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Enhancement of Productivity and Economic Analysis of Tubular Solar Still with Acrylic Cover Material

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ABSTRACT

The integration of solar stills with materials capable of changing the phase and acting as storage for latent heat is an effective option for producing potable water from brackish water. Nevertheless, no single organic phase change material exhibits all the necessary advantageous properties, such as a particular temperature of melting and latent heat of fusion, to function well in a solar still under varying environmental circumstances. A tubular solar still comprising five copper cylinders filled with paraffin wax has shown a significant increase in distillation yield.

The impact of depth of basin water on performance of stills was examined (PCM with water depth of 4 cm) using Modified Tubular Solar Still (MTSS) under environmental conditions for city of Bhopal located in Madhya Pradesh, India. The result revealed a collective yield for Conventional Tubular Solar Still (CTSS) and the Modified Tubular Solar Still (MTSS) as approximately 4.1 and 5.5 kg/m^2 respectively. The result reveals that total hourly yields for CTSS and MTSS are approximately 1.22 and 2.24 kg/m^2 respectively. The production of solar distillate rose by 50.26% with the use of PCM in MTSS, in contrast to the basic scenario without PCM, where the output of solar distillate was 46.44% in CTSS. Water costs per liter for CTSS and MTSS-Acrylic are 0.14 and 0.13 US dollars, respectively.

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تعزيز الإنتاجية والتحليل الاقتصادي للمقطرات الشمسية الأنبوبية باستخدام غلاف من مادة أكريليكية

أشيش كومار شريفاستافا، رافي كيران، أنيل سينغ ياداف.

ملخص: يعتبر دمج المقطرات الشمسية مع مواد متغيرة الطور والتي تعمل على تخزين للحرارة الكامنة هو خيار فعال لإنتاج المياه الصالحة للشرب من المياه قليلة الملوحة. ومع ذلك، لا توجد مادة عضوية واحدة متغيرة الطور تظهر جميع الخصائص المرغوبة، مثل درجة حرارة الانصهار وحرارة الانصهار الكامنة، لتعمل بشكل جيد في المقطر الشمسي في ظل ظروف بيئية مختلفة. أظهرت وحدة الطاقة الشمسية الأنبوبية المكونة من خمس أسطوانات نحاسية مملوءة بشمع البارافين زيادة كبيرة في إنتاجية التقطير. كما تم دراسة تأثير عمق مياه الحوض على أداء المقطرات (PCM بعمق ماء 4 سم) باستخدام نظام التقطير الانبوبي المطور (MTSS) تحت الظروف المناخية لمدينة بوبال الواقعة في ولاية ماديا براديش، الهند. أظهرت النتائج أن اجمالي الانتاجية الكلية للمقطر الشمسي للنوعين التقليدي CTSS والمطور MTSS يبلغ حوالي 4.1 و5.5 كجم/م^2 على التوالي. وأن الإنتاجية الساعية للنوعين CTSS و MTSS بلغت حوالي 1.22 و 2.24 كجم/م^2 على التوالي. تشير النتائج على ارتفاع إنتاجية المقطر الشمسي بنسبة 50.26% مع استخدام PCM في MTSS، على عكس السيناريو الأساسي بدون PCM، وبلغت الزيادة حوالي 46.44% في نموذج CTSS. تكاليف المياه لكل لتر من CTSS و MTSS هي 0.14 و 0.13 دولار أمريكي على التوالي.

الكلمات المفتاحية – المواد المتغيرة الطور، الطاقة الشمسية، المقطر الشمسي الانبوبي، الماء المقطر.

