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Enhancing Pyramid Solar Still Productivity Using Natural and Volcanic Pebbles as Sensible Heat Storage Media: An Experimental Study

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Summary

This study presents an experimental investigation on enhancing the performance of a pyramid solar still (PSS) using locally sourced natural and volcanic pebbles as passive thermal energy storage materials. Two modified systems—natural pebble (PSS-NP) and volcanic pebble (PSS-VP)—were compared with a conventional pyramid solar still (CPSS) under arid climatic conditions in Ghardaïa, Algeria. The integration of pebbles improved thermal storage within the basin, resulting in higher water temperatures and enhanced evaporation rates. Among the tested configurations, the volcanic pebble system exhibited the best performance due to its porous structure and higher solar absorptivity. The PSS-VP achieved a maximum basin water temperature of 48.04 °C and increased daily freshwater production by up to 75% compared to the conventional system. Furthermore, the proposed modification requires only minimal additional cost, ensuring economic feasibility. These results demonstrate that volcanic pebbles offer a simple, low-cost, and efficient solution for improving solar still productivity in arid regions with high solar irradiance.

Keywords: Heat storage materials, natural pebble, pyramid solar still, volcanic pebble.

Field of application for the findings: Sustainable Heat for Industrial Process

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1. Introduction

Water scarcity has become one of the most pressing global challenges, driven by rapid population growth, industrialization, and environmental degradation. This issue is particularly severe in arid and semi-arid regions, where limited freshwater resources and high evaporation rates exacerbate water stress. In this context, the development of sustainable, low-cost, and decentralized water production technologies is essential to ensure access to safe drinking water (M. Edalatpour et al. 2016). Solar desalination, especially solar distillation, offers a promising solution due to its simplicity, low energy requirements, and environmental sustainability. By mimicking the natural hydrological cycle, solar stills utilize solar energy to evaporate saline or brackish water and subsequently condense the vapor into potable water. Despite these advantages, conventional solar stills suffer from relatively low productivity, which limits their large-scale implementation (T. Chekifi et al. 2024). To address this limitation, numerous studies have focused on enhancing solar still performance through design improvements and thermal management strategies.

These include optimizing geometrical configurations, integrating thermal energy storage (TES) materials, and enhancing heat and mass transfer processes using advanced materials such as fins, nanofluids, and phase change materials. Among various configurations, pyramid solar stills have gained attention due to their ability to capture solar radiation from multiple directions, increase condensation surface area, and reduce shading effects, resulting in improved freshwater yield compared to traditional designs.

In parallel, the integration of low-cost and locally available thermal storage materials has emerged as an effective approach to enhance heat retention and prolong evaporation periods. In this regard, natural and volcanic pebbles represent attractive candidates due to their availability, thermal inertia, and favorable physical properties. In regions such as Ghardaïa (Algeria), these materials are widely accessible in mountainous areas and dry riverbeds (locally known as El Oued), making them a sustainable option for solar desalination applications (Rahbar et al.,2018) .

In this study, an experimental investigation is conducted on a square pyramid solar still enhanced with natural pebbles (PSS-NP) and volcanic black pebbles (PSS-VP) used as thermal energy storage media. The systems are evaluated under real arid climatic conditions at the URAER research center. The main objective is to improve freshwater productivity while assessing the technical and economic feasibility of utilizing locally sourced materials for scalable solar desalination systems in desert environments.

2. Materialsandmethods

Two identical Pyramid Solar Stills (PSSs) were installed at the URAER research facility in Ghardaïa, Algeria. Each still has a square base measuring 75 cm × 75 cm and a basin depth of 8 cm. The pyramid structure consists of four transparent glass sides, each 4 mm thick, inclined at an angle of approximately 48.7°. The peak height reaches about 47.6 cm above the basin. Each glass side has a slant edge length of roughly 53 cm, corresponding to a condensation surface area of 0.56 m² per side, or 2.24 m² in total.The conventional pyramid solar still (CPSS) features a basin made of aluminum with a black coating to maximize solar absorption. The second still was modified by adding 6 kg of thermal energy storage material, which was tested in two configurations: natural pebbles (PSS-NP) and volcanic pebbles (PSS-VP) (Figure .1).

Temperature measurements were carried out using type-K thermocouples positioned in the basin water, on the basin plate, on the inner glass surfaces, and in the ambient air. Solar radiation intensity was measured with a pyranometer. The distillate output from each face of the pyramid was collected hourly and measured using precise graduated cylinders.

