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# Experimental Evaluation of a Vacuum-Assisted Solar Still for Improved Desalination Efficiency

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**ABSTRACT**

The worsening challenge of accessing freshwater and the rising cost of energy required for its production through conventional desalination methods have intensified research efforts toward utilizing solar energy for seawater desalination. This study focuses on enhancing the performance of a solar still by integrating it with a vacuum-assisted system to create partial vacuum conditions inside the still. The modified design incorporates a closed-loop water circulation system equipped with a Venturi tube to reduce internal pressure, which in turn lowers the evaporation temperature and increases freshwater output. Field experiments were conducted under both atmospheric and reduced-pressure conditions, evaluating the effects of basin water depth, ambient temperature, and wind speed. The results showed up to a 30% increase in productivity under vacuum conditions, especially at higher water depths. These findings highlight the potential of low-cost, vacuum-enhanced solar stills for off-grid freshwater production in arid regions.

**Keywords:** solar desalination; vacuum system; freshwater production; solar still.

# دراسة تجريبية لمقطر شمسي معزز بالتفريغ لتحسين كفاءة إنتاج المياه العذبة

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## ملخـــــــص البحـــــــث

تناول هذه الدراسة مشكلة تزايد ندرة المياه العذبة وارتفاع تكاليف الطاقة المصاحبة لعمليات التحلية التقليدية، مما يعزز الحاجة إلى حلول مستدامة تعتمد على الطاقة الشمسية. يهدف البحث إلى تحسين أداء المقطر الشمسي عبر دمجه بنظام مساعد بالتفريغ الجزئي لتهيئة ضغط منخفض داخل المقطر. يعتمد التصميم المطوَّر على نظام تدوير مغلق للمياه مزوّد بأنبوب فنشوري لتقليل الضغط الداخلي، وبالتالي خفض درجة حرارة التبخر وزيادة إنتاجية المياه العذبة. أُجريت تجارب ميدانية تحت ظروف الضغط الجوي العادي والضغط المنخفض لدراسة تأثير عمق مياه الحوض، ودرجة الحرارة المحيطة، وسرعة الرياح على الأداء. أظهرت النتائج تحسنًا في الإنتاجية بنسبة تصل إلى 30 %عند التشغيل تحت ظروف التفريغ، لاسيما عند الأعماق المائية الأكبر. وتؤكد هذه النتائج جدوى استخدام المقطرات الشمسية منخفضة التكلفة والمعزَّزة بالتفريغ الجزئي كأحد الحلول الواعدة لتوفير المياه العذبة في المناطق الجافة وخارج نطاق الشبكة الكهربائية الملخص نفسه.

**الكلمات الدالة:** التحلية الشمسية؛ نظام التفريغ؛ إنتاج المياه العذبة؛ المقطر الشمسي.

## 1. Introduction

Clean freshwater access remains one of the most pressing global challenges of the 21st century. Although water covers approximately 71% of the Earth's surface, about 96.5% of it exists in the form of saline water in oceans and seas, leaving only 2.5% as freshwater. Of this small fraction, less than 1% is readily accessible for direct human use, primarily from rivers, lakes, and shallow groundwater sources [1,2]. The combination of population growth, rapid urbanization, industrial expansion, and the impacts of climate change has placed unprecedented pressure on existing freshwater supplies. According to the World Health Organization, around 2.2 billion people worldwide still lack access to safe drinking water [3].

To meet the growing demand for water, desalination has become one of the most important research areas in large-scale systems. Desalination technologies are broadly classified into thermal and membrane-based processes. Thermal methods—such as Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Vapor Compression Distillation (VCD)—utilize heat to evaporate water, separating it from dissolved salts. While MSF and MED are mature technologies commonly used in the Middle East, they are energy-intensive and often reliant on fossil fuels, making them costly and environmentally burdensome [5,6].

In contrast, membrane-based technologies, particularly Reverse Osmosis (RO), have gained prominence due to their higher energy efficiency, modularity, and adaptability. RO systems employ semi-permeable membranes to separate freshwater from saline solutions under high pressure. These systems are now widely deployed for both seawater desalination and wastewater reuse, offering advantages such as lower operational costs and minimal land requirements [7,8,9]. However, despite these advancements, the energy intensity of desalination remains a critical concern, particularly when conventional energy sources are used.

