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A COMPREHENSIVE ANALYSIS OF THE PERFORMANCE OF HEMISPHERICAL SOLAR DISTILLERS WITH VARIOUS CONFIGURATIONS

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ABSTRACT. Solar distillation has emerged as a key innovation within the alternative energy sector, offering a practical method for purifying saline or brackish water to produce potable water suitable for human consumption. While numerous studies have aimed to enhance solar still performance, identifying the most efficient and sustainable design for both industrial and residential use continues to be a major challenge. This study investigates the performance of hemispherical solar stills through a comparative analysis of different design modifications. The analysis indicates that design advancements can significantly improve the efficiency and output of hemispherical stills. For example, the integration of parabolic mirrors has been shown to increase productivity by 35% to 70%. Additionally, incorporating vacuum generation systems has demonstrated a further increase in output, reaching up to 70%.

KEYWORDS: Sustainability; Solar Desalination; Hemispherical Solar Distiller; Clean Water; Productivity Enhancement.

ABBREVIATIONS AND ACRONYMS

Abbreviation	Full Term
CHSD	Conventional Hemispherical Solar Distiller
MHSD	Modified Hemispherical Solar Distiller
HSD-N	Hemispherical Solar Distiller with Nanofluid
HSD-C	Hemispherical Solar Distiller with Cooling
PCM	Phase Change Material
CuO	Copper Oxide Nanoparticles
HSS	Heat Storage System
CHSS	Closed Heat Storage System
MHSD-RM	Modified Hemispherical Solar Distiller – Reflective Mirror
MHSD-RAFP	Modified Hemispherical Solar Distiller – Reflective Aluminum Foil with Paint
THSD-BW	Traditional Hemispherical Solar Distiller – Black Wall
RM	Reflective Mirror
RAFP	Reflective Aluminum Foil with Paint

1. INTRODUCTION

The continuous rise in global population, accompanied by increasing demands for energy and freshwater, presents major challenges to achieving sustainable development [1]. As pressure on natural resources intensifies, the need to implement efficient and innovative solutions becomes increasingly urgent. The interconnection between water scarcity and energy shortages further underscores the importance of integrated and forward-looking strategies [2]. Global estimates project that energy consumption will grow by approximately 48% between 2012 and 2040 [3]. Among the various solutions to address freshwater scarcity, solar desalination has emerged as a promising and sustainable option [4]. However, its energy demands remain a concern, emphasizing the need for systems that balance water production with minimal energy consumption [5]. This dual challenge calls for technologies that are both energy-efficient and environmentally sound [6]. Therefore, sustainable desalination methods—especially those leveraging renewable energy—are essential to building long-term resilience for both people and ecosystems [7]. Enhancing the performance of seawater purification technologies has become central to achieving sustainability goals. Although desalination has expanded rapidly in recent decades, producing over 100 million cubic meters of potable water per day [8], many existing systems still rely heavily on energy and contribute to environmental degradation [9]. As such, improving energy efficiency and reducing environmental impact remain critical goals [10]. Motivated by the need for low-cost and sustainable approaches, researchers have directed increasing attention to solar-powered desalination systems [11]. These technologies are especially valuable in off-grid or resource-limited regions. The integration of solar thermal energy, or even waste heat from power plants, offers dual-function solutions that reduce both operational costs and ecological burdens [12]. Such innovations, when combined with renewable sources, provide a pathway toward equitable and sustainable access to clean water [13]. While traditional solar stills offer an environmentally friendly solution, their limited water yield—averaging around 3 liters per day at roughly 30% efficiency—restricts their broader application [14]. In response, researchers have investigated several improvements to increase efficiency and output [15]. Among these, hemispherical solar stills have received growing attention due to their enhanced geometry, which supports better solar energy capture and thermal performance [16]. However, there remains a clear gap in the literature regarding the comparative performance analysis of different design enhancements specifically applied to hemispherical solar stills. This study aims to fill that gap by evaluating and comparing various configurations—such as the use of parabolic reflectors, phase change materials, and vacuum-assisted setups—focusing on their effectiveness in increasing water yield and thermal efficiency. Unlike previous studies that often focused on isolated enhancements, this work offers an integrated assessment that can inform practical design improvements and real-world applications.