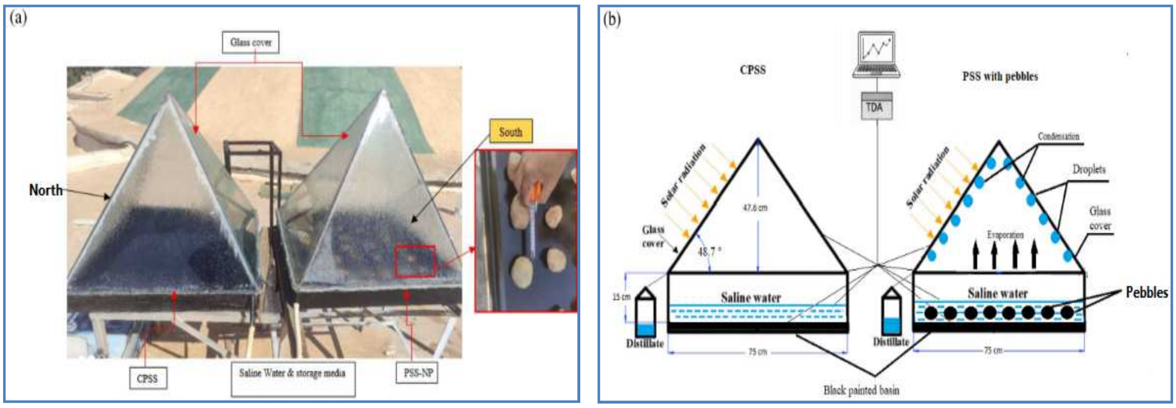

Fig. 1: Experimental Setup of the Conventional Pyramid Solar Still (CPSS).

Experiments were carried out on clear and sunny days from 9:00 AM to 7:00 PM, and the stills were oriented in the North–South direction to maximize solar exposure. All measurements were recorded simultaneously and under identical environmental conditions to ensure reliable comparison among the control pyramid solar still (CPSS), the natural-pebble still (PSS-NP), and the volcanic-pebble still (PSS-VP). Although several trials were performed over the experimental period, only a limited number of days were considered in the final analysis due to recurring issues encountered during preliminary tests, including waterproofing defects, malfunctioning of the data acquisition system, and improper placement or performance of sensors. During each selected experimental day, the water depth inside the basin was maintained at 5 cm. The heat-storage materials (natural and volcanic pebbles) were uniformly distributed while maintaining a consistent 10 cm spacing to promote homogeneous heat distribution and efficient evaporation. Measurements were collected every 10 minutes through a digital data-logging system. A multimeter was used regularly to verify sensor connectivity, and a ruler was employed to confirm the dimensions and spacing of the pebbles. This standardized setup ensured accurate assessment of the thermal behavior and freshwater productivity of the three configurations, allowing a robust comparison of how different heat-storage materials influence temperature profiles, heat retention, and distillate yield throughout the diurnal cycle. All components of the experimental setup were thoroughly inspected, documented, and continuously monitored throughout the testing period. Table 1 summarizes the primary measurement instruments including thermocouples, digital thermometers, a Keithley data acquisition system, and solar radiation sensors along with their respective measurement ranges and associated uncertainties (Khelifi R et al., 2021). Meteorological parameters such as ambient temperature, wind speed, and relative humidity were obtained from the on-site URAER weather station in Ghardaïa to accurately reflect real outdoor conditions. The integration of these environmental measurements ensured that the performance evaluation of the solar stills was conducted under realistic climatic conditions, thereby enhancing the validity and applicability of the results. Through this rigorous, instrument-based methodology, the influence of the selected heat storage materials on the thermal behavior and freshwater productivity of the pyramid solar stills was assessed with a high level of accuracy and confidence.

Table 1.Details of the Measurement Devices Employed in the Investigation

Instrument image	**Instrument**	**Quantity measured**	**Uncertainty %**	**Range**
	Solar radiation intensity	stations météorologiques	±2%	0–1W m^{-2}
	THERMOCOUPLE	Temperature	±5%	0-400°C
	Thermometer DM6802	Temperature	±5%	-50 to 1300°C
	Keithley 2010 Industrial Multimeters	Temperatures	±1%	-328-2501