1. INTRODUCTION

Freshwater, essential for life, is becoming increasingly scarce and difficult to access in its drinkable form. Although the Earth is rich in water, only about 2.5% is freshwater, and less than one percent of that is reachable for human consumption[1]. This imbalance has led to a significant global issue, as billions of people struggle to access safe drinking water. Factors such as population growth, pollution, climate change, and poor water management exacerbate the crisis, creating a challenge that impacts health, economies, and ecosystems worldwide[2].Climate change is another critical factor contributing to the freshwater issue. Rising global temperatures alter precipitation patterns, causing prolonged droughts in some regions and intense flooding in others[3]. Droughts lead to the drying up of rivers, lakes, and reservoirs, while floods overwhelm infrastructure and pollute water supplies with debris and waste. Melting glaciers, which serve as vital freshwater reserves for many regions, are shrinking at alarming rates, reducing the long-term availability of drinkable water[4]. The changes disrupt the natural water cycle and make freshwater sources increasingly unreliable[5]. In regions that receive a lot of direct sunlight, using renewable energy to power the distillation process is a great idea[6]. The water basin and its transparent cover are the two primary components of traditional solar stills, and they may be simply made from materials that are readily accessible in the area[7]. The apparatus exhibited a thermal efficiency of 50.55%, with a freshwater production cost of $0.0118 per litre and a daily output of 3.21 litres per square metre[8]. Optimisation of the Multi-Stage Flushing desalination apparatus was achieved by the use of conveniently accessible components and the use of a solar thermal collector system[9]. The unaltered CPC-TSS and CPC-CTSS systems generated 3710 ml/day and 4960 ml/day, respectively[10]. The use of gravel resulted in a thermal efficiency of 36.34% and a yield of 4.51 L/m^2 per day, in contrast to an efficiency of 31.9% and a yield of 3.96 L/m^2 per day without gravel [11]. A 40% decrease in TSS tube thickness resulted in a 21% enhancement in water productivity and a 13.35% rise in thermal efficiency, concurrently lowering water production expenses by 37.5%[12]. The research performed a quantitative evaluation across six Moroccan sites on typical days of each season [13]. The findings indicated that the most economical tracking system was 34.6% less costly than the priciest option. Furthermore, the minimum cost per liter (CPL) was $0.0074/L, representing a 43.1% reduction relative to the highest CPL category[14].

Notwithstanding these enhancements, the solar nonetheless stays less appealing in the market owing to its constrained productivity. Researchers around have tried to enhance the distillate yield of sun stills; however, none have yet pursued the commercialization of solar stills as a product.

A tubular solar still is a state-of-the-art water purification system that harnesses solar energy to distill water, making it suitable for drinking[15]. It consists of a transparent tubular chamber, typically made of glass or durable plastic, which acts as both the solar collector and evaporation chamber. Contaminated water is introduced into the bottom of the tube, where sunlight heats it, causing evaporation[16]. The vapor rises and condenses on the cooler interior surface of the tube, then collects in a clean reservoir. This procedure effectively eliminates contaminants like salts, bacteria, and heavy metals[17]. The tubular design optimizes sunlight absorption by providing a larger surface area and enabling a greenhouse effect, which enhances evaporation rates. Additionally, the cylindrical shape allows for easy rotation, ensuring maximum exposure to the sun throughout the day. Tubular solar stills are compact, cost-effective, and environmentally friendly, making them ideal for remote or arid regions where clean water is scarce.

The apparatus using PCM tubes exhibited a yield of 5.55 L/m²/day, an efficiency of 44.1%, and a cost of $0.00782 per litre, in contrast to 3.95 L/m²/day and 31.9% for a conventional system [18]. The TDSS with a nanoparticle coating attained a productivity of 6650 mL/m²/day, representing a substantial 137% increase compared to the 2800 mL/m²/day generated by the CSS system[19]. The results indicate that solar stills are environmentally sustainable desalination methods distinguished by their operational and design simplicity. Nevertheless, the solar energy conversion efficiency of existing desalination methods is below ten percent, underscoring the need for innovations to improve freshwater output. The current study demonstrates that the tubular solar still made of an acrylic glass material with a high light transmissibility boosts saline water productivity. In the ongoing review, Acrylic was utilized as the gathering surfaces to tentatively examine the CTSS and MTSS. In a similar paraffin wax , it is suggested that the CTSS and MTSS should investigate the potential advantages of employing a variety of phase change materials. During the experimental studies, it was noticed that some of the condensed droplets fell into the basin, which may influence the MTSS productivity. This requires additional investigation, and CTSS should investigate potential solutions to counteract this loss at night caused by atmospheric temperature. Therefore, MTSS was utilized with phase-change material, such as 5kg of paraffin wax. which was stuffed into five copper cylinder that were kept in the basin. It has likewise been noticed that the PCM gives the most elevated level of tubular solar still efficiency, however since its production required extensive expertise and time, it is exhorted that an affordable assembling technique be examined to deliver the low-thickness cylindrical glass cover for the MTSS. In this study maximum temperature 39.9^{0}C at 1 pm reached for water evaporation and find maximum hourly yield, cumulative yield, thermal efficiency and water cost. Research on a tubular solar still using Phase Change Material (PCM) assumes ideal cylindrical geometry with uniform heat transfer and perfect insulation. PCM properties (thermal conductivity, latent heat) are constant and homogeneous. Solar intensity is steady or averaged, with no shading or weather disruptions. Heat losses through radiation or convection are negligible, and water properties remain constant. The system operates continuously, efficiently converting absorbed heat into water evaporation and condensation. External environmental effects like wind or temperature variations are minimized. Measurements are accurate, and results are representative of real-world conditions, focusing on evaluating PCM's impact on solar still performance.

