for both systems on 12th May 2023 is shown in Fig. 5. The results show that the MCSS outer glass temperature was initially higher than that of the SCSS, with both reaching similar values around 12:00 noon, corresponding to the peak solar radiation. Beyond this point, the outer glass surface temperature of the SCSS increased more rapidly than that of the MCSS. This may be due to a larger fraction of incident solar radiation being absorbed within the MCSS chamber compared to the SCSS, resulting in relatively lower heat transmission to the outer surface.

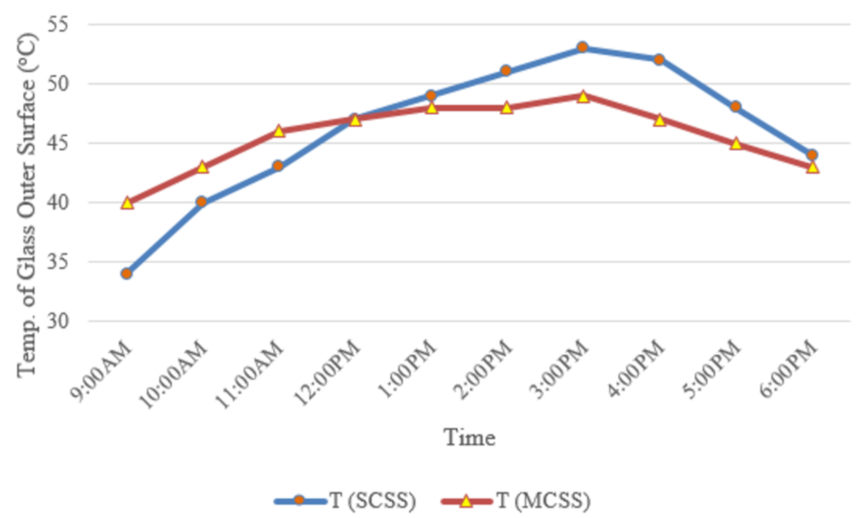


Figure 5. Comparison of temperatures of outer surface of cover glass for SCSS and MCSS

A similar trend was observed for the inner glass surface temperature, as shown in Fig. 6. Initially, the MCSS inner glass temperature was higher; however, after noon, the SCSS recorded slightly higher values. This reversal could be attributed to a greater proportion of incident radiation reflected through the glass cover in the SCSS than in the MCSS.

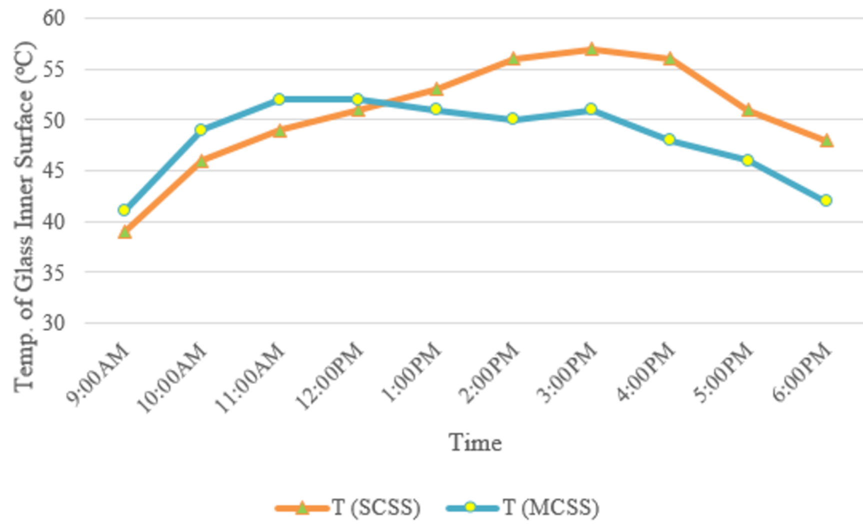


Figure 6. Comparison of temperatures of inner surface of cover glass for SCSS and MCSS

Fig. 7 depicts the hourly variation in distillate yield for both solar stills. At the start of the experiment (09:00 AM), both collection chambers were filled with 200 mL of water to ensure the outlet pipe remained submerged and prevented vapor leakage. Throughout the experiment, the MCSS consistently produced a higher distillate yield than the SCSS. The difference in cumulative production increased progressively throughout the day. The total distilled water collected at the end of the test period (09:00 AM–06:00 PM) was 2.91 L/m²/day for the SCSS and 4.06 L/m²/day for the MCSS, representing a 39.51% increase in productivity for the modified configuration.

The variation in specific humidity and productivity over time for both systems is shown in Fig. 8. As solar radiation increased during the day, the thermal energy in both chambers increased, resulting in higher air temperatures and specific humidity. Due to the larger effective evaporative surface area in the MCSS, both the temperature and humidity inside its chamber were higher than those in the SCSS, resulting in a higher distillate yield.