2.1. The thermal efficiency

The thermal efficiency of a solar still represents its ability to effectively convert incident solar radiation into useful distilled water output. It is a key performance indicator for assessing the overall effectiveness of the desalination process, particularly in arid and water-scarce regions. A higher thermal efficiency reflects better utilization of available solar energy, resulting in increased freshwater production and reduced thermal losses. Evaluating and improving thermal efficiency allows for the optimization of solar still design and operating conditions, thereby enhancing system performance and sustainability. In this study, the thermal efficiency (η) is determined based on the ratio of the useful energy associated with the evaporated water to the total incident solar energy received by the *system* (S. M. Elshamy and E. M. El-Said, 2018).

$$\eta_{d=}\frac{\sum \dot{m}\times h_{fg}}{A\times I}\times 100 \qquad \text{(eq. 1)}$$

Where ṁ is the distillate production rate, hfg is the latent heat ofvaporization, A is the system area, and I is the solar radiation intensity.The latent heat of vaporization is given by:

$$h_{fg} = 2501.67 - 2.389 \times T_w \qquad \text{(eq. 2)}$$

3. Results and discussion

This section presents a detailed evaluation of the experimental results related to the thermal performance of the pyramid solar still under different operational configurations. Key thermal parameters, including basin water temperature, absorber basin temperature, and glass cover temperature, are systematically compared for each enhancement technique. The objective of this analysis is to assess the influence of these modifications on heat storage, evaporation intensity, and the overall distillation efficiency of the system.

3.1. Meteorological Conditions

This subsection describes the local weather conditions during the experimental period, encompassingsolar radiation, ambient temperature, wind speed, and relative humidity. These environmental factors significantly impact the performance of solar stills and are vital for accurately interpreting the thermal and distillation outcomes of the study.

3.1.1.Solar radiation and ambient temperature

This subsection presents the daily variation of solar radiation and ambient temperature recorded during the experimental days. These parameters are fundamental in assessing the energy input available for the solar stills and in understanding their thermal response under real operating conditions. The data serve as a reference for analyzing the thermal behavior and productivity trends of the tested systems.

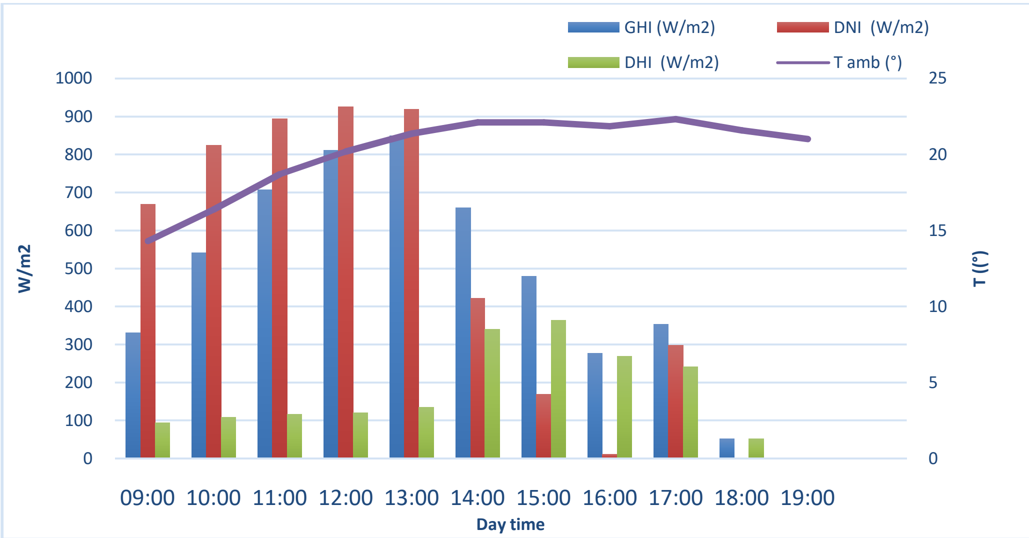

Fig .2: Evolution of ambient temperatures, DHI, DNI and GHI during 02 mars

Figure 2 illustrates the daily variation of solar irradiance components (GHI, DNI, and DHI) and ambient temperature on March 2, 2025. Solar radiation increases significantly in the morning, reaching peak values around midday (≈800 W/m² for GHI and ≈700 W/m² for DNI), before declining toward evening. Ambient temperature follows a similar trend, rising from 12°C to about 22°C, then decreasing later in the day.

These conditions indicate strong solar potential, supporting effective evaporation and high water temperatures, particularly for the enhanced system (PSS-VP). The presence of diffuse radiation contributes to stable performance under varying conditions. However, the limited duration of peak solar intensity highlights the importance of thermal energy storage. In this regard, volcanic pebbles improve heat retention compared to natural pebbles, helping sustain productivity beyond peak hours. Overall, the climate is favorable for solar distillation, though improvements in insulation and heat storage are needed to enhance performance during low-radiation periods.