Improvements in hemispherical designs have focused on several key aspects:

- **Maximizing solar absorption:** The curved geometry provides continuous exposure to sunlight, optimizing heat capture throughout the day.
- **Enhancing evaporation and condensation processes:** The integration of phase change materials (PCMs), selective coatings, and nanomaterials has shown significant potential in improving water productivity and thermal efficiency [17].

2. HEMISPHERICAL SOLAR STILL

2.1. SINGLE EFFECT

T. Arunkumar et al. [18] introduced a novel configuration for a solar distillation system, featuring a hemispherical transparent cover. This unique top structure not only facilitated the desalination process but also enabled the unit to operate effectively with or without a thin water film over the inner surface. Field experiments were conducted in India at geographic coordinates 11° N and 77° E to evaluate the system's freshwater production performance. During testing, parameters such as ambient temperature, basin water temperature, air temperature, cover surface temperature, and distilled water yield were continuously monitored, all exhibiting typical diurnal fluctuations. Additionally, the system's solar radiation exposure was recorded. The core operating principle of solar distillation relies on the temperature gradient between the heated basin water and the inner surface of the transparent cover, which drives the evaporation–condensation cycle (Figs. 1 and 2). Maintaining a continuous water feed at a rate of 10 mL/min improved the system's thermal efficiency from 34% to 42%, due to stabilized basin water temperature and reduced heat losses. Under identical solar irradiance, the integration of a hemispherical cover and cooling water flow on the outer surface increased the condensation rate, resulting in a 1.25-fold enhancement in water output compared to conventional flat glass covers. This improvement highlights the role of geometry in maximizing solar energy capture and promoting uniform condensation, which are essential factors in optimizing still performance.

Mohammed El Hadi Attia et al. [19] conducted an experimental study aimed at enhancing the efficiency of a hemispherical solar distillation unit through the incorporation of El Oued sand particles as a thermal energy storage medium. These sand particles, rich in SiO_3, Fe_2O_3, and Al_2O_3, demonstrated excellent thermal conductivity and heat retention properties, making them ideal for increasing solar energy absorption and improving heat transfer within the basin water. The study explored eight distinct mass concentrations of El Oued sand (ranging from 0.5% to 7%) to identify the optimal level for efficiency enhancement, as shown in Fig. 3. Three configurations were evaluated: a conventional hemispherical solar distiller (CHSD), units with different sand concentrations, and a modified hemispherical solar distiller (MHSD), which served as a benchmark. Experiments were conducted over four consecutive days, with two sand concentrations tested each day and compared to a reference setup. The results indicated that a 3% sand concentration yielded the best performance, increasing daily freshwater output from 4780 mL/m² to 7270 mL/m², representing a 52.1% improvement. Thermal efficiency also improved significantly, rising from 39.2% to 59.1% (a 50.8% enhancement). This improvement is attributed to the increased thermal mass provided by the sand, which stabilized basin temperature and extended the evaporation period. Compared to standard designs without thermal storage media, the use of sand not only enhanced energy retention but also reduced heat losses during low-radiation periods such as early morning and late afternoon. Among the tested enhancements, the use of 3% El Oued sand stands out as one of the most practical and cost-effective modifications for increasing the efficiency of hemispherical solar distillers, particularly in arid regions where such materials are readily available