2. EXPERIMENTAL SETUP

The cylindrical tube acrylic glass used with height of 100 cm and a diameter of 50 cm. The extended region of the CTSS and MTSS was 5000 cm². The length and width of the trough are 86 cm and 38 cm, respectively, across the CTSS and MTSS and trough is made from steel material with black paint painted for better heat absorption. Thickness of trough sheet is 0.15cm.

Table 1. Exiting and modified solar still.

Sr. no.	Experimental Date	Still Type	
		Conventional	Modified
01	01-06-2023	CTSS (4 cm basin water depth without PCM	MTSS (4 cm basin water depth without PCM

3. METHODOLOGY

The Between hours of 10:00 am and 5:00 pm in June 2023, experimental observations were taken. The encompassing temperature (T_a), temperature of basin water (T_b), temperature of vapor temperature (T_v), and solar radiation intensity (I_r) were estimated all the while during the trials. At depths of 4 cm, the temperature of the basin's water was measured. K-type thermocouples were used to measure all these temperatures, and a digital data logger was used to record the thermocouple outputs. An analog Pyranometer (PYRA300) was used to measure solar radiation's intensity (I_r). The consolidated fresh water was gathered in an aligned bottle. Solar radiation intensity, freshwater productivity, and various current measuring temperatures were tracked every hour. Depending on the state of the climate conditions the intensity of the solar radiation varied from 150 to 860 W/m^2. The performances of the solar still with PCM and the conventional solar still are tested at the same basin water depth of 4 cm and under the same ambient conditions at 37^{0}C temperature[3].

Table 2. Uncertainty error for various experimental measuring devices.

Device	Accuracy	Range	Error
Solarimeter	± 1w/m^2	0-5000 w/m^2	0.15%
Thermocouples	±1 ^{0}C	-200:1250 ^{0}C	1.81%
Calibrated flask	±5ml	0-2000 ml	1.175%

(a) **(b)**

Figure 1. (a) Copper bottles with PCM filling; and (b) Copper hollow tubes.

Eleven copper tubes, each with a diameter of 2 cm and a height of 80 cm, were used, each containing 200 grams of PCM. Additionally, five copper cylinder, each with a diameter of 6 cm and a height of 24 cm, were used to hold 900 grams of PCM each, as shown in Fig.1 (a) & (b). Absorber area was primarily augmented by combining copper tubes and copper cylinders. This resulted in higher intensity of sunlight absorbed for better heat release during lowered sunlight. Gas welding and a sealant coating ensured a tight seal at both ends. During the phase change, the PCM's thermal expansion behavior caused all the tubes and cylinders to fill up to 85% of their total capacity.

The tubular solar stills were assembled with cylinders and tubes of copper occupied with parallel eutectic material capable of changing the phase. A hot plate at a constant temperature was used to melt the material. A magnetic stirrer was used for 30 minutes at 500 rpm to stir the hot pool of material.

Table 2. Thermo physical parameters of PCMs used [20].

PCM	Melting Temperature (^{0}C)	Latent Heat (KJ/g)	Thermal Conductivity (W/mK)
PW	53.7	0.21	0.2

(a) (b)

Figure 2. (a) & (b) Conventional Tubular solar still without pcm & Modified Tubular solar still with copper bottles with inserted copper hollow tubes Conventional Tubular solar still without pcm.

In CTSS absence of effective thermal storage means heat energy is wasted when sunlight is unavailable, limiting productivity The system's output is low, particularly under suboptimal sunlight conditions or in regions with fluctuating solar intensity. By presenting these design elements and performance drawbacks, readers can better appreciate the motivations behind the modifications introduced in the MTSS. These improvements, such as integrating PCM for thermal energy storage and using advanced materials, directly address these limitations, making the MTSS a more efficient and reliable solution.

4. RESULTS AND DISCUSSION

Hypothetical Analysis Thermal Energy:

Daily efficiency of the solar still can be examined using the following equation to determine the performance enhancement achieved by incorporating various modifications[21].