3.2. Glass cover and basin absorber temperature

This subsection analyzes the transient thermal behavior of pyramid solar still configurations by examining the evolution of basin absorber temperature (T-B) and glass cover temperature (T-G). These parameters play a pivotal role in governing the evaporation–condensation mechanism and, consequently, the overall freshwater productivity. Evaluating these profiles under real climatic conditions provides insight into the effectiveness of thermal storage materials in enhancing heat retention and internal heat transfer processes.

As shown in Figure 3, the temporal variations of T-B, T-G, and ambient temperature (T-amb) are presented for different configurations. Figure 3a (March 6th) compares CPSS and PSS-NP, while Figure 3b (March 12th) compares CPSS and PSS-VP. In both cases, the systems exhibit a clear diurnal trend characterized by a progressive temperature rise from morning hours, peak values during mid-afternoon, and a subsequent decline toward sunset. For March 6th, the CPSS demonstrates a higher basin temperature, indicating stronger direct solar absorption. However, the PSS-NP exhibits a significantly higher glass cover temperature, revealing enhanced internal heat redistribution due to the presence of natural pebbles. This improved thermal coupling between water and glass promotes higher humidity levels and strengthens the condensation process, even with a slightly lower basin temperature. Similarly, on March 12th, although the CPSS reaches a higher peak T-B, the PSS-VP maintains a comparable T-G. This suggests that volcanic pebbles contribute effectively to thermal energy storage and delayed heat release, which helps sustain favorable condensation conditions beyond peak solar hours. Such behavior highlights the advantage of integrating thermal storage materials in stabilizing internal temperatures and improving the overall efficiency of solar desalination systems.

