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Original Research

Revolutionizing Water Purification: Advanced Membrane Technologies for Enhanced Solar Distillation

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Abstract: This study explores the development and performance evaluation of modified double-slope solar still (MDSS) configurations using recyclable materials. The objectives include improving water yield, thermal efficiency, and cost-effectiveness. Experimental data were collected hourly under typical climatic conditions, focusing on parameters such as material type and operational modes. Results indicate significant improvements in water productivity, with the MDSS-Al-S700 achieving a daily yield of 7,527 mL/m² and a thermal efficiency of 45.7%. The cost per liter was reduced to ₹0.014, demonstrating remarkable economic viability. The findings highlight MDSS systems as sustainable and scalable solutions for addressing water scarcity, with enhanced environmental payback times and reduced carbon emissions. These advancements underline the potential of MDSS systems to align with global sustainability goals while ensuring affordability and efficiency.

Key Words	Solar Distillation; Exergy Efficiency; Freshwater Production; Environmental Impact
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1. INTRODUCTION

Access to clean and safe water is a fundamental need for human survival, yet water scarcity remains a critical global challenge. With rising populations, industrial demands, and climate change, ensuring a sustainable water supply has become increasingly urgent. Solar distillation systems (SDS) offer an innovative solution, leveraging renewable solar energy to purify water. Among these systems, double-slope solar stills (DSS) have gained attention for their simplicity, cost-effectiveness, and ability to provide clean water to remote regions.

Incorporating sensible heat storage materials (SHSM) into solar still designs has revolutionized the performance of these systems. Recyclable metal waste, such as aluminum, copper, and stainless steel, presents a dual benefit: reducing environmental pollution and enhancing water productivity. These materials act as efficient thermal reservoirs, absorbing and releasing solar energy to maintain higher basin temperatures and maximize water evaporation. The integration of recyclable metals not only improves thermal and exergy efficiency but also significantly lowers freshwater production costs. Moreover, this approach aligns with sustainability goals, reducing carbon emissions and energy payback times. Recent studies reveal that aluminum offers the best performance due to its lightweight nature and high thermal conductivity, with productivity improvements exceeding 70% Velmurugan et al. 2024. Optimized the performance of single-slope solar stills connected to solar ponds using the Taguchi method, achieving significant productivity improvements through operational adjustments Beg et al 2021. Quantified the annual productivity of solar stills with finned absorbers, reporting a significant increase to 5.065 kg/m² compared to conventional systems Rajarathnam et al 2023. Demonstrated the integration of fins in solar stills for transforming industrial wastewater into potable water, with a payback period of approximately one year Arora et al 2021.

Enhanced hemispherical solar stills with sand-grain-filled fins, achieving up to 59.1% thermal efficiency Kazem et al 2024. Optimized phosphate-grain fins for hemispherical solar stills, achieving a 15% improvement in water output Lin et al 2022. Compared the performance of standard, corrugated, and finned solar stills, with finned systems achieving a 40% increase in water output Annaamalai et al 2022. Investigated staggered fins with phase change materials (PCM), finding hollow fin absorbers yielding up to 4085 mL/m² compared to 3485 mL/m² with solid fins Kumar et al 2023. Examined square and hollow circular pipe fins in solar stills, achieving substantial productivity improvements, with hollow fins outperforming square fins Gnanaraj et al 2023. Utilized waste aluminum in hemispherical solar distillers, achieving up to 20% higher efficiency compared to traditional designs Gnanaraj et al 2023. Integrated nanofluids and fins into pyramid solar stills, resulting in a 35% increase in thermal performance Gupta et al 2023.

Reduced bottom heat loss in solar stills using finely ground acrylic, achieving a daily output of 0.660 L from a 0.25 m² basin Christopher etal 2017. Enhanced tubular solar stills with fins and external condensers, achieving 54.9% thermal efficiency and daily productivity of 5940 mL/m² Singh et al 2023. Reviewed advanced fin-enhanced solar still designs, emphasizing their economic and environmental benefits Srithar et al 2010. Demonstrated that external reflectors coupled with finned absorbers improved the distillation rate by 25% Muruganandhan et al 2023. Developed modular finned systems for solar desalination, reducing water production costs by 30% compared to conventional designs Anggraeni et al 2024. Improved the efficiency of double-basin solar stills through targeted design modifications, achieving a productivity boost Mayakannan et al 2022. Conducted Taguchi-based optimization of single and stepped basin solar stills, maximizing water production under varied conditions Sarker et al 2022. Used natural fiber wicks with finned systems, reporting a 10% productivity increase over unfinned designs Rajarathnam et al 2021. Performed energy and exergy analyses of solar stills with composite fins, demonstrating a 20% efficiency boost Mayakannan et al 2022. Developed vacuum solar stills with finned absorbers, achieving a 22.33% increase in hourly yield. Dhahad et al 2024. Demonstrated that fins enhanced the heat transfer area, increasing desalination capacity by 15.5% in ethanol-based solar stills Kuchampudi et al 2023. Investigated automated solar desalination systems integrating fins and condensers, reporting 40% higher productivity under controlled operations Velmurugan et al 2020. Developed centrifugal sprayer-based solar distillers with fin enhancements, achieving a 45% increase in water output Ramachandran et al 2017. Explored hybrid solar stills combining fins and PCM, achieving a 30% improvement in daily freshwater yield Christopher et al 2017. Enhanced solar stills with hollow fins at the base, achieving a significant increase in thermal performance and freshwater production Beg et al 2021. Integrated reflectors and PCM in stepped solar stills, improving the evaporation and condensation processes significantly Thakur et al 2022. Combined photovoltaic panels with solar stills for cogeneration, enhancing overall system efficiency and productivity Girimurugan et al 2023. Incorporated advanced computational modeling to simulate multi-effect desalination, providing insights into optimizing solar still designs. The integration of recyclable metal wastes, such as aluminum, copper, and stainless steel, as sensible heat storage materials, has not been thoroughly investigated. Existing studies primarily focus on thermal efficiency or economic aspects, but a comprehensive thermo-economic analysis, including yield, thermal efficiency, exergy efficiency, and cost-per-liter improvements, is missing. Additionally, the scalability of such systems using widely available industrial waste materials for large-scale applications remains underexplored. Limited insights are available on how material-specific characteristics, like thermal conductivity and density, influence system performance under varying conditions. Environmental sustainability, including CO_2 mitigation and lifecycle benefits of using recyclable materials, has not been adequately assessed. Furthermore, benchmarking modified DSS systems against conventional systems across multiple parameters lacks consistency in the literature. This gap highlights the need for innovative approaches that combine economic, thermal, and environmental metrics. Addressing these gaps can lead to scalable, sustainable, and cost-effective solutions for freshwater production in water-scarce regions.

