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RESEARCH ARTICLE

Maximizing Solar Still Efficiency: Advanced Integration of Reflectors, Internal Fan, and Passive Condenser

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ABSTRACT

Water scarcity remains a pressing global issue, particularly in remote, arid regions. Solar stills offer a cost-effective, sustainable solution for water desalination, yet their efficiency is often limited. This study explores the integration of internal and external reflectors, an axial fan, and an air-cooled passive condenser into a conventional single-slope solar still. Experimental results demonstrate significant performance enhancements, with up to a 135.5% increase in water yield, showcasing the potential of these modifications to optimize solar still efficiency.

INTRODUCTION

A lack of accessible water resources is a significant issue globally, particularly for those living in arid and semi-arid zones. Factors such as climate change, population growth, and the unsustainable use of water resources further aggravate the situation. This challenge is particularly severe in remote areas, where limited infrastructure and resources hinder access to clean and safe water. As access to potable water is a fundamental human necessity, the demand for practical, sustainable solutions is more critical than ever (Pandey and Naresh 2024, Bakhtierkhalzi et al. 2024). In addressing this crisis, solar desalination has emerged as a promising technology. By harnessing solar energy to convert saline or brackish water into freshwater, it offers a renewable and eco-friendly approach. Among desalination techniques, solar stills stand out for their affordability, ease of construction, and adaptability to resource-limited environments. These devices provide a feasible method to supply safe drinking water in regions with abundant sunlight but scarce water resources. [Ahmed 2016, Jodah et al. 2024, Mugisidi et al. 2023)] The working principle of solar stills replicate natural processes such as evaporation and condensation. They typically consist of a shallow basin sealed with insulated walls and a sloped transparent cover, often made of glass. Sunlight heats the water, causing evaporation. The vapor condenses on the cooler surface of the cover, and droplets flow into a collection trough. These systems are cost-effective, low-maintenance, and highly accessible, making them essential tools for alleviating water scarcity and ensuring sustainable water security in underserved areas. [Kumar and Ramasamy 2024, Jeyaraj et al. 2024, Hossain 2024, Ibrahim and Ahmed 2021). The main drawback of solar stills is their limited productivity. On average, they produce only 2-3 liters of drinkable water daily, with an efficiency hovering around 30%. These performance metrics are influenced by the solar still's design and the geographic conditions in which it operates (El-Sebaey et al. 2023, Hammoodi et al. 2023). The low water output and limited efficiency of solar stills are major factors restricting their widespread adoption and commercial appeal. Their inability to produce sufficient quantities of potable water makes them less practical for large-scale applications or competitive in broader markets. (Davra et al. 2024, Katekar and Deshmukh 2022). To address these challenges and improve solar still performance, researchers are exploring various design innovations, modifications, and configurations. The focus is on optimizing evaporation processes to significantly boost freshwater production and enhance the efficiency of the system (Diarra et al. 2024, Bait 2024, Rajasekaran and Kulandiavelu 2024). Recent advancements focus on incorporating additional features, such as reflectors, fans, and condensers, to improve evaporation and condensation processes. These modifications aim to enhance solar energy absorption, thermal efficiency, and overall water yield, making solar stills more viable for widespread use (El Hafid and Abderafi 2024, 17-18].

Elamy et al. 2024, investigated methods to enhance the efficiency of a Coiled Solar Still by incorporating a fan, reflectors, and a condenser. The study revealed that adding a fan improved airflow and evaporation rates, leading to a 68% productivity boost. By combining internal reflectors, a heating coil, and a Vertical Wick Solar Still, distillate output increased by 209%. The integration of a condenser further enhanced performance, achieving a remarkable 269% increase compared to a traditional solar still. Monowe et al. 2021, introduced an innovative design for a portable thermal-electrical solar still equipped with an external reflective booster and an external condenser. This design focuses on minimizing latent heat loss by channeling it into the condenser, which can either preheat saline water for household use or sustain the still's operation during nighttime. Findings indicate that utilizing preheated water for domestic applications enhances efficiency to 77%, while employing it for nighttime operation further elevates efficiency to 85%. Ahmed, 2012, conducted a study featuring an innovative approach where three identical conventional solar stills were designed, constructed, and tested in Bahrain's environmental conditions, incorporating external cylindrical air-cooled passive condensers. The results showed a 35.8% increase in distilled water production for the enhanced solar still. Elamy et al 2024, conducted a study utilizing a solar concentrator, phase-change materials with nanomaterials, and a fan linked to an external condenser. This setup achieved a 300% production increase compared to conventional solar stills. Vapor drawn by the fan passed through a copper coil in the feed tank, preheating water and lowering glass temperature, enhancing condensation and achieving 72.4% efficiency. Hadj-Taieb et al 2024, used external reflectors, a vapor extraction fan, a water-cooled condenser, and sand beds as thermal storage to experimentally enhance the performance of hemispherical solar stills. Their results showed a 154% increase in production rate. Ibrahim and Ahmed 2018 examined the impact of incorporating a passive built-in condenser to a conventional solar still, revealing a 38.2% enhancement in production rate.