After 4:00 PM, as solar intensity decreased, the evaporation rate declined; however, the condensation rate increased due to the higher temperature difference between the vapor and the glass cover. Consequently, the specific humidity dropped rapidly after 4:00 PM, particularly in the MCSS. This indicates that while the heat input was reduced, the available surface area in the MCSS continued to promote effective condensation, thereby maintaining a higher cumulative productivity than the SCSS throughout the observation period.

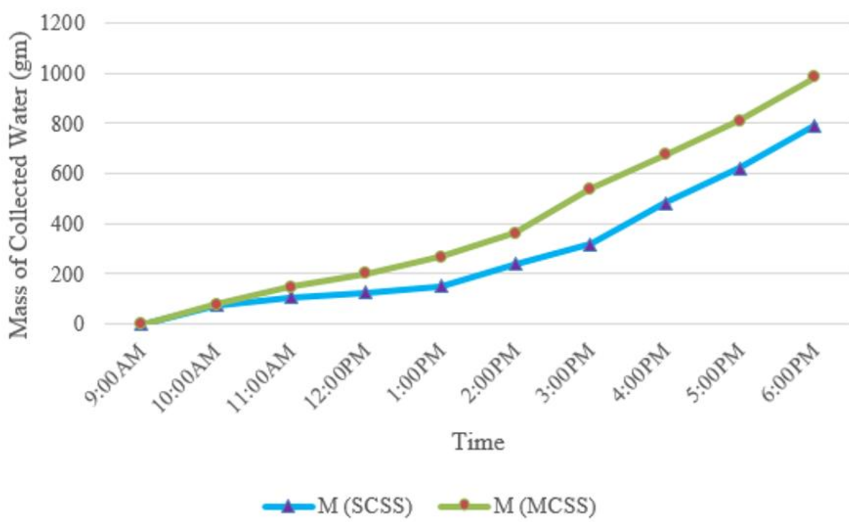


Figure 7. Hourly variation of productivity

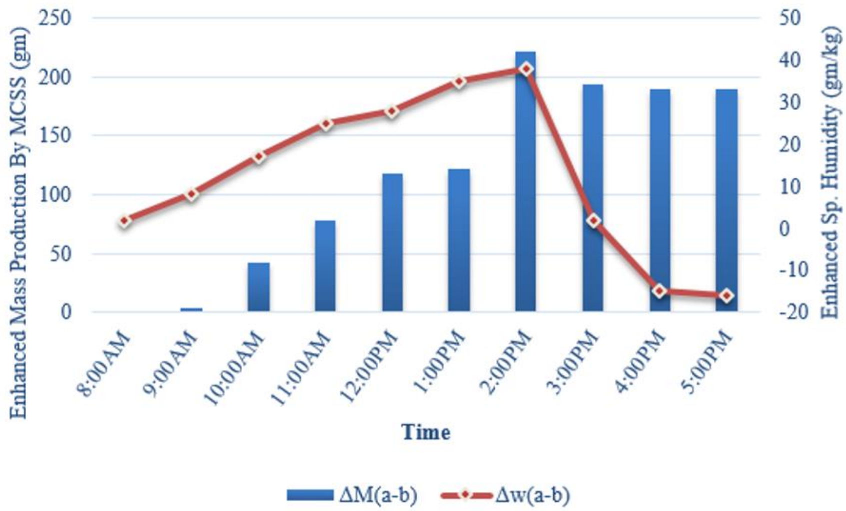


Figure 8. Variation of enhanced productivity and enhanced sp. humidity

4. Conclusion:

In this experimental study, the performance of a single-cover solar still (SCSS) and a modified solar still (MCSS) was investigated. The MCSS was designed with four black hanging cloths attached to its vertical walls to enhance internal heat and mass transfer. Continuous experiments were conducted under clear-sky conditions during May and June 2023, with both systems operated at a uniform basin water depth of 10 cm. Based on the experimental observations, the following conclusions are drawn:

i. The incorporation of black hanging cloth in the conventional solar still (CSS) notably enhances its evaporation rate, productivity, and overall efficiency.
ii. At a basin water depth of 10 cm, the cumulative distillate output increased by 39.15% when the black hanging cloths were introduced.
iii. The presence of wet black cloth significantly improved the night-time evaporation rate due to retained heat and enhanced surface area for evaporation.
iv. The total yield increased from 2.91 L/m²/day for the SCSS to 4.06 L/m²/day for the MCSS, confirming the effectiveness of the modification.
v. The MCSS proved to be more economical, reducing the cost of distilled water from ₹0.72/L (SCSS) to ₹0.51/L (MCSS).

In summary, integrating black hanging cloths into a traditional solar still design can significantly enhance distillate yield, energy efficiency, and cost-effectiveness, making it a promising modification for sustainable water purification applications.

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Nomenclature

A_c	Concentrator area (m2)
T	Temperature (◦C)
Subscripts:	
a	Ambient
U	Useful
v	Vapor
W	water

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