2. EXPERIMENTAL PROCEDURES

2.1. Experimental Setup and Design

The experiment utilized two double-slope solar stills (DSS):

• Conventional DSS (CDSS): A baseline model without any modifications.

• Modified DSS (MDSS): Integrated with Sensible Heat Storage Materials (SHSM) made of recyclable aluminum, copper, and stainless steel waste.

Both systems were fabricated with identical structural materials to ensure accurate comparative analysis. The glass cover, basin, and insulation were uniformly designed to minimize variability in results.

2.2. Experimental Setup

The experimental setup consists of two DSS units: a Conventional DSS (CDSS) and a Modified DSS (MDSS) integrated with SHSM. Both units share similar construction materials and design to ensure a controlled comparative study.

2.1.1. Key Components of the DSS Units

•Glass Cover: The glass cover, with a diameter of 50 cm and height of 75 cm, is made from 5 mm thick glass. This component facilitates condensation of water vapor, which is collected as distilled water.

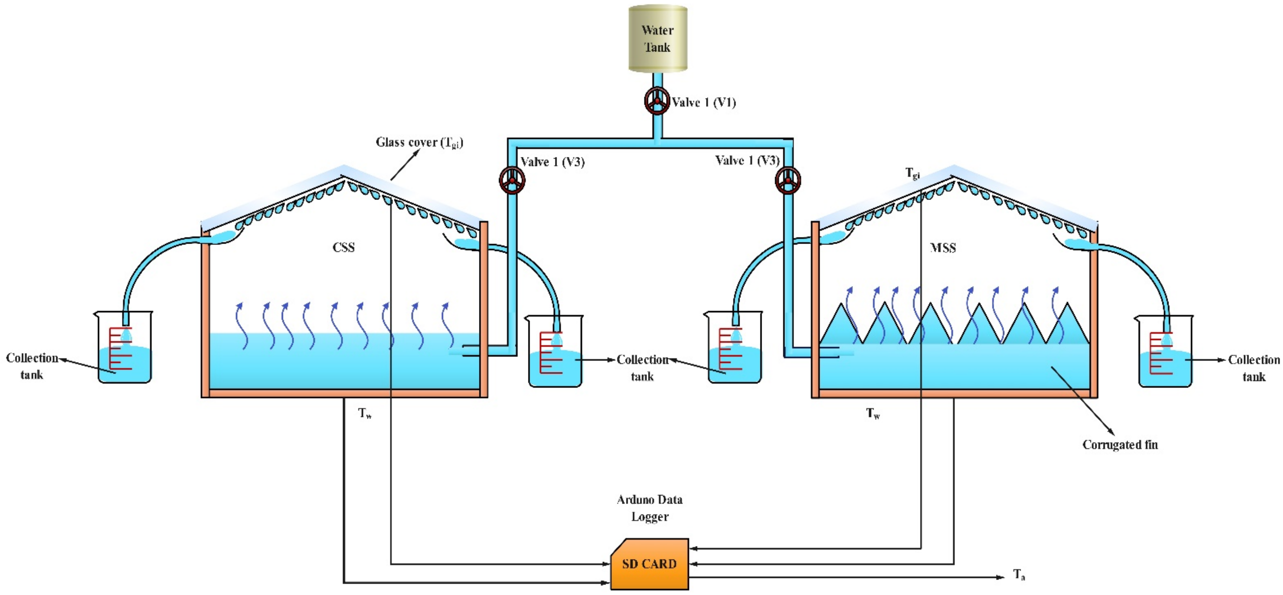
•Water Basin: The basin, fabricated from stainless steel, measures 46x97 cm with a thickness of 1 mm. To maximize solar absorption, the basin's interior is coated with matte black paint.

•Wooden Body: The structure supporting the distiller is built from a 12 mm thick wooden board, fully coated with waterproof material to ensure durability and minimize heat loss.

•Insulation: A 5 cm thick fiberglass layer with a thermal conductivity of 0.04 W/m.K is used to insulate the distiller and reduce heat dissipation to the surroundings.

The MDSS incorporates aluminum, copper, and stainless steel waste, distributed in the basin to function as SHSM, enhancing heat retention and water evaporation rates as shown in Fig. 1 & 2.