In this context, solar desalination emerges as a sustainable alternative that leverages abundant and renewable solar energy to drive the separation process. Among the simplest and most accessible forms of solar desalination is the solar still, which mimics the natural hydrologic cycle by evaporating saline water using solar radiation and condensing the vapor to yield freshwater. These systems are well-suited for decentralized, small-scale applications in remote or off-grid communities. Nevertheless, conventional solar stills suffer from inherently low productivity, often limited by high evaporation temperatures, thermal losses, and inefficient heat transfer [9].

To address these limitations, researchers have explored various performance enhancement techniques, including geometric modifications, the use of advanced materials, and system integration with auxiliary energy sources. One promising approach is the application of vacuum-assisted systems to reduce the internal pressure of the solar still. Lowering the pressure decreases the boiling point of water, enabling evaporation at lower temperatures and potentially increasing freshwater yield without the need for additional thermal input.

Enhancing the productivity of solar stills has been the focus of extensive research, with various approaches including system integration, material modification, geometric optimization, and hybrid configurations. These innovations aim to overcome the inherently low yield of conventional solar stills and improve their viability for decentralized water treatment, especially in arid and off-grid regions. [10]

Freshwater scarcity poses an urgent challenge in many parts of the world, particularly in arid and remote regions lacking access to centralized infrastructure. Solar distillation has emerged as a sustainable and low-cost method for water purification, offering the ability to convert saline or brackish water into potable water using abundant solar energy. Despite its simplicity and eco-friendliness, the traditional solar still suffers from limited productivity due to low thermal efficiency and evaporation rates.

To address these limitations, numerous strategies have been explored. The integration of vacuum systems into solar stills has shown great potential to enhance evaporation by lowering the boiling point of water. Danish et al. (2019) demonstrated that coupling a geothermal heat exchanger with a vacuum pump led to a 30.5% increase in daily freshwater yield [11]. Mohamed et al. (2023) reported that forced vacuum systems could improve productivity by up to 80% compared to natural vacuum setups, highlighting the substantial gains achievable through pressure manipulation.[12]

In parallel, thermal energy storage using phase change materials (PCMs) has been widely studied to extend the operational period of solar stills beyond peak solar hours [13]. Elmghari et al. (2025) achieved a 27.7% increase in output using 2 kg of paraffin wax [14], while Karthikeyan et al. (2023) emphasized the high latent heat capacity of PCMs as critical to thermal stability. [15]

Basin enhancements have also played a pivotal role. AbdAllah et al. (2018) found that using wick materials like jute and sponge can boost productivity by up to 180% [16], and Agrawal and Rana (2023) recorded a 50% increase in yield using floating V-shaped black jute wicks. Geometrical and auxiliary enhancements [17], such as thermoelectric modules. (Esfe et al., 2021) and evacuated copper heat absorbers (Jaafar & Hameed, 2021), further contribute to temperature gains and higher distillation rates.

Hybrid desalination systems—combining solar stills with reverse osmosis, humidification–dehumidification (HDH), geothermal, or waste heat recovery techniques—have gained traction for their enhanced performance [18,19]. Abdelaziz et al. (2021) and Shalaby et al. (2023) reviewed such systems, noting higher gain out put ratios and reduced specific energy consumption [20,21], while Abdullah et al. (2024) demonstrated the viability of solar-powered hybrid HDH/RO systems achieving high water productivity at a low cost [22].

Despite these advancements, the complexity, cost, and energy requirements of active systems often hinder widespread adoption in low-resource contexts. Therefore, this study presents a novel passive vacuum-assisted solar still design that incorporates a Venturi tube within a closed-loop water circulation system to generate partial vacuum conditions without the need for external power. This innovation aims to combine the efficiency benefits of reduced pressure with the simplicity and affordability necessary for off-grid deployment.