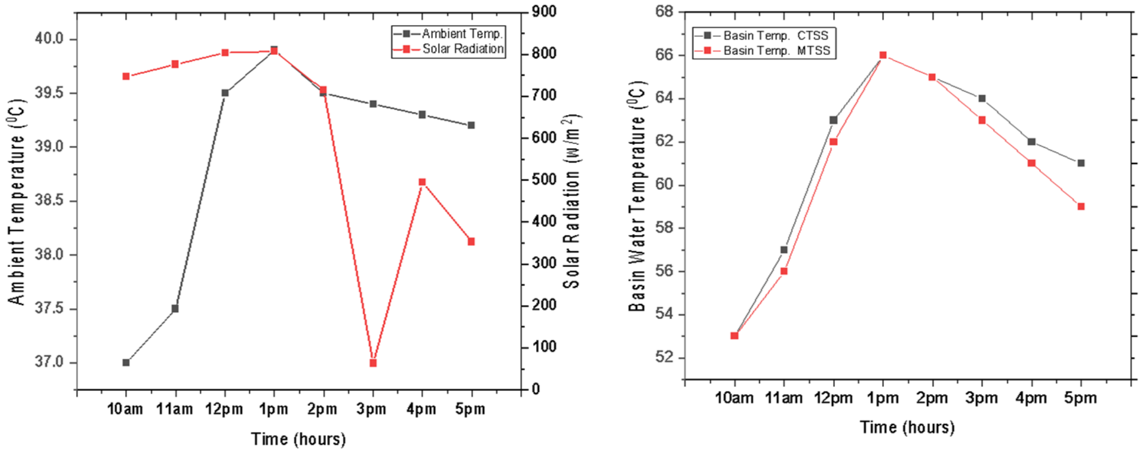
$$\eta_d = \frac{\sum h_{fg} \times m_p}{\sum A \times I(t)} \tag{1}$$

Where, m_p denotes the hourly new water supply (Kg/s), h_{fg} represents the latent heat of vaporisation (kJ/kg), *I(t)* indicates the average solar radiation value (KW/m^2), and An signifies the projected glass surface area (m^2)[14].

$$h_{fg} = 10^3 \left[2501.9 - 2.40706T_w + 1.192217 \times 10^{-3} T_w^2 - 1.5863 \times 10^{-5} T_w^3 \right] \tag{2}$$

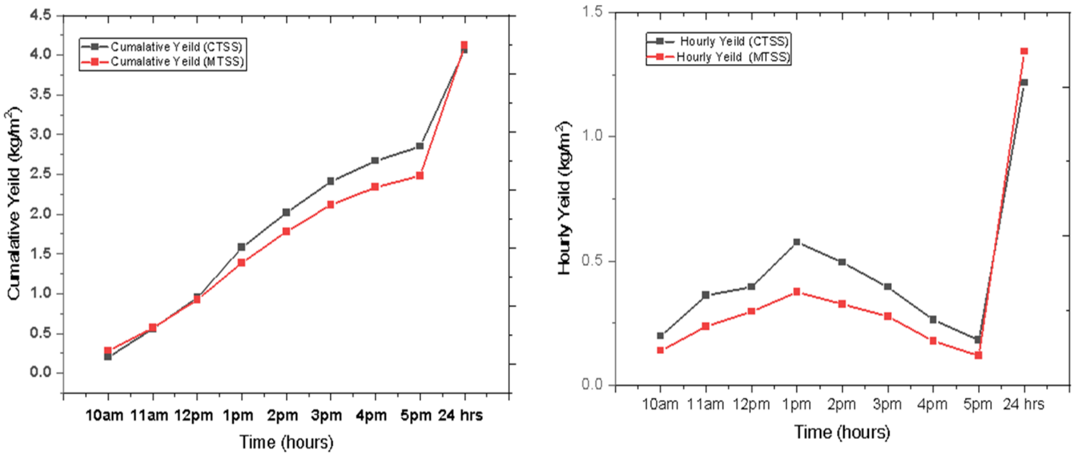
Where, T_w is the water temperature (°C).

This experimental investigation assessed the hourly collective yield, hourly freshwater output, and thermal efficiency of the Conventional Tubular Solar Still (CTSS) and the Modified Tubular Solar Still (MTSS). The two distinct examples of CTSS and MTSS. The performance of all quantified instances were evaluated by hourly measurements of several parameters, including solar radiation, water temperature, basin temperature, phase change material (PCM), ambient temperature, and fresh water production.



(a) **(b)**

Figure 3. (a) & (b) Solar Radiation v/s Ambient Temperature with time and Basin water temperature and ambient temperature with time.