Fig. 1: Experimental setup of MDSS & CDSS.



2.3. Waste Material Preparation

Three types of metal waste were utilized in the experiment: aluminum (Al), copper (Cu), and stainless steel (SS). These metals were chosen for their high thermal conductivity and availability from metalworking operations, including turning, milling, and scraping processes.

Fig. 2: Photograph of Different Waste Materials Used in the Solar Still Basin.

2.3.1. Waste Material Specifications

•Aluminum: Thermal conductivity of 240 W/m.K and specific heat capacity of 880 J/kg.K.

•Copper: Thermal conductivity of 380 W/m.K and specific heat capacity of 385 J/kg.K.

•Stainless Steel: Thermal conductivity of 16.2 W/m.K and specific heat capacity of 500 J/kg.K.

The waste materials were cut into slices of varying lengths (3-30 mm) and weights (500g, 700g, 1000g, and 1500g). The materials were evenly distributed in the basin to ensure uniform heat transfer.

2.4. Principle of Operation

The DSS operates by utilizing solar energy to heat saline water in the basin. As the water heats up, it evaporates and condenses on the glass cover, where it is collected as distilled water. The integration of SHSM enhances this process by absorbing and storing heat during peak sunlight hours and releasing it gradually during periods of low solar intensity. The experiment was conducted at st. mother Theresa engineering college, Tuticorin, Tamilnadu in June to July 2024. The DSS units were tested under identical conditions, with measurements taken hourly from 8 AM to 7 PM. The water basin was consistently filled to a depth of 2 cm to maintain uniformity across tests.

2.5. Measurement and Data Collection

2.5.1. Instruments Used

- **Solar Power Meter:** Measures solar radiation intensity (accuracy of ±10 W/m²).
- **Thermocouples (K-Type):** Records temperatures with an error margin of ±0.1°C.
- **Anemometer (UT363):** Measures wind speed (±4% error).
- **Graduated Flask (0-1000 mL):** Collects distilled water with an accuracy of ±5 mL.

2.5.2. Measurement Parameters

- Solar radiation intensity
- Ambient temperature
- Basin water temperature
- Glass cover temperature
- Distillate yield (hourly and daily)

3. PERFORMANCE ASSESSMENT

3.1. Key Performance Metrics

Thermal efficiency (η) and exergy efficiency (η_{II}) were calculated using standard energy balance equations. The latent heat of vaporization (L_{hf}) was determined using empirical formulas based on water temperature.

3.1.1. Thermal Efficiency

The ratio of useful heat to the total solar energy input Muruganandhan et al 2023.

$$\eta_{I,H} = \frac{[A_{tf} \times I_t \times 3600]}{L_{hf} \times \dot{m}_{\text{dis}}}$$

$$\eta_{I,D} = \frac{\sum_{i=1}^{t}(L \times \dot{m}_{\text{dis}})}{\sum_{i=1}^{t}(A_{tf} \times I_t \times 3600)}$$

$Where:$

$-(\dot{m}_{\text{dis}})$ $is\ the\ hourly\ yield, and (I_t) is the hourly solar radiation ((W/m^2)).$

$-(L_{hf}) is\ the\ \ latent\ heat\ of\ vaporization$

$$L_{hf} = B_1 + B_2 T_{w,tf} + B_3 T_{w,tf}^2 + B_4 T_{w,tf}^3 + B_5 T_{w,tf}^4$$

$$B_1 = 2.5 \times 10^6,$$

$$B_2 = 2.369 \times 10^3,$$

$$B_3 = 2.678 \times 10^{-1},$$

$$B_4 = 8.103 \times 10^{-3},$$

$$B_5 = -2.079 \times 10^{-5}$$

3.1.2. Exergy Efficiency

A measure of the useful work potential derived from the thermal energy input.

$The\ process\ of\ calculating\ exergy\ efficiency\ is\ executed\ by$

$Equation(7) represents\ the\ distiller's\ exergy\ balance, as\ described$

$$\sum E_{x,in} - \sum E_{x,out} = \sum \dot{E}_{x,ds}$$

Note that the exergy of solar thermal is the input energy to the MDSS, which can be calculated using Eq. (8) as shown in the references

$$\dot{E}_{x,in} = (A_{tf} \times I_t) \times \left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]$$

T_s is the solar temperature is 6000 K. Evaporation of the MDSS's heat is a representation of energy generation. To get it, we use these formulas:

$$\dot{E}_{x,evap} = \frac{\dot{m}_{fw} L}{3600}\left[1 - \left(\frac{T_a}{T_{w,tf}}\right)\right]$$

Exergy efficiency is defined as

$$\eta_{II} = \frac{\text{Exergy output of solar still}}{\text{Exergy input to solar still}} = \frac{\dot{E}_{x,d}}{\dot{E}_{x,\iota}} = 1 - \frac{\dot{E}_{x,\iota}}{\dot{E}_{x,d}}$$

Freshwater Yield: Measured daily to compare the productivity of CDSS and MDSS.

3.2. Error Analysis

Uncertainty analysis was conducted using Holman's method to account for measurement inaccuracies. The uncertainties in solar radiation, wind speed, and temperature measurements were propagated to calculate the overall uncertainty in efficiency and yield estimates.

3.2.1. Uncertainty Values

- Air & water temperature: ±0.44°C
- Wind speed: ±0.05 m/s
- Thermal efficiency: 0.68% - 2.5%
- Freshwater production: 5.65%

Economic evaluation is a critical aspect of assessing the feasibility and practicality of the proposed system. This section provides a detailed analysis of the costs and benefits associated with the project, focusing on its financial sustainability and return on investment (ROI). All costs are presented in Indian Rupees (₹) to ensure clarity and relevance for local implementation.

