Performance Enhancement and Sustainable Utilization of Waste Cement Stone and Mountain Stones as Thermal Storage Materials in Solar Distillation

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Abstract – *This study presents an experimental investigation into improving the performance of a single-slope solar still through the integration of economical and locally sourced thermal storage materials: mountain stones and cement stone waste, compared to a reference still. The experiment quantified the impact of these materials on daily water yield and overall thermal efficiency. The results demonstrated a clear performance hierarchy: (MSM > DPC > AR). The MSM unit achieved the highest cumulative daily yield (940 ml), corresponding to a maximum daily thermal efficiency of 28.82%, representing a 42.4% improvement over the reference still (20.23%). Significantly, the DPC unit, using recycled construction waste, achieved a remarkable efficiency of 25.75%, with a daily yield of 840 ml. From an economic standpoint, the performance gains translate into exceptionally rapid returns on investment: the SSms unit recorded the shortest payback period (13.4 days), closely followed by the SScs unit (15.0 days). This result confirms the techno-economic feasibility and environmental viability of using readily available construction waste as an effective construction waste management solution. The successful application of cement waste offers a sustainable and cost-effective model for simultaneously improving water production and managing construction waste, thus providing a robust solution for sustainable desalination in resource-limited regions.*

Keywords: *Solar energy, Solar Distillation, Pure water, Thermal Storage Material (TSM), Thermal Efficiency.*

Received: 17/10/2025 – Revised: 06/11/2025 – Accepted: 09/12/2025

I. Introduction

Freshwater scarcity remains one of the most critical global challenges, particularly in arid and semi-arid regions where groundwater resources often exhibit high salinity and chemical contamination [1]. In southeastern Algeria, for example, several studies have confirmed that groundwater exceeds WHO drinking standards, making desalination indispensable for safe water supply [2]. Solar distillation has long been recognized as a promising solution because of its simplicity, low cost, and ability to operate without electricity, making it highly suitable for remote and economically constrained regions [3–5]. However, despite its environmental advantages, the widespread deployment of solar stills is limited by their inherently low productivity and poor thermal efficiency [6,7].

Numerous studies have shown that the performance of solar stills depends strongly on climatic parameters such as solar radiation, ambient temperature, and wind speed

[8], as well as controllable design factors including water depth, glazing thickness, cover angle, insulation, and absorber properties [9,10]. Reviews conducted in recent years emphasized that although a wide variety of enhancement techniques have been proposed—such as wicks, PCM materials, nanofluids, nanocoatings, multi-effect stages, and reflective systems—there is no universal optimum, and the efficiency of each modification depends on local availability, simplicity of implementation, and cost considerations [11–13].

A large body of experimental research conducted in Algeria has extensively investigated structural modifications. Studies on glass thickness demonstrated that thinner glazing improves heat transmission and distilled output [14], while adjusting the cover tilt angle according to seasonal conditions improves condensation efficiency [15]. Other investigations revealed that some expected improvements can be counterproductive: double glazing, for instance, significantly reduces thermal performance and productivity [16,17]. External reflectors have been shown to effectively increase incident solar energy and yield [18], whereas double-air-chamber glazing decreased performance by more than 50% [19].

Another major research direction has focused on thermal storage materials (TSM), which improve thermal inertia and prolong evaporation during late afternoon and early night hours. Many low-cost and locally available TSMs have shown promising results. Metallic materials such as zinc plates enhanced basin temperature and productivity [20], while aluminum waste, abundant in several southern Algerian regions, generated substantial increases in freshwater production [21]. Waste-derived materials including industrial coal debris [22,23], small iron pieces [24], natural charcoal blocks [25], and various carbon-based materials like activated carbon, graphite, coal, and wood charcoal demonstrated considerable productivity gains [26].

Organic agricultural residues have also been explored. Palm fibers, widely available in Algerian oases, significantly improved water output in several configurations [27,28]. Palm stems yielded more than a 50% improvement in fresh water output due to their high absorptivity and porosity [29]. Date and olive kernels used as sensible storage materials produced exceptional enhancements—over 175% and 225% respectively—under identical operating conditions [30].

Other enhancement strategies target the manipulation of interfacial and thermal behavior. Reducing surface tension via the addition of coal powder in hemispherical stills enabled a substantial increase in evaporation rate and thermal efficiency [31]. Several geometric modifications, such as the incorporation of plastic fins in the basin or on the condenser, demonstrated that improving heat transfer pathways can positively affect the evaporation–condensation cycle [32,33]. The integration of iron rods into the basin enhanced heating and increased total daily output compared to conventional stills [34]. Meanwhile, absorber redesigns using multilayer composites showed that not all complex modifications ensure improvement, highlighting the importance of cost-effective, low-risk solutions [35].