This study enhances conventional solar still efficiency by integrating an axial fan, passive air-cooled external condenser, and internal/external reflectors into a conventional basin-type design. The fan improves air circulation, the condenser enhances vapor condensation, and reflectors maximize solar radiation capture. These modifications aim to optimize heat transfer, increase condensation rates, and substantially boost freshwater output, addressing key challenges in solar distillation technology.

EXPERIMENTAL SETUP AND METHODOLOGY

A single-slope solar still was designed and fabricated with 1.4 mm thick galvanized steel, offering a net basin area of 1 square meter. Black epoxy paint was applied to the inner surfaces of the steel basin and side walls to improve solar energy absorption. The metal solar still was surrounded by a slightly larger wooden frame, with a 60 mm gap between them filled with glass wool to minimize heat loss. A 3 mm thick glass cover was fixed at a 30º angle to the horizontal and securely sealed to prevent any vapor leakage from the solar still. Condensed water was directed into an L-shaped channel positioned at the base of the cover, enhancing both solar capture and condensation efficiency. The back of the solar still was designed with two circular openings, each 10 cm in diameter as can be seen in Figure 1. An axial fan was installed in the lower opening to facilitate the circulation of vapor. An external air-cooled condenser with a cuboid design was fabricated using 1.4 mm thick galvanized steel. It measured 40 x 40 cm at the base with a height of 60 cm, providing a total surface area of 1.28 m^2 as can be seen in figure 2. The condenser was attached to the still using short plastic pipes fitted through the circular openings and featured a half-inch valve at its base for collecting and draining condensed water.

Figure 1: Figure solar still structure

Figure 2: External passive condenser

The initial experiments were carried out with only the solar still in operation, with the two openings completely sealed. This setup replicated a standard single-slope solar still, serving as a baseline for comparison against other configurations incorporating modified features. In the second set of experiments, the connection between the solar still chamber and the condenser was opened, allowing vapor to move naturally to the condenser without the use of the axial fan. For the third set, the axial fan was activated, actively driving the vapor flow between the solar still chamber and the air-cooled condenser. To examine the impact of internal reflectors on solar still performance, mirror pieces were installed along the interior walls to serve as reflectors as dispatched in Fig. 3. The fourth set of experiments was conducted with the solar still operating and the two openings sealed, focusing solely on the effect of these internal mirrors.

Figure 3: Placement of interior mirror reflectors

To study the impact of using external mirrors as reflectors, a 1.0 m x 0.75 m mirror was positioned at a right angle to the upper edge of the solar still, functioning as an external reflector, as illustrated in Figure 5. The fifth experimental setup was then carried out, utilizing both internal and external mirror reflectors exclusively.

Figure 4: Placement of external mirror reflector

A sixth set of experiments was performed, integrating all the enhancements: the axial fan, the external condenser, and both internal and external reflectors. This setup aimed to assess the combined impact of these modifications on the overall performance of the system. The solar still was installed in the university yard and oriented towards the south. The water level inside the still was carefully maintained at a consistent depth of 1 cm. Experimental observations were conducted between 7:00 am and 6:00 pm, with hourly data collection. Recorded parameters included temperatures of the basin, basin water, vapor inside the still chamber, interior and exterior glass surfaces, inner and outer surfaces of the condenser, and the condenser interior. Additionally, ambient air temperature, solar radiation intensity, and wind speed were measured. The water level in the still was consistently maintained at a depth of 1 cm.

RESULTS AND DISCUSSIONS

Outdoor experiments were performed to assess the impact of incorporating design improvements into a conventional solar still. These improvements include an external air-cooled passive condenser, an internal fan for vapor circulation between the still chamber and condenser, and internal and external mirror reflectors.