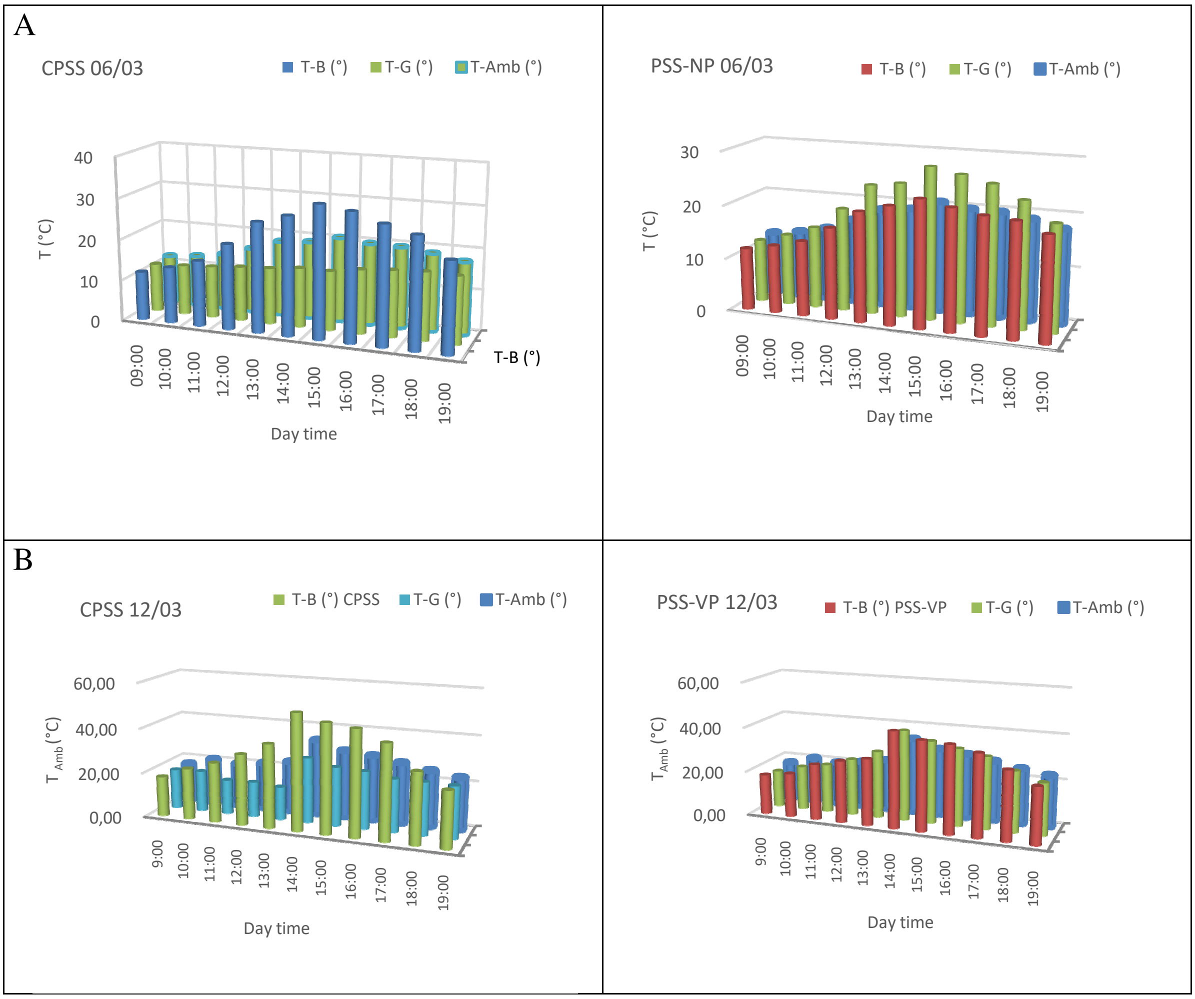

Fig. 3: Variation of surfacebasin absorber and glass cover temperature in for conventional solar still, solar still with pyramid solar till for: A:CPSS and PSS-NP during 6th mars. And B: CPSS and PSS-VP during 12th mars.

3.3. Brackish water and Basin

This subsection evaluates the thermal behavior of brackish water and basin absorber temperatures across different pyramid solar still configurations. The findings show that integrating thermal storage materials significantly enhances heat retention compared to the conventional system (CPSS). The PSS-NP configuration reaches peak water temperatures of approximately 54 °C (March 7) and 45 °C (March 9), exceeding those of the CPSS due to the heat storage effect of natural pebbles (Figure.4). Meanwhile, the PSS-VP demonstrates the highest performance, with peak water and absorber temperatures of about 57 °C and 50 °C, respectively, recorded on March 12.
These results confirm that thermal storage materials improve temperature stability and evaporation conditions, with volcanic pebbles providing the most effective enhancement in thermal efficiency and distillation potential.