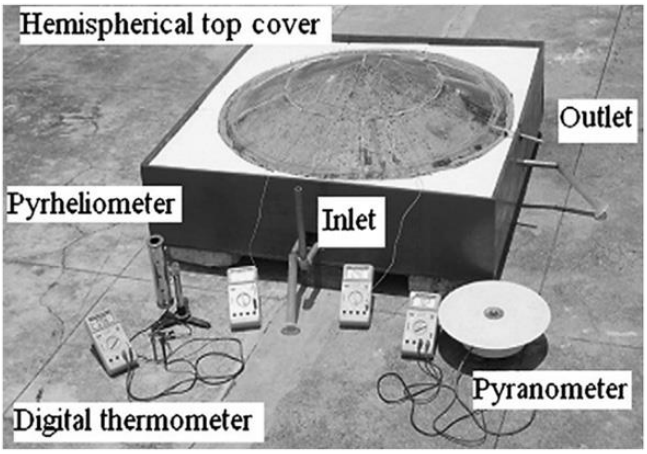

Fig. 1. Hemispherical solar distiller [18].

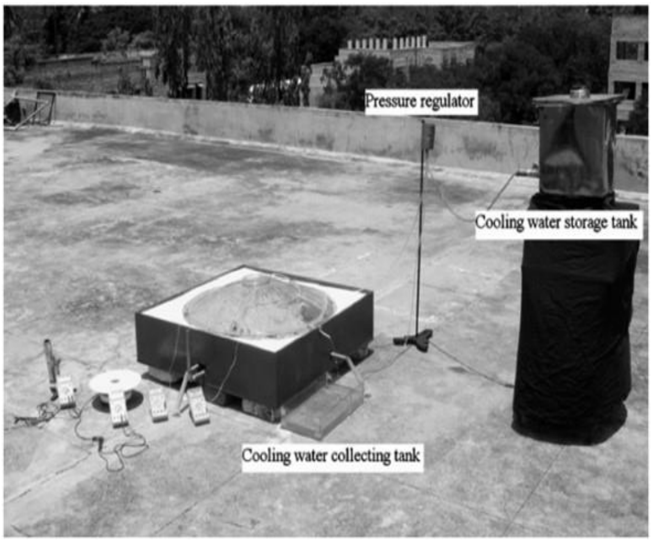

Fig. 2. View of cooling cover [18].

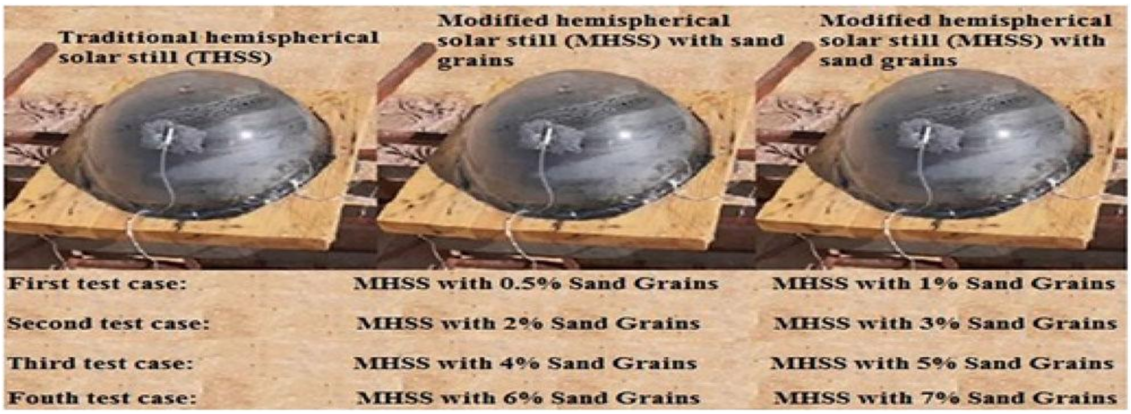

Fig. 3. Manufacturing the modified solar still with three cases [19]