Hybrid systems combining solar stills with other technologies such as humidification–dehumidification (HDH) systems or stepped solar stills with PCM tubes have recently been shown to dramatically increase productivity due to extended heat retention and improved energy transfer [36–38]. Nanofluid encapsulation, which enhances thermal conductivity while preventing contamination, represents another emerging technique aligned with sustainable development goals [39].

Addressing the twin challenges of water scarcity and construction waste management, this study presents a novel approach to enhance solar distillation efficiency using low-cost, locally sourced Thermal Storage Materials. This study systematically investigates the comparative performance and techno-economic viability of recycled waste cement stone alongside natural mountain stones in a single-slope solar still. The primary objective is to experimentally quantify the resulting enhancement in daily water yield and thermal efficiency, aiming to establish a robust framework that confirms the feasibility of repurposing construction waste for sustainable desalination in arid regions.

II. Methodology

The comparative experimental program was conducted in El Oued, Algeria, at the end of June 2024, under the same climatic conditions characteristic of the region. The main objective of this experiment was to quantify the difference in performance – particularly in terms of daily water yield and thermal efficiency – of two economical thermal storage materials (natural mountain stones and cemented stone waste), compared to a reference still. The study used three identical, single-slope solar stills, each with a 50 cm × 50 cm basin, representing a collection area of 0.25 m². All stills were placed in the same orientation and operated simultaneously to ensure rigorous control of external variables such as solar intensity.

The methodology consisted of introducing an equal mass of 1.7 kg of natural mountain stones into the SSms unit basin and cemented stone waste into the SScs unit basin, while the SSref unit remained empty as a control as shown in Figure 1. All three stills were initially filled with the same quantity of water. The experiment was conducted over an 11-hour period, from 8:00 h. to 7:00 h. During this period, the volume of pure water produced was accurately measured and recorded hourly for each still. This systematic data collection allowed for the precise determination of the instantaneous hourly productivity, the cumulative daily yield (Figure 3), and, consequently, the calculation of the overall daily thermal efficiency (Figure 4) for each configuration, thus providing a solid basis for comparative performance analysis.

Figure 1. Experimental Setup Showing the Three Solar Still Configurations

III. Results

3.1. Solar radiation

Figure 2 illustrates the hourly distribution of solar radiation and ambient temperature recorded during the experimental test day. Relevant analysis confirms that the experimental conditions were ideally suited for solar distillation, with a peak in intense solar radiation of approximately 1009 W/m² at 13:00h. Crucially, the ambient temperature reached its maximum value of 40°C one hour later, at 14:00h. This time lag between the two peaks is a key indicator of the heat accumulation dynamics within the system. The afternoon period is particularly significant because the distillation efficiency during this time is highly dependent on the thermal storage material's ability to retain and release stored heat, making it the primary differentiating factor between the performance of the two materials tested.

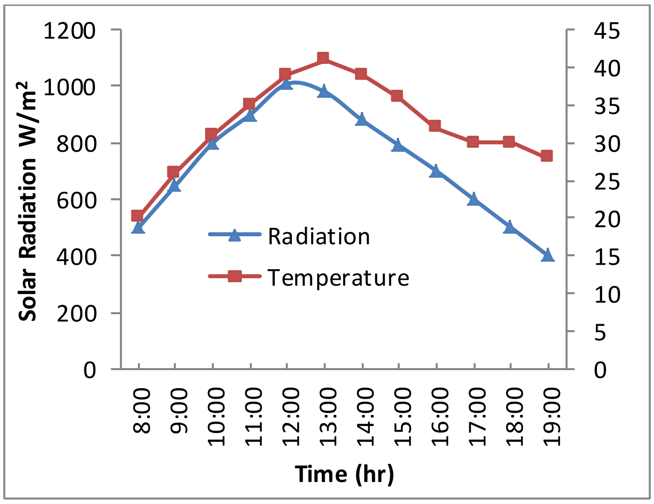

Figure 2. Variation of Solar Radiation and Ambient Temperature

3.2. Horary Output

Figure 3 compares the amount of pure water produced hourly by the three solar stills configurations. The results clearly highlight the crucial role of the added materials in improving distillation performance. The distiller enhanced with mountain stones (SSms) recorded the highest hourly production, peaking at approximately 122 ml at 14:00 h. It is closely followed by the distiller with cement stones (SScs), which achieves a maximum hourly production of 105 ml. The momentary superiority of the SSms distiller during the hours of maximum sunlight can be attributed to the thermal properties of the stone, potentially allowing for faster heat absorption and transfer than the denser cement, resulting in higher water temperatures during the period of maximum sunlight. However, the most important observation is the sustained production of the two improved stills in the late afternoon (17:00 h– 19:00 h) compared to the SScs still. This confirms that both materials act effectively as a thermal flywheel, extending the evaporation period and utilizing stored energy well beyond peak hours.