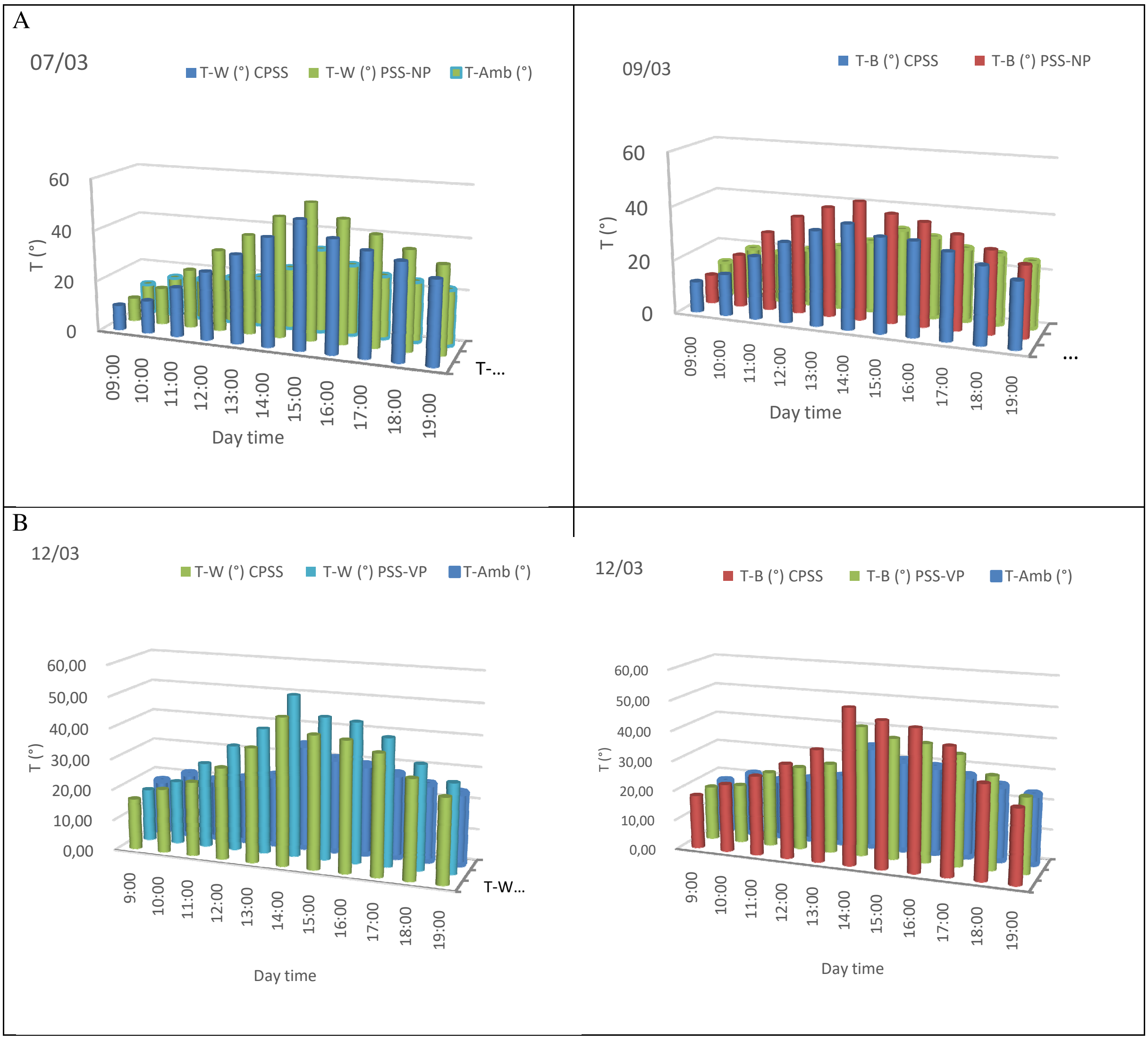

Fig. 4: Hourly variation of brackish water and basin absorber temperatures compared to ambient temperature for (A) CPSS and PSS-NP on March 7 and 9, and (B) CPSS and PSS-VP on March 12.

4. Distillation efficiency analysis

4.1. Productivity analysis

This section examines the freshwater productivity of different pyramid solar still configurations by comparing daily distillate yields. The objective is to evaluate the influence of design modifications and the incorporation of thermal storage materials on system performance. By analyzing trends over multiple days, the effectiveness of natural and volcanic pebbles in enhancing evaporation rates and overall efficiency, relative to the conventional system (CPSS), is clearly demonstrated.

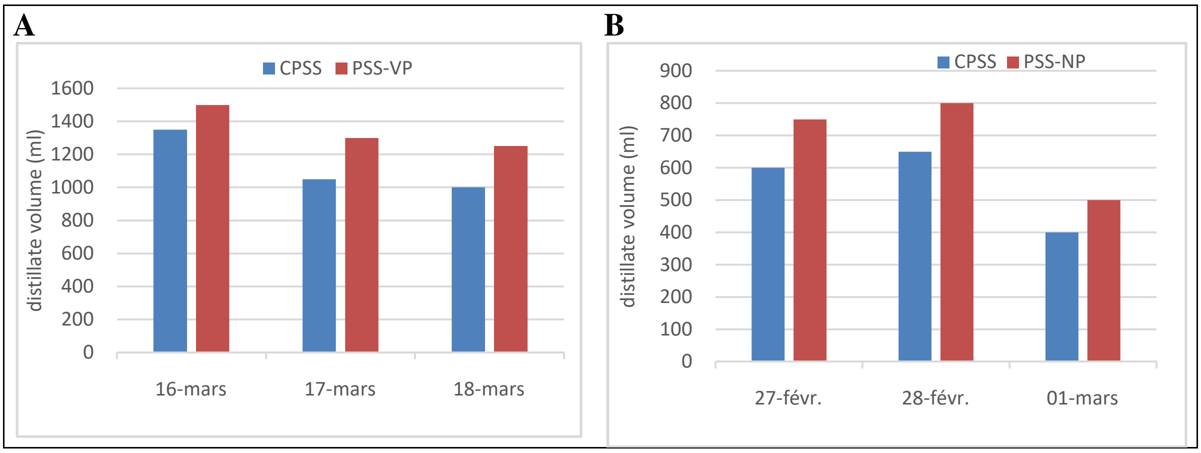

Fig.5: The distillate collected at 20 PM for the three days for: A: CPSS and PSS-NP, PSS-NP and CPSS and PSS-VP.