Attia et al. [20] investigated two key modifications aimed at improving the performance of hemispherical solar distillers. The first modification involved the addition of CuO nanoparticles to the basin water at different concentrations (0.10%, 0.20%, and 0.30%) to enhance solar energy absorption and accelerate vapor generation. The second approach applied glass cover cooling using a thin film of water, with flow rates of 2.5 L/h, 2.0 L/h, and 1.5 L/h, to promote efficient condensation of water vapor. Experimental tests were conducted on three configurations: a conventional hemispherical solar distiller (CHSD), a distiller with glass cover cooling (HSD-C), and a distiller using CuO-water nanofluids (HSD-N). Results indicated that the CHSD produced 3850 $mL/m^2/day$, while the HSD-N achieved between 5750 and 6800 $mL/m^2/day$, corresponding to an improvement of 49.3% to 76.6%, depending on the nanoparticle concentration. The HSD-C configuration recorded daily productivity between 4900 and 5700 $mL/m^2/day$, an increase of 27.3% to 48.0% with different water film flow rates (see Fig. 4). The performance enhancement from CuO nanoparticles is attributed to their superior thermal conductivity, which boosts heat transfer within the basin, leading to higher evaporation rates. In contrast, the water film cooling enhances the condensation process by maintaining a lower glass surface temperature, thereby increasing the condensation rate. Among the tested modifications, the use of 0.30% CuO nanoparticles exhibited the highest productivity, making it a highly promising enhancement for practical applications, particularly where maximizing output is critical. Compared to previous studies that examined these improvements separately, this integrated analysis offers a clearer understanding of their combined and individual effects on overall system performance.

Wisam A. Abd Al-Wahid et al. [21] carried out an experimental investigation to evaluate the impact of incorporating various quantities of river stones into the saline water basin of a solar desalination system, as shown in Fig. 5. The steady-state experiments aimed to assess how this modification affected solar energy absorption and freshwater output. River stones, acting as thermal energy storage media, enhanced the system's capacity to absorb and retain solar radiation. This led to an increase in the temperature of the basin liner and more efficient heat transfer to the water layer (Fig. 6). The results showed significant improvements in distillate yield: water production increased by 52% and 58% when 0.3 L and 0.6 L of river stones were added, respectively (Fig. 7). This enhancement is primarily due to the high thermal mass of the stones, which stored heat during peak solar hours and gradually released it, prolonging the evaporation process. Compared to conventional setups without thermal storage, the use of river stones offers a low-cost and practical improvement with minimal system complexity. Additionally, upgrading the distiller's outer cover (e.g., through better insulation or selective coatings) further boosted efficiency and freshwater output. These findings underscore the potential of passive thermal storage integration as a viable method to enhance solar still performance, particularly in remote or water-scarce regions.

On the other hand, R. Fallahzadeh et al. [22] conducted an outdoor experimental investigation in Mashhad, Iran, to assess the performance of an improved hemispherical solar distillation unit. The daily freshwater yield from the modified solar still ranged between 2720 $mL/m^2/day$ and 3170 $mL/m^2/day$, depending on environmental conditions. A comparative analysis was performed between the experimental results and predictions from various thermal models. Among these, Clark's model demonstrated the closest alignment with the actual performance data, validating its reliability for forecasting solar still productivity. The modeling results highlighted several key design parameters affecting efficiency. Specifically, reducing the thickness of the glass cover was found to enhance thermal efficiency by over 1%, primarily due to reduced thermal resistance and faster heat transfer. Additionally, both the thermal conductivity of the basin materials and the insulation thickness were shown to significantly influence performance, with optimized configurations potentially increasing efficiency to approximately 60%. These findings emphasize the importance of precision in material selection and geometric design in improving thermal behavior and water productivity. Unlike studies focusing solely on empirical modifications, this work provides valuable insights into the predictive capabilities of modeling tools, aiding in the optimization of future solar distiller designs.