The first set, with the two circular openings (one intended for fan installation) blocked, allowed the solar still to function as a typical conventional single-slope solar still. The water condensate was collected only through runoff from the inner surface of the glass cover. This data set served as a comparison with the other sets that incorporated additional design features. For the second experimental setup, the two circular openings were left unsealed, with the fan kept inactive, enabling natural vapor circulation into the condenser without forced airflow. This configuration was designed to evaluate the effect of using only the external condenser. A performance comparison between the conventional solar still and the one fitted solely with an external condenser showed a 29.09% increase in overall yield. Figure 7a displays the hourly performance comparison, while Figure 7b highlights the daily results. Of the total condensate, 73% was collected from the glass cover, and the remaining 27% was obtained from the condenser. The improvement in the condensation process is realized by integrating an external air-cooled passive condenser, which adds additional surface area for condensation. Furthermore, the metal construction of the condenser, with its higher thermal conductivity compared to glass cover, effectively boosts condensation efficiency. Consequently, the overall yield and performance of the solar are improved.

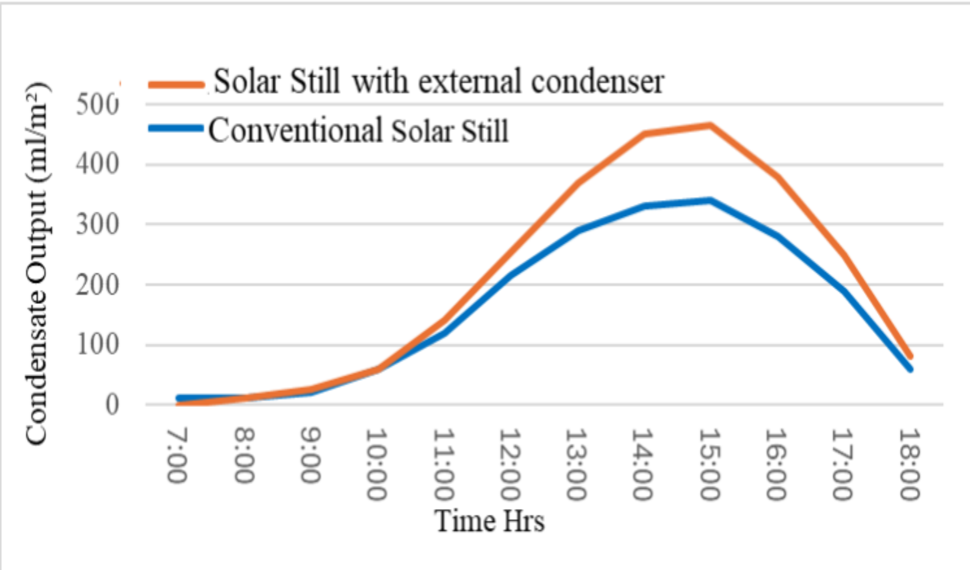

Figure 6a: Hourly performance: conventional vs. condenser-enhanced solar still

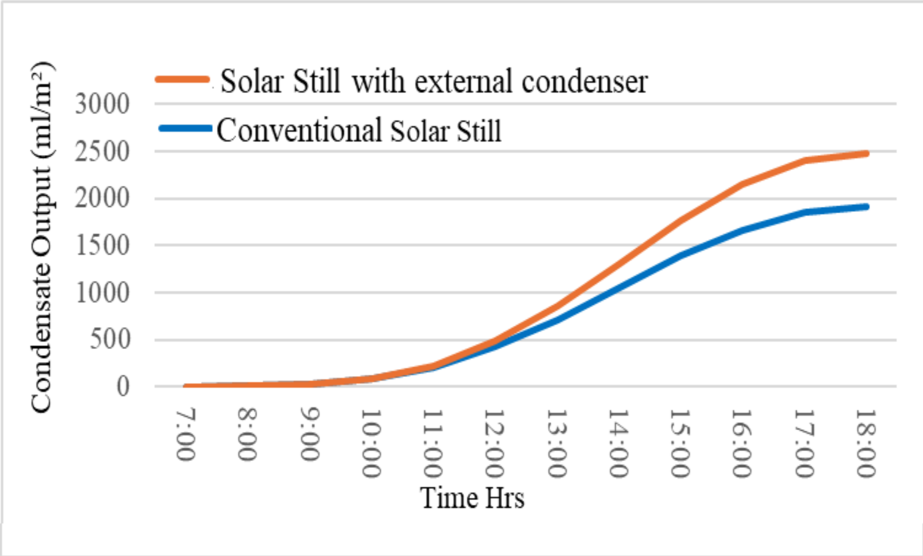

Figure 6b: Daily performance: conventional vs. condenser-enhanced solar still