The system is experimentally evaluated under varying conditions of water depth, ambient temperature, wind speed, and time of day to assess its thermal performance and freshwater output compared to a conventional solar still. The goal is to offer a cost-effective, energy-efficient, and scalable desalination solution tailored for water-stressed regions.

## 2. Materials and Methods

This study presents an innovative solar still design aimed at enhancing freshwater production efficiency through vacuum-assisted solar distillation. The system incorporates a closed-loop water circulation circuit integrated with a Venturi tube as shown in fig. 1, which induces a partial vacuum within the evaporation chamber. This pressure reduction lowers the boiling point of water, thereby increasing the evaporation rate—particularly during the early stages of solar heating—and improving overall productivity compared to conventional atmospheric-pressure designs.

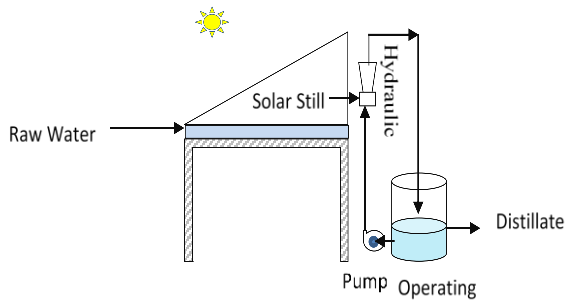


**Fig. 1.** Schematic diagram of the vacuum-assisted solar still.

Key design considerations included optimizing the tilt angle of the glass cover to maximize year-round solar radiation absorption, employing a black-coated iron basin for enhanced solar heat absorption, and using thermal insulation (5cm thick polystyrene) on the basin base and walls to reduce heat losses. The Venturi tube, driven by water flow, creates a localized pressure drop that facilitates vapor suction and accelerates evaporation.

**Fig. 2.** On-site image of the vacuum-assisted solar still.

An external reservoir and small water pump were incorporated to ensure continuous circulation and vapor extraction. Condensation occurred in the reservoir, further enhancing water recovery efficiency. The glass cover was upgraded from standard 4 mm to 10 mm heat-treated glass to withstand internal pressure differences without compromising thermal transparency.

Materials were selected based on cost, durability, and local availability, with an emphasis on recycled and easily accessible components such as repurposed glass panels, metal tank parts, plastic pipes, and pumps. This approach enabled low-cost fabrication, ease of maintenance, and scalability of the system in resource-constrained environments figure 2.
To enable performance evaluation, sensors and measurement devices were installed at critical points in the system to monitor thermal conditions and environmental variables without disrupting system function. The overall design supports sustainable, affordable, and replicable freshwater production solutions for arid and off-grid regions.

## 3. Results

This study investigates the performance of a solar still operating under atmospheric and vacuum-assisted conditions through a series of controlled field experiments conducted from August to November 2024. Many experimental cases were investigated with and without vacuum assistance.

The experiments were conducted under varying environmental conditions and water depths, with an emphasis on evaluating the impact of vacuum integration on the system productivity.

### 3.1. Impact of Solar Radiation on Productivity

Table 1 shows the results related to the effect of solar radiation rate on the amount of the produced distilled water.

**Table 1:** Daily average solar radiation and productivity readings for both cases.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Without vacuum** | **AV(I)W/m²** | **738.25** | **688.19** | **654.77** | **616.25** | **489.13** | **418.82** | **409.96** | **403.62** |
| | M ml | 4750 | 3350 | 3200 | 2630 | 2200 | 1647 | 1511 | 1171 |
| **With vacuum** | AV(I)W/m² | 599.41 | 596.06 | 553.50 | 549.00 | 477.03 | 444.44 | 408.34 | 364.75 |
| | M ml | 4200 | 3600 | 3500 | 2960 | 2920 | 1900 | 1816 | 1243 |

The obtained results show a strong positive correlation between solar radiation intensity and distillate output. The system productivity is directly proportional to the solar irradiance, reaching a maximum of 4750 ml/day at 738 W/m², and a minimum of 1171 ml/day at 403 W/m², figure 3. The vacuum-assisted system exhibited enhanced sensitivity to solar input, particularly during early hours of operation.