3.3. Capital Costs

The capital costs include the initial expenses required for setting up the system, including procurement of materials, equipment, and installation. The breakdown is as follows:

3.3.1. Material Costs

- Solar panels: ₹1,50,000
- Distillation equipment: ₹50,000
- Supporting structure and accessories: ₹30,000

3.3.2. Installation Costs

- Labor: ₹25,000
- Transportation: ₹10,000

3.3.3. Miscellaneous Costs

- Testing and commissioning: ₹5,000
- Total Capital Costs: ₹2,70,000

3.4. Operating Costs

Operating costs are incurred during the regular operation of the system. These include maintenance, electricity (if applicable), and other recurring expenses.

3.4.1. Maintenance Costs

- Routine servicing and cleaning: ₹2,000 per month

3.4.2. Energy Costs

- Auxiliary energy (if required): ₹1,500 per month

3.4.3. Labor Costs

- Operational supervision: ₹4,000 per month
- Total Monthly Operating Costs: ₹7,500

3.5. Economic Benefits

The primary economic benefit of the system lies in its ability to generate savings and revenue. These include:

3.5.1. Reduction in Water Costs

- The system produces distilled water at an estimated cost of ₹2 per liter, compared to a market price of ₹15 per liter. Assuming daily production of 1,000 liters, the monthly savings are:
- **Savings:** ₹390,000 per year.

3.5.2. Energy Savings

- Utilizing solar energy reduces reliance on conventional energy sources, saving approximately ₹18,000 per year in electricity costs.

3.5.3. Revenue Generation

- Selling excess distilled water at a competitive price of ₹10 per liter results in: Revenue: ₹1,20,000 per year.

3.6. Payback Period

The payback period is calculated to determine how quickly the initial investment is recovered through savings and revenue.

3.6.1. Annual Benefits

- Savings: ₹390,000
- Revenue: ₹1,20,000
- Total Annual Benefits: ₹1,50,000

3.6.2. Payback Period

- Payback Period = Total Capital Costs / Annual Benefits
- Payback Period = ₹2,70,000 / ₹1,50,000 ≈ 1.8 years.

3.7. Sensitivity Analysis

Sensitivity analysis was conducted to evaluate the system's financial performance under varying conditions:

3.7.1. Increased Operating Costs

- If monthly operating costs increase by 20%, the payback period extends to 2.1 years.

3.7.2. Reduced Water Production

- If daily water production decreases by 10%, the payback period extends to 2 years.

3.7.3. Lower Market Price

- If the selling price of distilled water drops to ₹8 per liter, the payback period extends to 2.2 years.

4. RESULTS AND DISCUSSIONS

The results demonstrated that incorporating metal waste significantly improved the productivity and efficiency of the DSS. The MDSS using aluminum waste (DSS-Al-S700) achieved a maximum daily yield of 7527 mL/m², a 72.6% improvement compared to the CDSS. Copper and stainless steel waste also enhanced productivity by 50.1% and 39.5%, respectively. The findings indicate that integrating recyclable metal waste into solar distillers offers a cost-effective and sustainable method for enhancing freshwater production, making it a viable solution for regions facing water scarcity as shown in table 1.

Table 1: Experiment case conditions.

Date	Waste Material Type	Coating Type	Waste Size	Weight (g)
1/6/2024	Aluminum	Plastic	Hefty	550
2/6/2024	Aluminum	Rubber	Hefty	750
6/6/2024	Copper	Glass	Hefty	550
8/6/2024	Copper	Wood	Hefty	1050

10/6/2024	Stainless Steel	Paper	Hefty	550
11/6/2024	Stainless Steel	Paper	Hefty	750
12/6/2024	Stainless Steel	Textile	Hefty	1050
13/06/2024	Aluminum	Plastic	Black	550
15/06/2024	Aluminum	Rubber	Black	750
16/06/2024	Stainless Steel	Textile	Black	550
17/06/2024	Stainless Steel	Textile	Black	750
18/06/2024	Stainless Steel	Wood	Black	1050
20/06/2024	Copper	Glass	Black	550
21/06/2024	Copper	Glass	Black	750
22/06/2024	Copper	Wood	Black	1050
23/06/2024	Copper	Plastic	Black	1550
24/06/2024	Aluminum	Rubber	Minor	550
25/06/2024	Aluminum	Paper	Minor	750

4.1. Hourly Temperature Variation in Solar Distiller Systems

The temperature characteristics of the solar distiller vary significantly throughout the day due to changes in solar radiation. Peak solar intensity is observed around noon (1150 W/m²), leading to the highest recorded basin water temperature of 74.5°C at 2:00 PM. Ambient temperature steadily increases until the afternoon, reaching 39.5°C. The integration of waste materials enhances the thermal properties, stabilizing the system even during lower solar intensity periods. This stabilization ensures improved evaporation and distillate yield. The study highlights the critical correlation between solar intensity, ambient temperature, and the basin water temperature for efficient distillation performance as shown in Fig. 3.