In the third experimental setup, the internal fan was activated to actively circulate vapor between the solar still chamber and the condenser's internal space, enhancing vapor movement and system efficiency. The operation of the fan significantly boosted airflow and heat exchange, resulting in a 70.65% increase in water yield compared to the conventional solar still without fan assistance. This performance improvement is illustrated in Figure 7a (hourly data) and Figure 7b (cumulative daily results). The fan's role in enabling forced convection led to more efficient condensation and enhanced overall output. Of the total condensate, 63.9% was collected from the glass cover, while 36.1% was captured by the condenser.

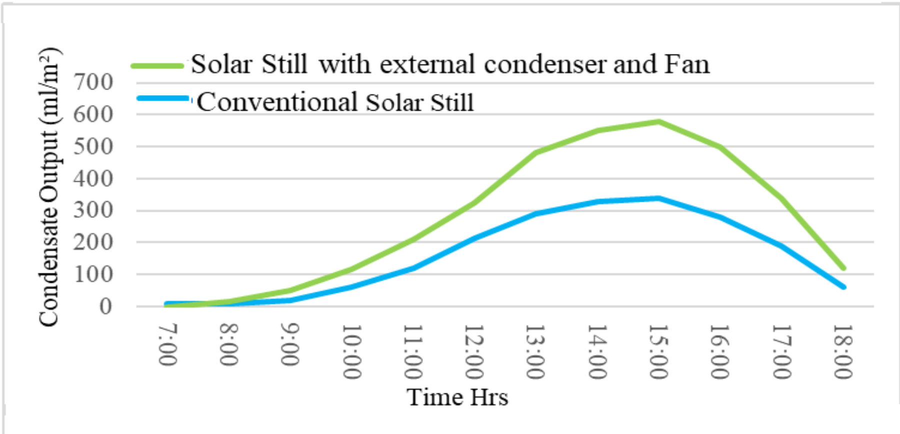

Figure 7a: Hourly performance: conventional vs. condenser and fan-enhanced solar still

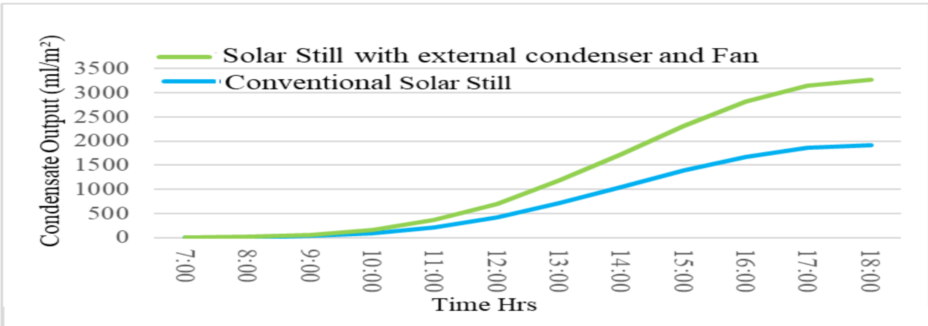

Figure 7b: Daily performance: conventional vs. condenser and fan-enhanced solar still

The inclusion of internal and external mirror reflectors significantly increased the sunlight entering the solar still, redirecting and concentrating more solar rays onto the water basin. This enhancement resulted in a remarkable 135.5% increase in water yield compared to the conventional solar still. The improvement in performance is clearly depicted in Figure 8a (hourly data) and Figure 8b (cumulative daily results). Internal reflectors are used to intensify solar radiation by directing sunlight onto the water surface, minimizing energy loss from the walls. This concentrated reflection enhances energy absorption by the water, improving evaporation and condensation efficiency. At the same time, external reflectors gather additional sunlight and direct it into the solar still, increasing the overall solar energy input.