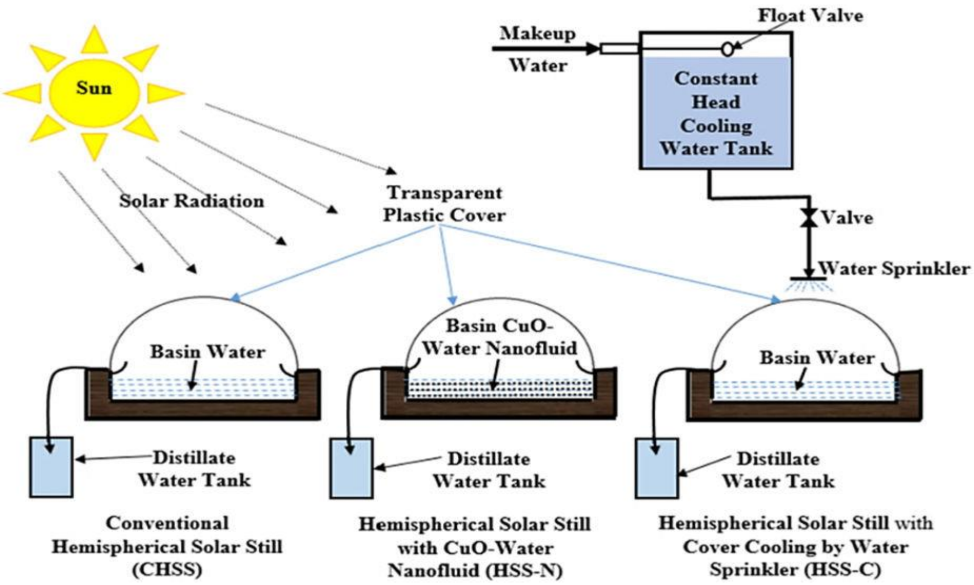

Fig. 4. Three stills configuration [20].

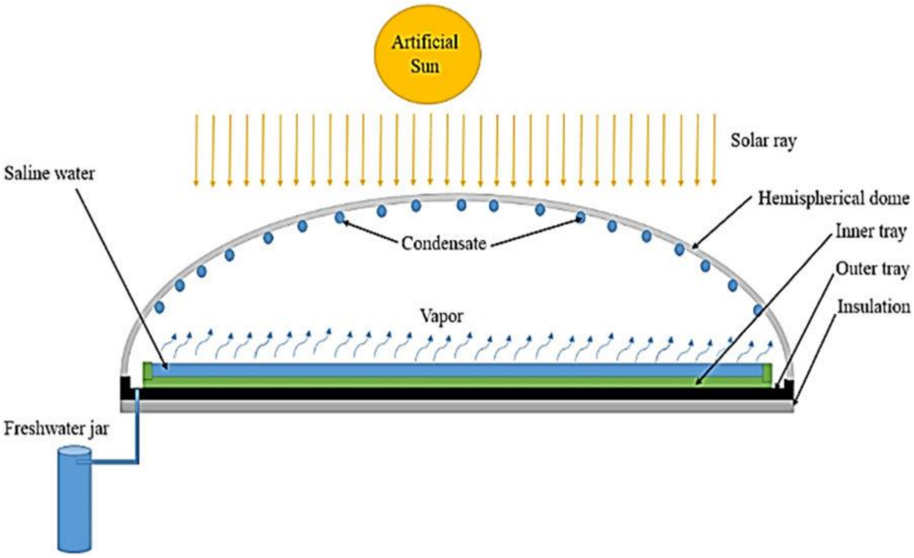

Fig. 5. View of configuration diagram (HHD) [21]

Fig. 6. Shape of actual work [21].

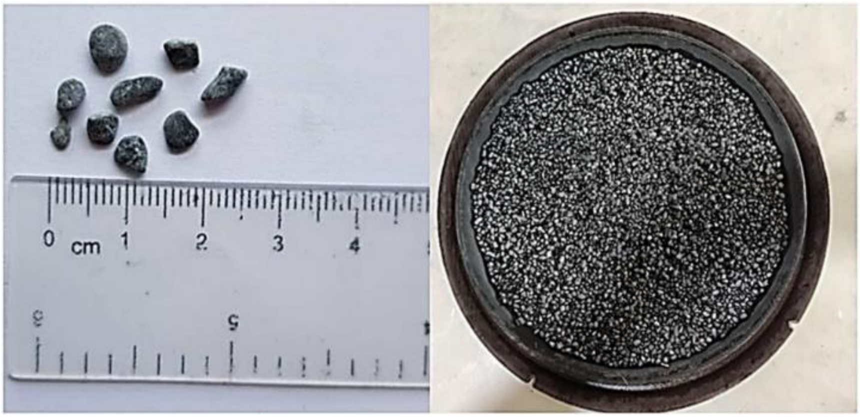

Fig. 7. River stones used in experiment [21].