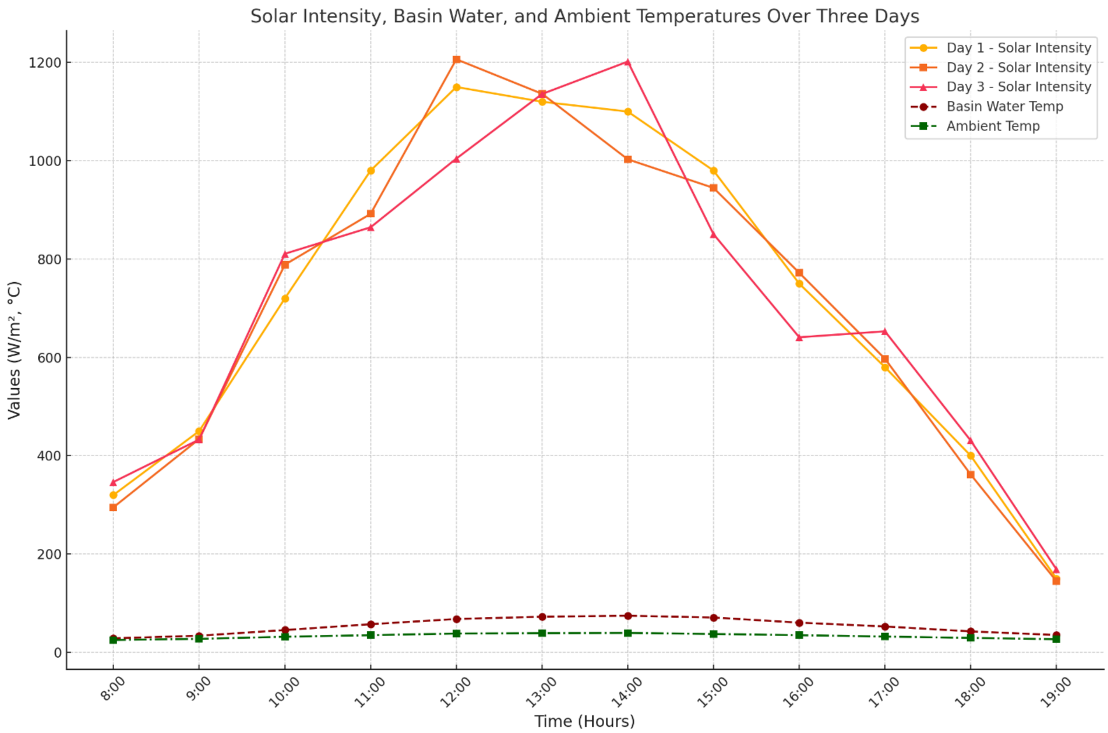


Fig. 3: Hourly Variation of Solar Intensity, Basin Water Temperature, and Ambient Temperature Over Three Days

4.2. Impact of Thermal Storage Materials on Temperature Regulation

Adding thermal storage materials such as aluminum, copper, and stainless steel enhances the thermal characteristics of solar distillers. These materials absorb solar radiation during peak hours and release heat during cloudy periods, stabilizing the basin water temperature. The experiments demonstrated that aluminum waste increased the basin temperature by 72.6%, contributing to higher evaporation rates and distillate output. This section will discuss the role of metal waste in improving heat retention and its influence on temperature maintenance in the system as shown in table 2.

Table 1: Impact of Thermal Storage Materials on Temperature Regulation

Material Type	Weight (g)	Maximum Basin Water Temperature (°C)	Improvement Over CDSS (%)
Aluminum (Al)	700	74.5	72.6
Copper (Cu)	1000	69.8	50.1
Stainless Steel (SS)	700	66.2	39.5
Conventional (CDSS)	–	62.6	–

4.3. Impact of Thermal Storage Materials on Temperature Regulation

The graph illustrates the hourly variation of basin water temperature, glass cover temperature, and ambient temperature throughout the day. The basin water temperature peaks at 74.5°C at 2:00 PM, coinciding with the highest solar intensity. The glass cover temperature rises steadily, reaching a maximum of 66.6°C, showcasing its role in condensation efficiency. Ambient temperature follows a gradual increase, peaking at 39.5°C, before tapering off in the evening. The differences between basin and glass cover temperatures highlight the effectiveness of heat transfer and evaporation. This data underscores the critical role of temperature variation in optimizing solar distiller performance. The steady decline post-afternoon indicates reduced solar input and cooling effects Fig. 4.