As illustrated in Figure 5 (A–B), the hourly distillate production follows the typical diurnal solar irradiance pattern, with a sharp increase after 10:00, peak values observed between 13:00 and 14:00, and a gradual decline toward evening. The integration of solid thermal storage materials significantly alters the basin's thermal behavior. Both PSS-NP and PSS-VP configurations exhibit extended evaporation periods beyond peak solar hours, attributed to their ability to store sensible heat and release it progressively.Among the tested systems, the PSS-VP configuration demonstrates superior performance. This is mainly due to the high porosity, irregular surface structure, and enhanced thermal diffusivity of volcanic pebbles, which promote efficient heat absorption, internal energy storage, and sustained vapor generation. Additionally, their relatively higher specific heat capacity and lower density contribute to improved thermal responsiveness, reducing temperature fluctuations and delaying heat loss after sunset.In contrast, the PSS-NP configuration provides moderate improvement compared to CPSS. Although natural pebbles possess lower porosity and thermal storage capacity than volcanic pebbles, they still act as effective passive thermal regulators by stabilizing basin temperature and enhancing evaporation under lower solar radiation conditions.

4.2. Distillation performance

This subsection provides a detailed evaluation of the distillation efficiency of pyramid solar stills, focusing on daily freshwater output. It compares the conventional pyramid solar still (CPSS) with enhanced versions incorporating natural pebbles (PSS-NP) and volcanic pebbles (PSS-VP) as heat storage materials. By analyzing distillate collection over several days, this section underscores the impact of thermal mass, heat retention, and material properties on water productivity. The findings illustrate how integrating affordable, locally sourced materials can substantially improve distillation rates, offering a practical upgrade to conventional solar desalination systems.

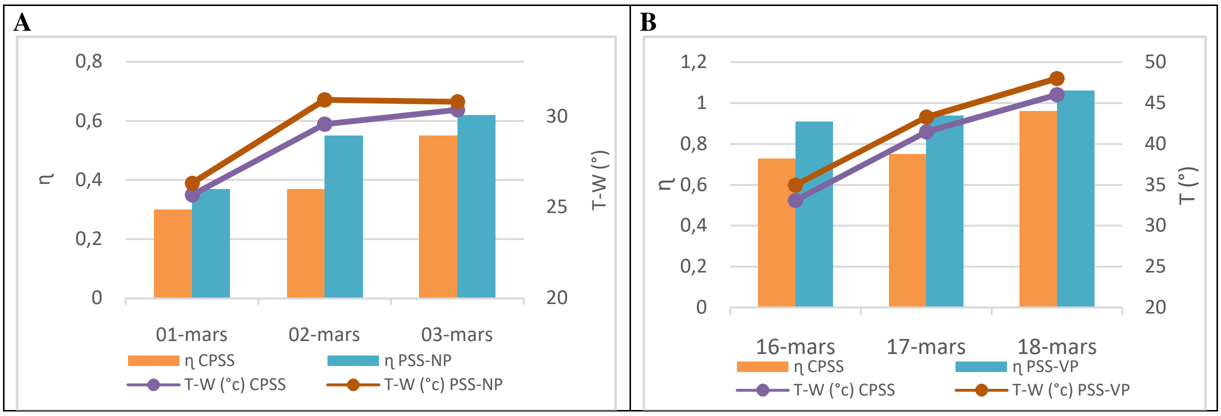

Fig. 6: Thermal efficiency of three days comparing conventional PSS and with Pebbles, A: CPSS and PSS-NP, B: CPSS and PSS-VP

Figure 6 presents the thermal efficiency (η) and water temperature (T-W, °C) of the solar distillation system in Ghardaïa (32.36° N, 3.81° E), a desert region characterized by high direct normal irradiance (DNI ≈ 2305 kWh/m²/year). The performance of three configurations—CPSS, PSS-NP (natural pebbles), and PSS-VP (volcanic pebbles)—is compared over selected days in March. Favorable climatic conditions, including solar intensity ranging from approximately 530 to 550 W/m² (09:00–19:00) and a high frequency of clear skies (>75%), contribute significantly to system performance. From March 1 to March 3, the thermal efficiency of CPSS increases from 0.30 to 0.55 (≈83%), while PSS-NP rises from 0.37 to 0.62 (≈68%). During the same period, water temperature (T-W) for CPSS increases from 25.67 °C to 30.35 °C (≈18%), and for PSS-NP from 26.33 °C to 30.79 °C (≈17%). These results indicate that natural pebbles improve efficiency by approximately 0.07–0.18 and increase water temperature by about 0.44–1.33 °C. This enhancement is attributed to their dense structure, which supports heat retention and stabilizes vapor generation, although their relatively smooth surface limits further thermal gains.From March 16 to March 18, higher performance levels are observed. The CPSS efficiency increases from 0.73 to 0.96 (≈32%), whereas PSS-VP rises from 0.91 to 1.06 (≈16%). Water temperature increases from 33.13 °C to 46.02 °C (≈39%) for CPSS and from 35.01 °C to 48.04 °C (≈37%) for PSS-VP. Volcanic pebbles outperform CPSS by approximately 0.10–0.18 in efficiency and 1.88–2.02 °C in temperature.