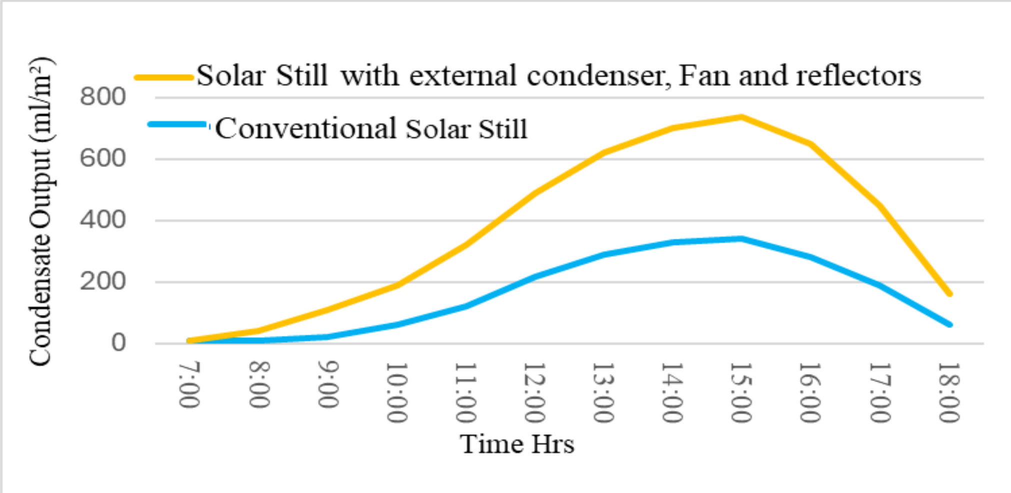

Figure 8a: Hourly performance: conventional vs. condenser, fan and reflector-enhanced solar still

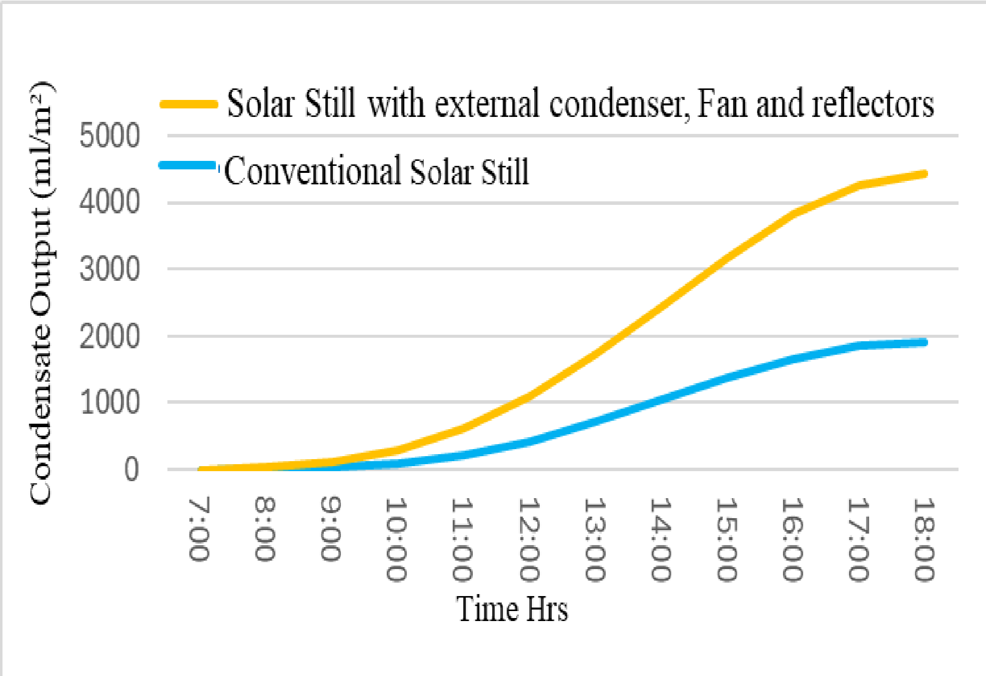

Figure 8b: Daily performance: conventional vs. condenser, fan and reflector-enhanced solar still

The comparison of the three design modifications with the conventional solar still is illustrated in Figure 9a for hourly performance and Figure 9b. These figures clearly highlight the differences in condensation yield between the modified configurations and the standard setup. Among the modifications, the integration of internal and external reflectors had the most pronounced effect, significantly improving solar radiation absorption and achieving the highest yield increase. The performance improvements across all modifications demonstrate their effectiveness in enhancing the solar still's functionality and water production. The combined implementation of a condenser, axial fan, and internal and external reflectors further maximizes energy capture, absorption, and utilization, resulting in higher efficiency and output.