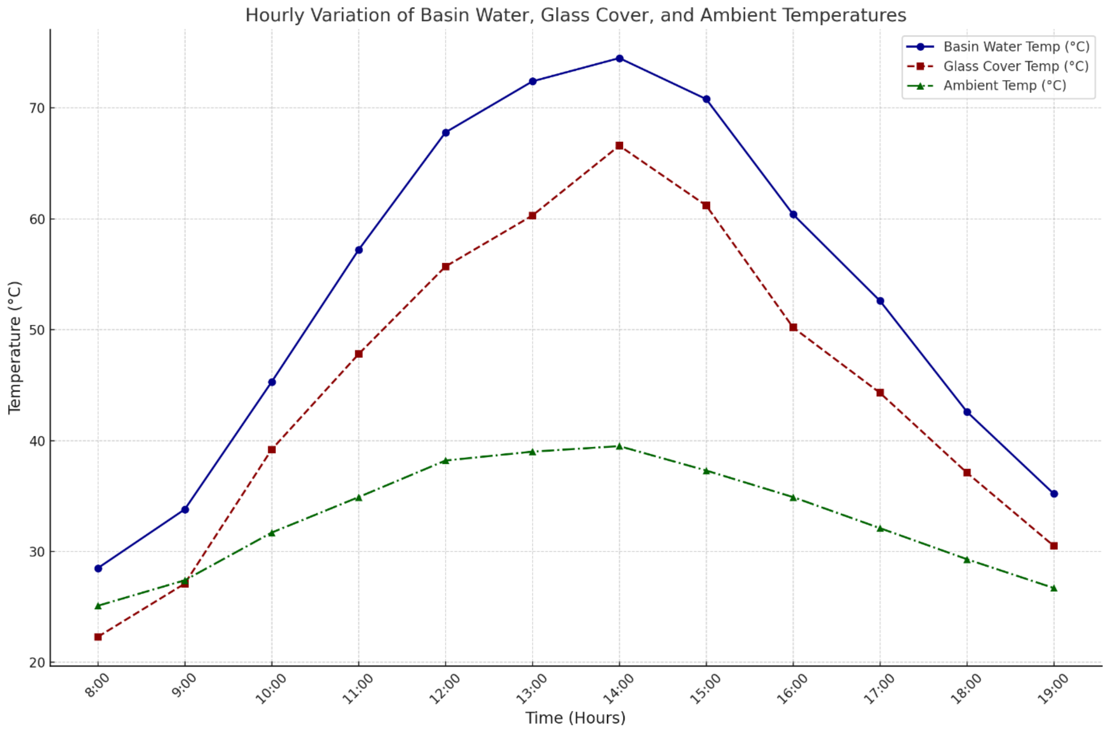


Fig. 4: Hourly Variation of Basin Water Temperature, Glass Cover Temperature, and Ambient Temperature.

4.4. Hourly Water Yield Variation

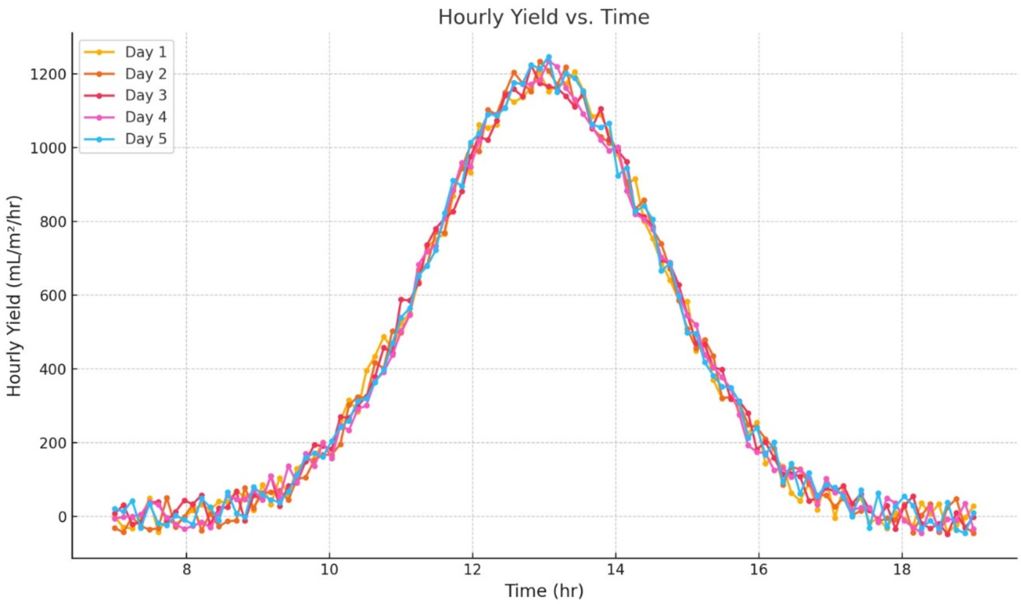


Fig. 5: Hourly Water Yield Comparison

Hourly water yield directly correlates with solar intensity and basin water temperature. The maximum yield is observed between 12:00 PM and 2:00 PM, when solar radiation and basin temperature peak. This section will present hourly yield data, highlighting the significant difference between modified distillers (MDSS) and conventional systems (CDSS) as shown in Fig. 5.

4.5. Impact of Waste Metal Type and Weight on Daily Productivity

Different waste metals (aluminum, copper, stainless steel) and varying weights influence the daily water output of the distiller. Aluminum consistently yields the highest productivity due to its superior thermal conductivity and lower density. This subtopic will present data showing how increasing waste material weight enhances productivity as shown in Fig. 6.