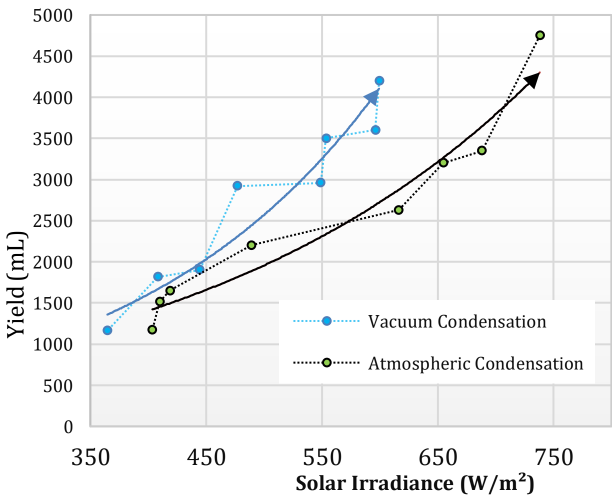


**Fig. 3.** Effect of Solar Irradiance on Distillate Productivity under Different Condensation Condition.

### 3.2. Effect of Basin Water Depth

Table 2 shows the relationship between the water productivity and the basin water depth As can be noted, the system productivity is inversely proportional to the water depth. Shallower water levels facilitates faster heating and higher distillation rates. Under vacuum conditions, a 1.5 cm depth yielded 4200 ml/day, while 4 cm depth yielded only 1243 ml/day, figure 4.

The effect was more pronounced in the vacuum system due to the greater thermal sensitivity of reduced-pressure environments.

**Table 2:** Daily Average distillate yield and basin water level under atmospheric conditions.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Without vacuum** | **Water Level(cm)** | **1.5** | **2.0** | **3.0** | **3.5** | **4.0** | **2.0** | **2.0** | **1.0** |
| | M ml | 3200 | 2200 | 1647 | 1511 | 1171 | 3350 | 2630 | 4750 |
| **With vacuum** | Water Level(cm) | 1.5 | 2.0 | 3.0 | 3.5 | 4.0 | 2.5 | 2.0 | 1.0 |
| | M ml | 4200 | 2920 | 1900 | 1816 | 1243 | 2960 | 3500 | 3600 |

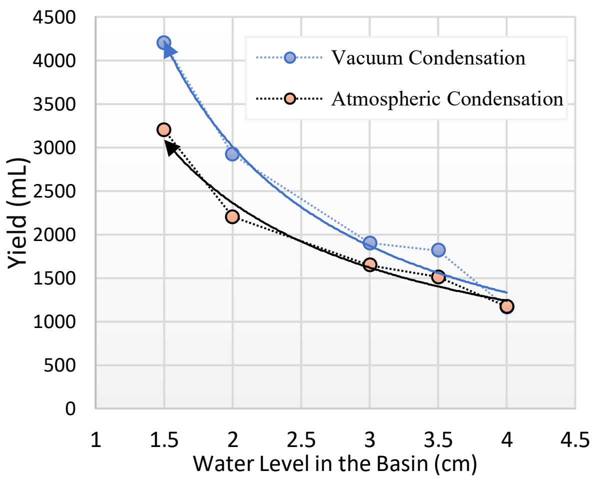


**Fig. 4**. Variation of Distillate Yield with Water Level in the Basin for Vacuum and Non-Vacuum Modes.

### 3.3. Influence of Wind Speed

As is well known, wind speed contributes to the convective heat transfer process, which in turn affects the still's productivity. Table 3 shows the relationship between wind speed and still's productivity. Wind speed was found to negatively affect condensation efficiency in both systems due to increased convective heat losses from the system.

**Table 3:** Daily distillate yield and wind speed readings reading for both cases.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Without vacuum** | **Wind speed(m/s)** | **1.9** | **1.7** | **1.47** | **1.03** | 0.7 |
| | M ml | 1243 | 1816 | 2920 | 2960 | 3600 |
| **With vacuum** | Wind speed(m/s) | 1.4 | 1.17 | 0.84 | 0.60 | 0.47 |
| | M ml | 1647 | 1511 | 2200 | 2630 | 3200 |

This effect was stronger under vacuum conditions, where higher vapor concentrations made the system more sensitive to cooling. As shown in figure 5, the maximum productivity was 1243ml at lower wind speed of 0.7ml/s. On the other hand, the maximum productivity was 3600 ml for a wind speed of 1.9 m/s.