2.2. COMBINED EFFECT

. Milad Mohsenzadeh et al. [23] assessed a novel floating-based desalination approach (Fig. 8), which uses a low-vacuum evaporation chamber to facilitate salt removal and improve evaporation efficiency. This system employed solar heat absorption to increase evaporation rates, while preventing salt accumulation through a combination of evaporative and radial water circulation mechanisms. The basin was designed in a tubular configuration and integrated multiple layers of hydrophilic cellulose fabric and porous foam to promote uniform water distribution via capillary action. Condensation was enhanced by external coils fully submerged in surrounding saltwater reservoirs (e.g., oceans), allowing for continuous natural cooling and improved condensation efficiency. A cost-effective hemispherical transparent acrylic dome was used as the cover, enabling maximum sunlight penetration from various angles. Under summer conditions in Australia, the system produced 4300 mL/m²/day of distilled water, achieving a distillation efficiency of 35.6%. The improved performance is primarily attributed to the increased heat absorption from the transparent dome, enhanced water circulation within the basin, and the efficient heat dissipation from submerged condensing coils. Compared to traditional fixed-basin designs, this floating, vacuum-assisted system shows significant promise for large-scale, off-grid seawater desalination in remote coastal regions

V. Sa et al. [24] examined the limitations of the Closed Heat Storage System (CHSS) and proposed design enhancements by incorporating wick materials and rubber layers of varying thicknesses within the basin, as shown in Fig. 9. Three identical Heat Storage System (HSS) units were constructed, each featuring wick materials with thicknesses of 1.5 mm, 3 mm, 4.5 mm, and 6 mm, alongside rubber sheets of thicknesses 2.5 mm, 5 mm, 7.5 mm, and 10 mm. The units were evaluated under consistent operational conditions over four consecutive days in El Oued, Algeria. The results indicated a clear positive correlation between material thickness and system performance. Specifically, rubber sheet thicknesses of 2.5 mm, 5 mm, 7.5 mm, and 10 mm increased daily water productivity by 14.29%, 26.53%, 35.71%, and 46.94%, respectively, compared to the baseline CHSS. Similarly, increasing wick material thickness enhanced water output by 12.24%, 22.45%, 30.61%, and 40.81% in the respective thicknesses (Fig. 10). These improvements are attributed to enhanced heat retention and improved thermal conductivity within the basin, resulting from thicker wick layers and rubber sheets, which optimize the heat storage and release cycle. Compared to previous designs, the incorporation of these materials significantly improves the heat dynamics, leading to greater distilled water yield and overall system efficiency.

Mohammed El Hadi Attia et al. [25] conducted an experimental study aimed at enhancing solar energy absorption in hemispherical solar distillation units by integrating reflective components—specifically mirrors and aluminum foil—on the interior basin surfaces. Three configurations were developed and tested under identical environmental and operational conditions: a conventional unit with black interior walls (THSD-BW), a modified design with mirrored surfaces (MHSD-RM), and a second modified unit featuring aluminum foil with reflective coating (MHSD-RAFP). The results demonstrated that the MHSD-RAFP configuration achieved a 42.3% increase in total distilled water output and a 37.5%

improvement in thermal efficiency compared to the conventional black-wall unit. Meanwhile, the MHSD-RM unit showed a modest 2.6% increase in cumulative water production, but a significant thermal efficiency gain of 57.26% over the baseline system. Additionally, energy efficiency improvements of 69.61% for the aluminum foil-enhanced unit (MHSD-RAFP) and 123.1% for the mirror-based system (MHSD-RM) were observed relative to the standard design, as illustrated in Fig. 11. These enhancements are primarily attributed to the increased reflection and redistribution of solar radiation within the basin, which elevates the water temperature and promotes higher evaporation rates. Compared to traditional designs, the integration of reflective materials inside the basin demonstrates a practical and effective strategy for improving the performance of hemispherical solar stills, with potential applicability in both residential and industrial desalination systems.