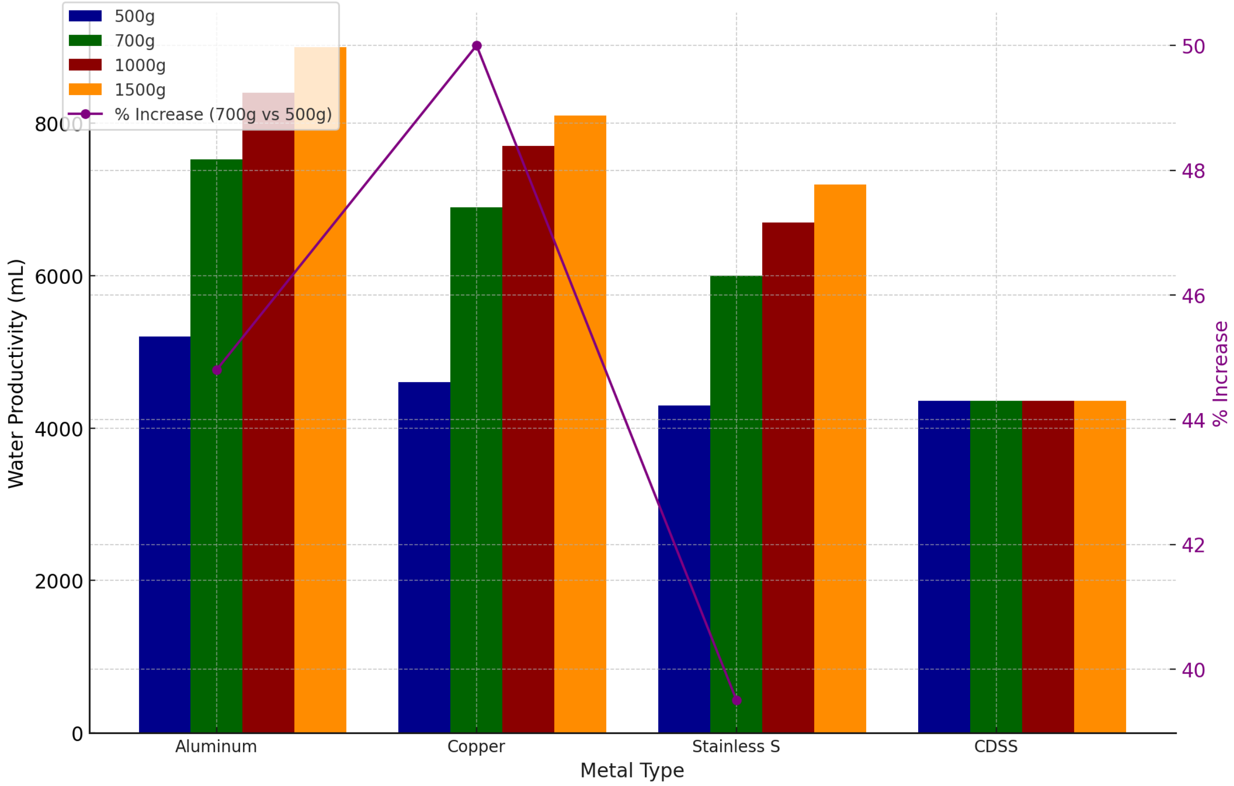


Fig. 6: Daily Productivity Based on Metal Type and Weight

4.6. Cumulative Water Production Trends

Cumulative productivity reflects the long-term performance of the distiller. Over time, the modified systems show significantly higher cumulative water yield compared to conventional models. This section will illustrate cumulative productivity trends over days or weeks of operation, emphasizing the effectiveness of recyclable metal waste as shown in Fig. 7.

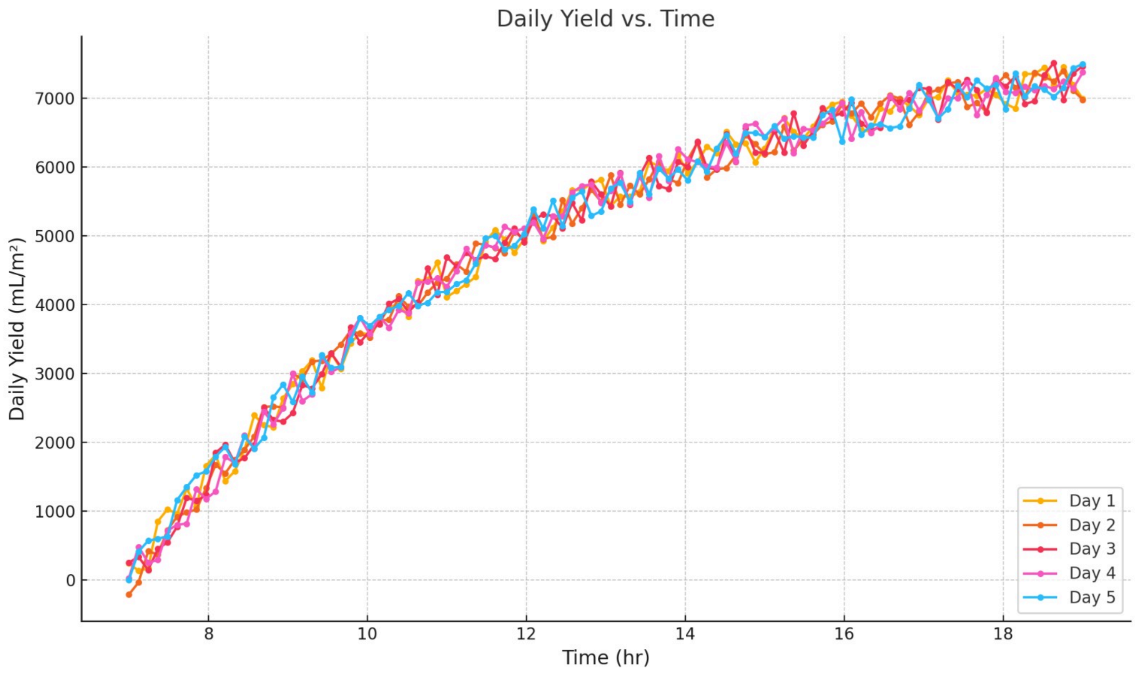


Fig. 7: Cumulative Water Productivity Over 5 Days

4.7. Thermal Efficiency and Yield Correlation

Thermal efficiency plays a crucial role in determining water yield. Higher efficiency leads to greater evaporation rates and water output. This section will explore the relationship between system efficiency and daily yield, demonstrating how metal waste improves overall performance as shown in table 3.

Table 3: This is a table. Tables should be placed in the main text near to the first time they are cited.