(a) **(b)**

Figure 4. (a) & (b) Hourly cumulative yields of MTSS and CTSS & Hourly freshwater yield of MTSS and CTSS.

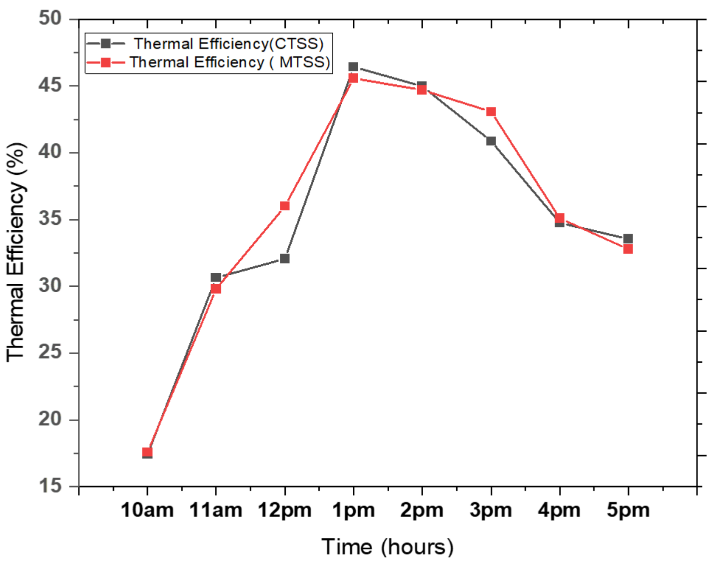


Figure 5 Thermal efficiency of MTSS and CTSS.

Execution of rounded sunlight based still with altered cylindrical sun powered still. When

selecting the materials for the current project, the most important considerations were availability, affordability, resistance to sunlight, transparency, and adaptability to the outdoor environment. As CTSS and MTSS covers, this work made use of Acrylic and PCM material for MTSS. The analyses were completed utilizing two unique CTSS setups with comparable determinations, yet involving one different material like PCM for the time of one month. The research can be used to make the following inferences.
CTSS and MTSS daily energy efficiency at 5 cm water depth was enhanced by (46.44%), and (50.26%).
Water costs per liter for CTSS and MTSS are 0.14 and 0.13 US dollars, respectively.
• The most cost-effective option is MTSS .
• A PCM has a higher rate of heat transfer inside the MTSS basin, which boosts evaporation and lowers condensing temperature.

Cost analysis of distilled water:
The economic analyses for the distilled water obtained from the CTSS and MTSS were calculated. The total fixed costs (F) of the CTSS and MTSS are 109.6$ and 145.6 $. Also, it assumed that the lifetime of system (n) = 10 years, and the interest rate (i) = 15%. Then , governing equations for the economic analyses as following[5]. The capital recovery factor equals.
CRF = i (1+i)n/ ((1+i)(n – 1))
Also , the fixed annual cost (FAC)
FAC = F (CRF)
As well , the sinking fund factor (SFF) is:
SFF = i/ ((1+i)(n - 1))
Furthermore , the salvage value (S) is:
S = 0.2 F
Also, the annual salvage value (ASV) is:
ASV = S (SFF)
The annual maintenance cost (AMC) are:
AMC = 0.15 (FAC)
And the total annual cost (TAC) is:
TAC = FAC + AMC – ASV
Then, the distilled water cost (CPL) in $/L is.
CPL = TAC/ Total distilled water production in the design life[1].

(CTSS) Total Fixed Cost =109.6 $
Calculations For CTSS System CPL
TAC= 2511.6 $
Yearly Productivity= m* operating days
=4.1*340
= 1394
Total distilled water production in the design life = yearly Productivity* n
= 1394*10
= 13940
CPL = TAC/ Total distilled water production in the design life
(CTSS) CPL = 0.14 $