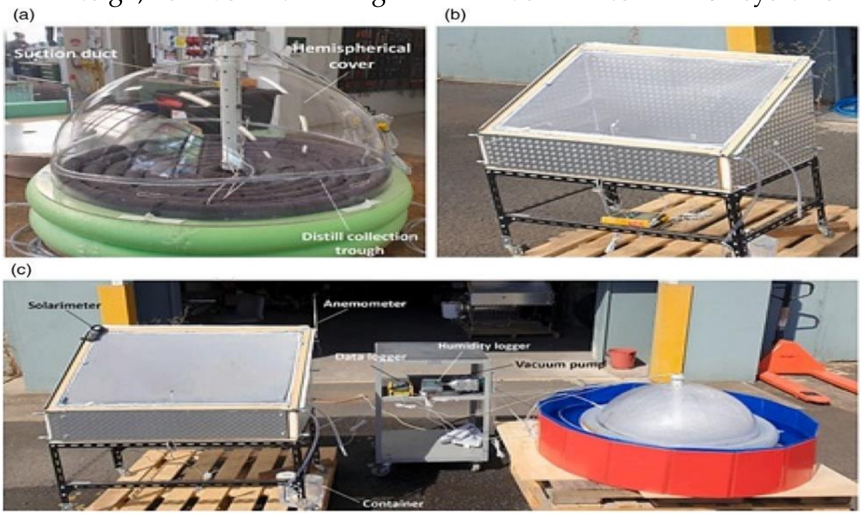

Fig. 8. Schematic view of the solar floating design system [23]

Fig. 9. New method used in basin [24].

Fig. 10. An experimental work of (HSS) [25].