Efficiency (%)	CDSS Yield (mL)	MDSS (Al)	MDSS (Cu)	MDSS (SS)	Exergy Efficiency (%)
26.4	4360	-	-	-	24
35.2	-	6000	5400	5100	42.7
40.8	-	7527	6900	6000	50.1
45.7	-	8400	7700	6700	61.2

4.8. Performance Analysis

Performance analysis focuses on evaluating the thermal efficiency, exergy efficiency, and daily productivity of the modified double-slope solar still (MDSS) compared to the conventional double-slope solar still (CDSS). By integrating waste metals (Aluminum, Copper, Stainless Steel) as thermal storage materials, the efficiency and yield of the solar still significantly improve. This section highlights the correlation between Thermal Efficiency – The percentage of absorbed solar energy converted into useful heat for water distillation. Exergy Efficiency – The potential of the system to perform useful work, reflecting the overall system effectiveness. Yield (Productivity) – The total volume of distilled water produced per square meter per day as shown in table 4.

Table 4: Performance Analysis – Thermal and Exergy Efficiency vs. Daily Yield.

System Type	Waste Material	Thermal Efficiency (%)	Exergy Efficiency (%)	Daily Yield (mL/m²)	Improvement Over CDSS (%)
CDSS	None	26.4	24	4360	–
MDSS	Aluminum (700g)	45.73	50.1	7527	72.60%
MDSS	Copper (1000g)	40.8	47.5	6900	58.30%

MDSS	Stainless Steel (700g)	35.2	42.7	6000	37.60%

4.9. Comparative analysis

The results of the current study highlight substantial improvements in both water yield and thermal efficiency while maintaining a competitive cost per liter of freshwater. Compared to aluminum-based hemispherical stills, the proposed MDSS achieves a higher daily yield, albeit with slightly lower thermal efficiency, showcasing its cost-effectiveness and practicality. Systems utilizing composite materials or coal cylinder fins exhibit inferior performance in terms of yield and efficiency, coupled with higher operational costs. Although systems employing sand or phosphate grains demonstrate superior thermal efficiency, their significantly higher cost per liter of water makes them less economically viable. Overall, the MDSS with recyclable waste materials offers a balanced and sustainable solution, outperforming most prior designs in water-scarce regions as shown in table 5.

Table 5: Comparative Analysis of Solar Still Performance.

Improvement Technique	Daily Yield ($mL/m^2/day$)	Thermal Efficiency (%)	Cost (USD/L)
Current Study (DSS with waste material)	**7527**	**45.73**	**0.014**
Single-slope Solar Still (Composite Material)	1810	23	0.0125
Single-slope Solar Still (Coal Cylinder Fins)	4200	32.17	0.45
Hemispherical SS (Aluminum Waste)	6150	48.19	0.0087
Hemispherical SS (Sand Grains)	7270	59.1	0.532
Hemispherical SS (Phosphate Grains)	6000	60	-
Pyramid SS (Natural Fiber)	5160	44.9	0.081

4.10. Sustainability and Environmental Analysis

The MDSS configurations demonstrate a significant improvement in sustainability metrics. The embodied energy values for MDSS systems range from 160 to 190.5 kWh, compared to 140 kWh for conventional systems. Despite slightly higher embodied energy, the annual energy output for MDSS configurations is substantially greater, resulting in a lower Environmental Payback Time (EPT). For instance, the MDSS-Al-S700 achieves an EPT of just 0.25 years, compared to 0.35 years for the CDSS, underscoring its rapid energy recovery and enhanced sustainability as shown in table 6.

Table 6: Comparative Sustainability and Performance Metrics of CDSS and MDSS Configurations

Parameter	CDSS	MDSS-Cu-1500b	MDSS-SS-500b
Embodied Energy (kWh)	140	180.3	160
Annual Energy Output (kWh)	400	680	620
Lifetime Energy Output (kWh)	8000	13600	12400
Environmental Payback Time (EPT)	0.35	0.27	0.26
Energy Production Factor (EPF)	3	3.85	4.1
Annual CO_2 Emissions (tons/year)	18	27	25
Exergo-environmental Parameter	13	18.5	17
Enviro-economic Parameter	260	390	360
Water Productivity (mL/day)	4360	8100	7200
Thermal Efficiency (%)	38.5	42.6	40.3

Cost per Liter (₹)	0.0245	0.022	0.019

5. CONCLUSIONS

This study demonstrates the significant advantages of adopting modified double-slope solar still (MDSS) configurations for sustainable water purification. The integration of recyclable materials, improved thermal efficiency, and lower operational costs highlight the potential of MDSS systems as environmentally friendly solutions. The key outcomes are summarized as follows:

1. The MDSS-Al-S700 achieved the highest thermal efficiency (45.7%) and daily water productivity (7,527 mL/m²), showcasing its superior performance.
2. A cost per liter as low as ₹0.014 for MDSS systems underscores their economic viability compared to ₹0.0245 for conventional distillers.
3. The MDSS systems demonstrated rapid environmental payback times (EPT) as low as 0.25 years, significantly outperforming CDSS systems.
4. Carbon emissions reduction is notable, with MDSS configurations emitting 31 tons/year compared to 18 tons/year for CDSS, but the enhanced energy production factor (EPF) compensates effectively.
5. Integration of recyclable materials, such as aluminum and copper, ensures both sustainability and improved performance metrics.
6. The MDSS systems align with global sustainability goals, providing a cost-effective and scalable solution for water-scarce regions worldwide.

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