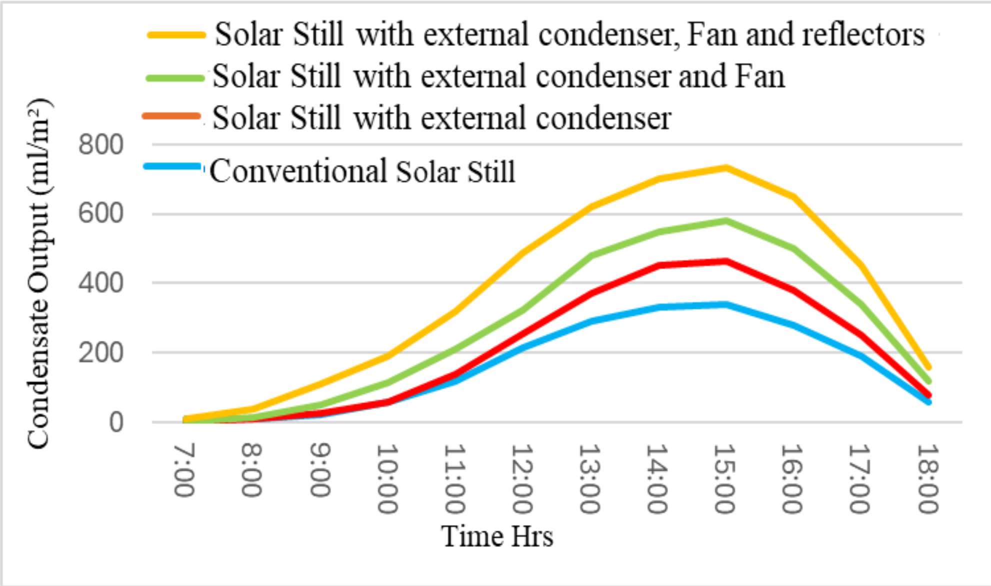

Figure 9a: Comparison of hourly performance across four experimental configurations

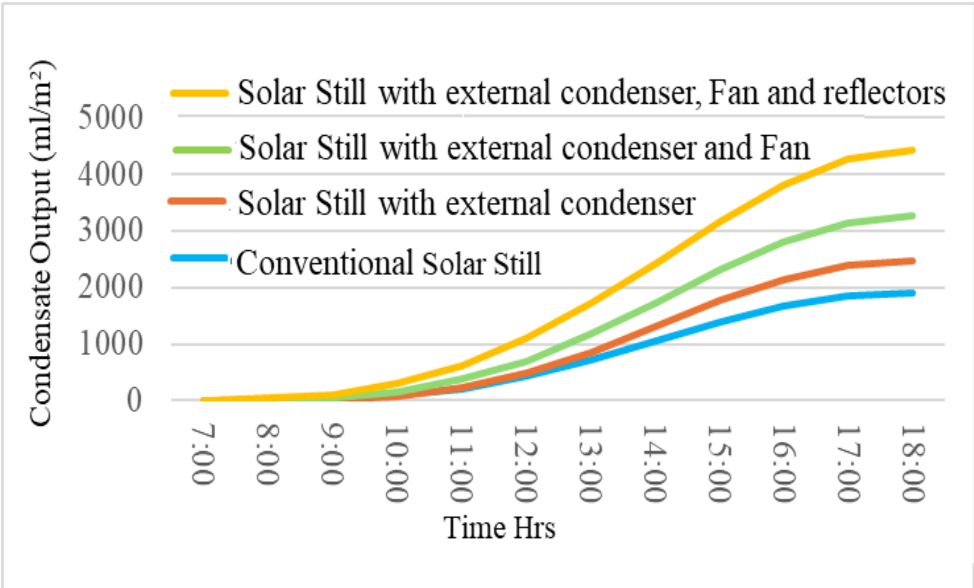

Figure 9b: Comparison of daily performance across four experimental configurations

CONCLUSIONS

The study highlights the potential of integrating design improvements into a conventional solar still to enhance its performance. Among the tested modifications, incorporating an external air-cooled passive condenser increased condensation efficiency, yielding a 29.09% improvement in water production. Adding an internal fan further boosted vapor circulation and heat exchange, leading to a 70.65% increase in yield. The best enhancement of 135.5% rise in water production was achieved with the use of internal and external mirror reflectors, which optimized solar radiation absorption while reducing energy losses.

The combined application of an external condenser, axial fan, and internal and external reflectors emerged as an effective approach, maximizing energy efficiency and significantly improving output. These findings emphasize the value of systematic design upgrades in improving the functionality and productivity of solar stills, making them more practical for addressing water scarcity in arid regions. The results pave the way for further advancements in solar still technology, aiming to maximize freshwater production and operational efficiency.

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