4.3. Comparison with previous research

This subsection provides a comparative analysis of the current study against prior research in solar still technology, emphasizing design variations and enhancement techniques, including nanomaterials, reflectors, and phase change materials, and their impacts on water productivity and efficiency. By comparing the performance of pyramid solar stills using natural and volcanic pebbles with existing studies, this section highlights the practical and economic feasibility of utilizing locally sourced thermal storage materials. It aims to illustrate how cost-effective modifications can achieve competitive productivity rates, providing sustainable freshwater solutions for regions with abundant solar radiation and scarce water resources.

Tab. 2: Comparison of our work and previous studies on solar still designs, modifications, additives, productivity, and rate of increase

Design of SS	**Ref.**	**Modification/Additives**	**Productivity (Kg/m^2.day)**	**Rate increase (%)**
Single slope solar distiller	(Elango et al. 2015)	-0.1 wt% SnO_2 NF -0.1 wt% Al_2O_3 NF -0.1 wt% ZnO NF	0.805 0.935 0.750	18.62 29.95 12.67
Tubular solar still	(Kabeel et al.2021)	Wicks and v-corrugated basin	6.01	6.010
Trays solar distiller	(Abdullah et al.2020)	-Internal reflectors -Reflectors +CuOnano black paint -Reflectors +CuOnano black paint+CuOnano mixed PCM	3.45 4.10 5.00	57.00 70.70 108.0
Single slope solar distiller	(Johnstone and m adhlopa.2009)	External condenser	6.08	62.01
Tubular solar still	(Elshamy and El-said.2018)]	Hemi-circular v-corrugated basin	4.30	26.47
PSS-NP PSS-VP	Present work	Pyramid solar still with natural pebbles Pyramid solar still with volcanic pebbles	1.68 2.49	46.15% 75 %

Table 3 presents a comparison of solar distiller designs and modifications, including the effects of additives, nanomaterials, and PCMs on productivity and efficiency. In previous studies, the best results were obtained with Al_2O_3 nanofluids, CuO nanomaterial paints combined with PCMs, or external capacitors, achieving up to 6.08 kg/m^2/day and productivity increases exceeding 100%. In the present study in Ghardaïa, the PSS-NP produced 1.68 kg/m^2/day (+46.15%) and the PSS-VP 2.49 kg/m^2/day (+75%), confirming that mineral-rich volcanic pebbles enhance heat absorption and storage. Although the absolute productivity is lower than that of some advanced designs, the rates of increase remain competitive in a high-solar desert environment.

5. Conclusion

This study demonstrates the effectiveness of incorporating natural and volcanic pebbles as passive thermal energy storage materials in pyramid solar stills (PSS) operating under the climatic conditions of Ghardaïa (32.36° N, 3.81° E), a region characterized by high solar potential. The main conclusions are as follows:

The integration of natural and volcanic pebbles significantly enhances the thermal and productivity performance of pyramid solar stills compared to the conventional configuration, improving heat retention, evaporation rates, and overall distillation efficiency.

The pyramid solar still with volcanic pebbles (PSS-VP) shows superior performance, achieving a maximum thermal efficiency of 1.06 and basin water temperatures up to 48.04 °C, compared to 0.62 and 30.79 °C for the natural pebble system (PSS-NP). This improvement is mainly attributed to the porous and mineral-rich structure of volcanic pebbles, which enhances heat absorption and storage under high solar irradiance conditions.

The productivity increase of 75% obtained with PSS-VP is competitive with more complex enhancement techniques (e.g., reflectors and phase change materials), while maintaining a simpler and more cost-effective system design.

Further improvements in insulation and thermal retention are recommended to minimize heat losses during early morning and late afternoon periods, thereby extending operation time and improving long-term system performance.

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