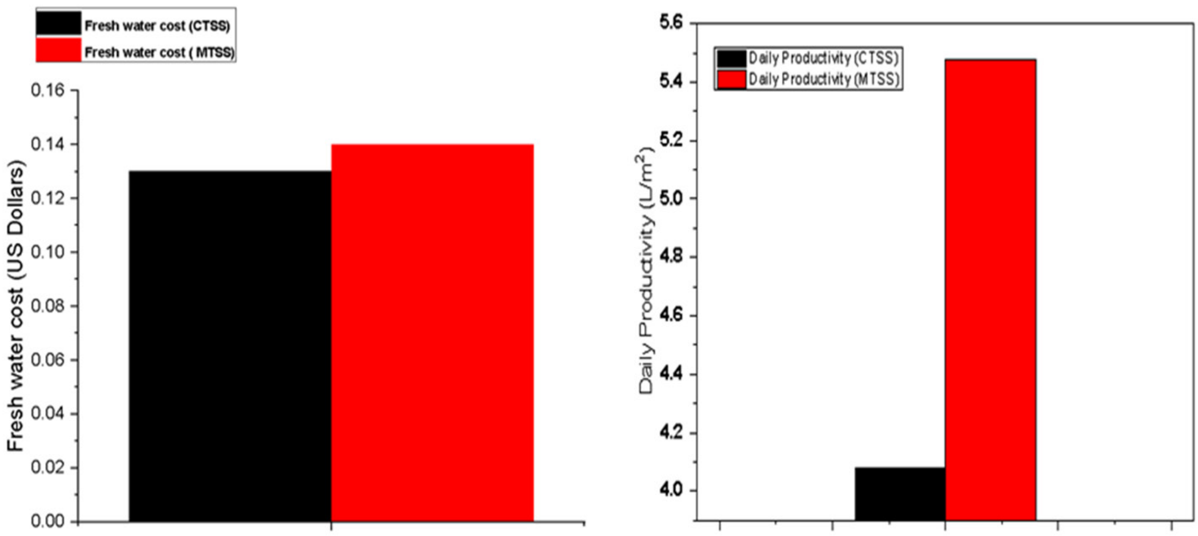
Calculations For MTSS System CPL
(MTSS) Total Fixed Cost – =145.6 $

Yearly Productivity= m* operating days
=5.5*340
= 1870

Total distilled water production in the design life = yearly Productivity* n
= 1870*10
= 18700

TAC= 2511.6 $

CPL= C/ Total distilled water production in the design life
= 252.08 /18700
= 0.13$



(a) (b)

Figure 6. (a) & (b): The daily freshwater cost for both CTSS and MTSS setup and Daily productivity of CTSS and MTSS Production.

CTSS: Produces water at $0.14 per liter, making it the less cost-effective option in terms of direct monetary expenditure.
MTSS : Costs $ 0.13 per liter. This lower cost may be attributed to improved system features or material enhancements.
The price difference appears minor on a per-liter basis but becomes more significant at higher production scales.
MTSS is more cost-effective, producing desalinated water at $ 0.13 per liter compared to CTSS $ 0.14 per liter. However, MTSS potential for higher efficiency and enhanced design may justify its higher costs in certain scenarios. The choice between these systems ultimately depends on priorities such as budget, scalability, and efficiency needs. Future innovations should aim to use MTSS solar still.

5. CONCLUSIONS

The results revealed a collective yield for CTSS and MTSS are approximately 4.1 and 5.5 kg/m^2 respectively. The result reveals that total hourly yields for CTSS and MTSS are approximately 1.22 and 2.24 kg/m^2 respectively.
The production of solar distillate rose by 50.26% with the use of PCM in MTSS, in contrast to the baseline scenario without PCM, where the output of solar distillate was 46.44% in CTSS.
Water costs per liter for CTSS and MTSS-Acrylic are 0.14 and 0.13US dollars, respectively.

Desalinated water production often peaks during summer months due to increased demand for water. Seasonal factors like higher temperatures lead to greater water consumption for drinking, irrigation, and cooling purposes. Additionally, in regions with limited natural freshwater resources, desalination plants ramp up production during summer to meet this increased demand. Explaining this context would clarify the connection between seasonal factors and the operational adjustments of desalination plants.

A summary of the main technical enhancements introduced in the Modified Tubular Solar Still (MTSS) would be valuable. For instance, highlighting the role of materials capable of changing the phase, PCM in enhancing storage of thermal energy and extending operational efficiency, the use of advanced materials to improve durability and heat retention, and any design modifications that boost water evaporation and condensation rates would effectively underscore the value of these improvements.

Explore alternative PCM materials with higher thermal storage capacities, better compatibility with the system, and reduced costs to enhance overall efficiency. Investigate the scalability of the design for larger installations and assess how the system can be integrated with other renewable energy technologies, such as photovoltaic panels, to maximize output. Incorporate smart sensors and automated control systems to monitor and regulate the still's performance in real time, ensuring optimal operation. Perform detailed economic assessments to determine the cost-effectiveness of the PCM-based solar still and identify ways to reduce production costs for broader market adoption.

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