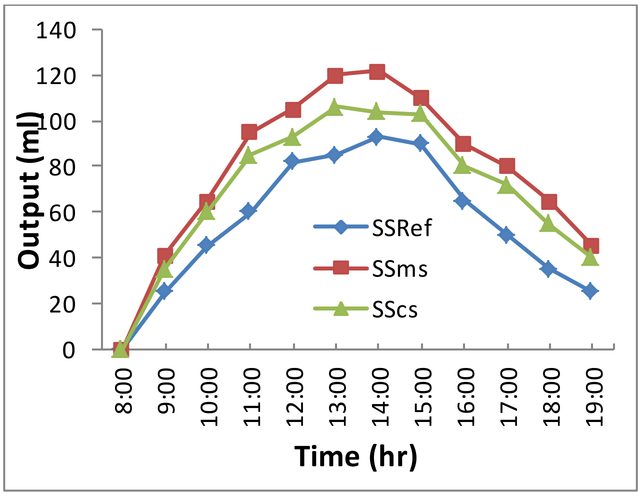

Figure 3. Hourly Pure Water Output

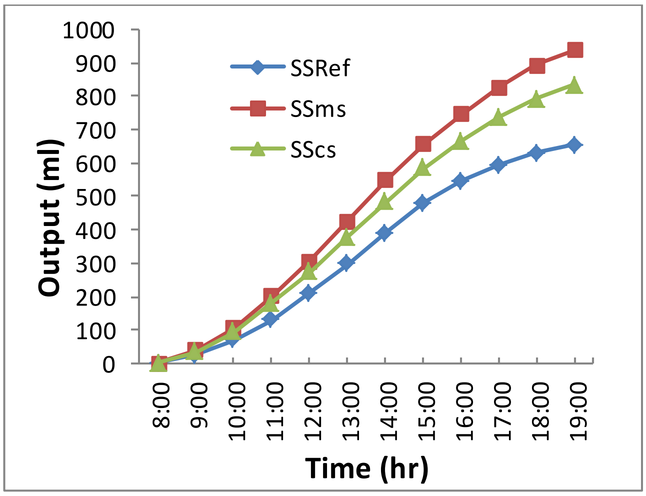

Figure 4. Cumulative Daily Pure Water Output

3.3. Accumulated Output

Figure 4 summarizes the overall daily performance by comparing the cumulative water production of the three solar stills from 8:00 h. to 7:00 h. This figure illustrates the overall performance of the systems, clearly demonstrating a substantial improvement thanks to the two storage materials. The mountain stone unit (SSms) achieved the highest final cumulative yield at 7:00 p.m., exceeding 940 ml. This result far surpasses that of the cement stone unit (SScs), which produced over 840 ml, and that of the reference still (SSref), which reached only 660 ml. This represents a remarkable performance improvement of over 42% for the mountain stone unit. Although the mountain stone unit achieved the highest absolute yield, the performance of the cement stone waste (SScs) unit remains significantly superior to that of the reference still. This confirms the technical viability and environmental benefits of this process. The use of readily available construction waste as a recycled and inexpensive thermal storage material (TSM) is promising. The difference in cumulative production warrants further investigation of the specific heat capacity and density parameters of the materials, but the data clearly confirm the advantages of using natural and recycled materials for sustainable water production.

3.4. Daily thermal efficiency

Figure 5 presents the calculated daily thermal efficiency (η) for the three solar still configurations, based on experimental data. The bar graph clearly highlights the superior energy conversion efficiency of the improved systems. The SSms (mountain stone) unit achieved the highest overall efficiency at 28.82%, closely followed by the SScs (cement waste) unit at 25.75%. The reference still (SSref) recorded the lowest efficiency at 20.23%. The absolute efficiency gain of 8.59% provided by the mountain stone demonstrates its optimal thermophysical properties for this application. More importantly, the 25.75% efficiency achieved with the use of cement waste proves a dual environmental benefit: efficient water production combined with the sustainable use of construction waste. This result strongly supports the use of recycled materials in solar thermal applications for cost-effective and environmentally friendly desalination.