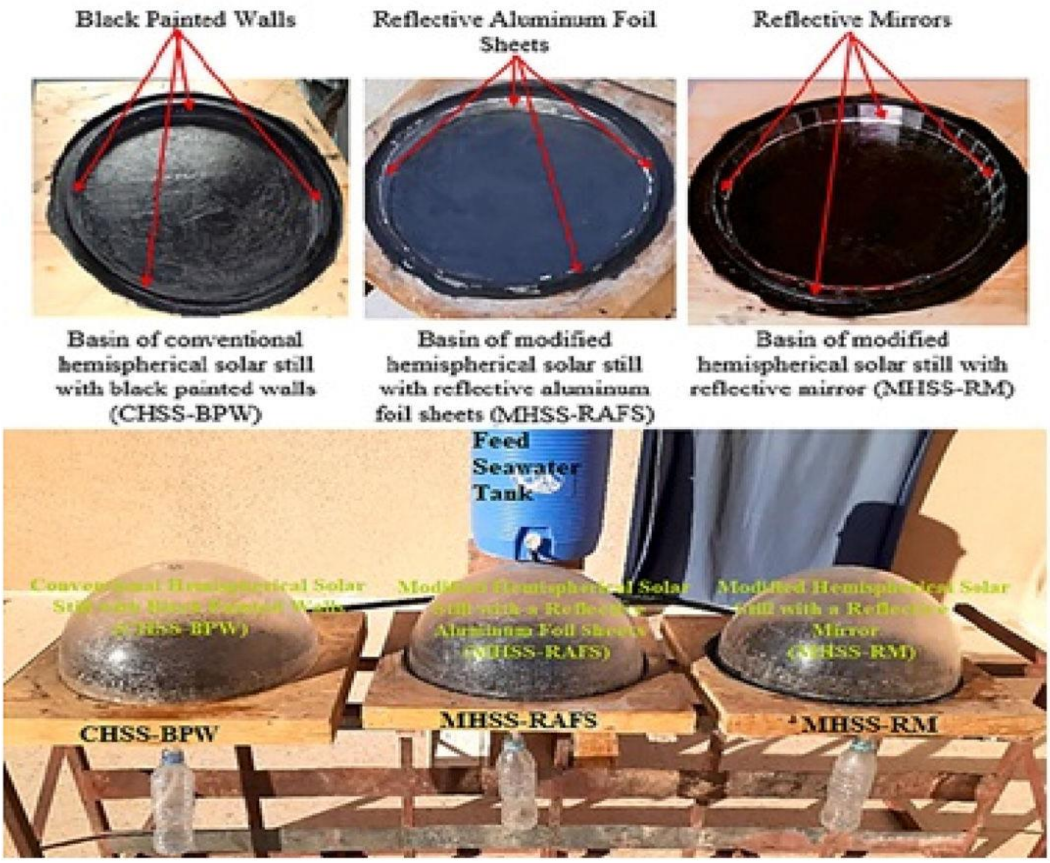

Fig. 11. View of three types of hemispherical solar distillers [25].

3. Comparison with Previous Studies and Novelty of the Present Work

The present study offers a unique and comprehensive analysis of the hemispherical solar still (HSS) technology, distinguishing itself from prior works in several key aspects:

1. **Integrated Comparative Review**:

Unlike most existing studies that examine a single design modification, this paper presents a detailed comparison of various enhancement methods—including the use of nanofluids (CuO), reflective surfaces (mirrors and aluminum foil), PCM integration, glass cooling, and novel geometries such as vacuum chambers and floating structures—within the specific context of hemispherical distillers.

2. **Quantitative Benchmarking of Enhancements**:

This work summarizes the performance improvements (e.g., percentage increase in water yield and thermal efficiency) reported across multiple studies, providing a consolidated benchmark that is currently lacking in the literature.

3. **Exclusive Focus on Hemispherical Geometry**:

Many prior reviews deal broadly with basin-type stills. This paper exclusively targets the hemispherical configuration, highlighting its unique thermal behavior, optical properties, and compatibility with passive and active modifications.

4. **Practical Implications and Future Potential**:

Beyond technical comparison, the study identifies the most practically promising designs—those with high scalability potential and minimal energy input requirements—offering guidance for future experimental research and real-world implementation.

5. **Enhanced Physical Interpretation**:

The study offers clear physical explanations behind observed improvements, such as improved heat retention via sand and stones, better evaporation through nanoparticles, and enhanced condensation by surface cooling.

Together, these contributions underscore the novelty and practical relevance of the current review and its value to both researchers and engineers focused on sustainable water desalination technologies.

4. CONCLUSIONS

This study focused on hemispherical solar stills and reviewed a variety of enhancements and modifications that have demonstrated significant improvements in performance.

Key findings reveal that the integration of parabolic reflectors within hemispherical designs can increase water output by 35% to 70%, by effectively concentrating solar radiation onto the basin surface.

Additionally, advancements in cooling mechanisms of the condenser help maintain an optimal temperature gradient, which directly leads to higher distillation productivity.

Internal design improvements, such as the incorporation of rotating components and the use of phase change materials (PCMs), further enhance thermal management and evaporation rates.

Preheating the feedwater accelerates evaporation but introduces additional energy inputs, requiring a balance between efficiency and energy consumption.

Advanced methods like creating a vacuum inside the still have shown potential to boost performance by up to 70%, due to reduced boiling temperatures and enhanced vapor formation.

Moreover, the application of nanomaterials—either suspended in water or integrated with PCMs—significantly improves thermal conductivity, accelerating the evaporation process and increasing overall system efficiency.

Redesigned hemispherical lids that allow controlled water flow over the surface have improved operational flexibility and increased water yield.

In summary, the hemispherical solar still emerges as an effective and adaptable technology for sustainable desalination, especially when combined with modern thermal, material, and mechanical enhancements, setting it apart from conventional solar distillation systems.

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