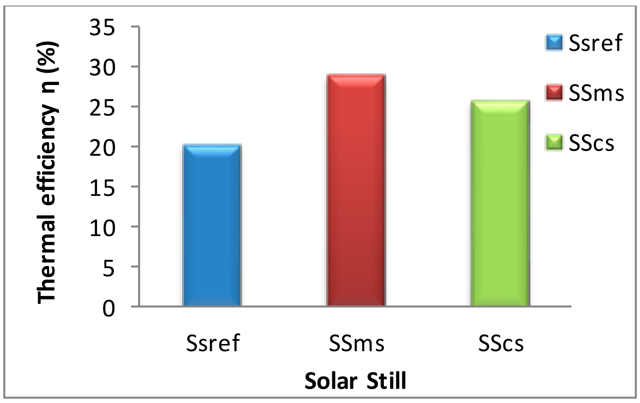

Figure 5. Daily Thermal Efficiency Comparison

3.5. Discussion of Results

The experimental comparison confirmed the significant role of thermal storage materials (TSMs) in improving the performance of solar stills, with thermal efficiency (η) serving as the primary comparison criterion. As shown in Table 1, the unit using mountain stones (SSms) exhibited the highest daily thermal efficiency at 28.82%, representing a substantial 42.4% improvement in cumulative efficiency compared to the reference still (SSref). This superior performance is primarily due to the optimized thermophysical properties of the mountain stones, which facilitate rapid heat absorption during peak sunlight and efficient heat retention afterward, consistent with the trends observed in hourly production (Figure 2). It is worth noting that the unit using cement stone waste (SScs) achieved a very respectable efficiency of 25.75%. This result is crucial because it translates into a significant 27.3% increase in daily output compared to the reference unit, thus validating the technical viability of recycling construction waste as a cost-effective thermal storage material in solar desalination technology. Although the SSms units demonstrated slightly superior performance due to presumably better heat transfer characteristics, the success of the SScs units fully justifies the adoption of a sustainable and economical solution that simultaneously addresses the challenges of water scarcity and construction waste management.

Table 1. Comparative table

Still Setup	TSM Material	Daily Output Increase vs. SSref	Daily Thermal Efficiency (η)
SSref	/	0.0%	20.23%
SSms	Mountain Stones	42.4%	28.82 %
SScs	Cement Stone Waste	27.3%	25.75%

IV. Economic and Environmental Feasibility Analysis

The economic viability of the enhanced solar stills was rigorously assessed by normalizing performance to a standard 1 m^2 area and calculating the Cost of Produced Water (CPW) and the Payback Period (PBP) over an assumed 10-year lifespan. Given the zero material cost for both Mountain Stones and Cement Stone Waste due to local availability, the final CPW is determined solely by the system's efficiency against the fixed initial capital investment (38.46 USD). As detailed in Table 2, the Mountain Stone unit (SSms) proved technically superior and most profitable, achieving the lowest CPW (0.0034 USD/L) and the fastest return on investment (13.39 days). However, the SScs unit, utilizing recycled material, remained highly competitive, registering a CPW of (0.0038 USD/L) and an extremely rapid PBP of only 15.01 days.

Crucially, this minor economic trade-off is overshadowed by the substantial environmental and societal benefit offered by the SScs configuration. The use of Cement Stone Waste provides a dual-solution pathway: it enhances water production while simultaneously facilitating the diversion of construction waste from landfills. This inherent value makes the SScs unit the most justifiable and globally sustainable solution. Its ability to deliver high technical performance alongside robust economic viability (a 21.4% reduction in production cost vs. the reference still) makes it the ideal model for adoption under the principles of the circular economy in arid regions like El Oued.

Table 2. Comparative Economic Feasibility Analysis (Per 1 m^2 Normalized Area/ 1 USD = 129.7 DZD)

Setup	Total Lifetime Production (L) (10 years)	Cost of Produced Water (CPW)	Payback Period (PBP) (days)	Reduction in CPW vs. SSref
SSref	7,920	0.0049 USD/L	19.06	0.0%
SSms	11,280	0.0034 USD/L	13.39	29.8%
SScs	10,080	0.0038 USD/L	15.01	21.4%

V. Conclusion

The study leads to the following key conclusions:

- Optimal Performance: The Mountain Stone (SSms) proved to be the most efficient, yielding the highest daily thermal efficiency of 28.82%. This confirms its superior thermophysical properties for maximizing solar energy capture and release within the still.
- Viability of Waste Material: The use of Cement Stone Waste (SScs) achieved a substantial efficiency of 25.75%. This result is highly significant because it establishes the technical feasibility and environmental merit of repurposing readily available construction waste as an effective TSM in solar desalination.
- Rapid Return on Investment: The extremely short payback periods for both enhanced units (under 16 days) confirm that the initial investment in these small-scale solar stills is highly justified and presents a robust, profitable

model for decentralized water production in arid regions facing water scarcity and high salinity challenges.

Based on these findings, future research should focus on:

- Optimizing the particle size and surface area of the Cement Stone Waste to potentially improve heat transfer characteristics and further narrow the performance gap with Mountain Stones.
- Conducting long-term economic analysis comparing the material costs and expected lifespan of SSms versus SScs to determine the most economically viable solution over a project's lifecycle.

Overall, the updated modeling approach and the new set of reconstructed figures offer a clearer and more modern representation of the physical behavior. Future work may extend this study to three-dimensional domains, transient heat transfer, or coupling with radiative and convective effects to better simulate real solar distillation systems.

Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism

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