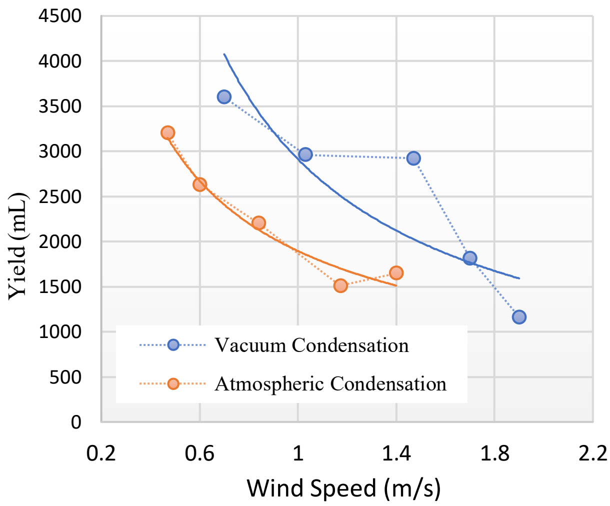


**Fig. 5**. The relationship between wind speed (m/s) and daily productivity for atmospheric and vacuum condensation systems.

### 3.4 Effect of Ambient Temperature

Table 4 presents the relationship between ambient temperature and distillation productivity in the two mentioned situations. The obtained productivity increased with rising ambient temperatures due to reduced heat losses and therefore, enhanced energy retention. The vacuum system maintained more stable output across temperature ranges. For example, at 31.2°C, the vacuum system produced 4200 ml, compared to 1243 ml which was produced at an ambient temperature of at 20.3°C.

**Table 4:** Average ambient temperature and daily productivity of the solar still for both cases.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Without vacuum** | **Ambient Air Temperature (°C)** | **32.2** | **29.7** | **29.5** | **23.2** | **22.1** | **20.7** | **20.3** |
| | M ml | 4200 | 3600 | 3500 | 2920 | 1900 | 1816 | 1243 |
| **With vacuum** | Ambient Air Temperature. (°C) | 30.6 | 30.1 | 30.1 | 28.6 | 27.0 | 25.0 | 22.1 |
| | M ml | 4750 | 3350 | 3200 | 2200 | 1647 | 1511 | 1172 |

The atmospheric system showed a similar trend but with steeper increase at higher temperatures, figure 6.

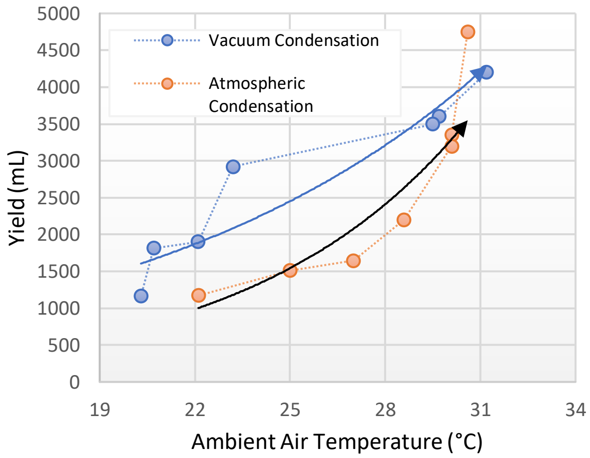


**Fig. 6.** Effect of Ambient Air Temperature on Daily Yield of Atmospheric and Vacuum Condensation System.

### 3.5 Productivity Variation with Time of Day

The hourly productivity trends in Table 5 show that the discharge system achieved higher productivity early in the day. Typically, productivity peaks earlier in discharge conditions than in atmospheric operation.

The differences between the two conditions are most evident during the morning hours because less heat is required in the discharge condition to initiate evaporation, as shown in Figure 7. They then gradually converge towards midday when solar energy input is high.

**Table 5:** Hourly Productivity Measurements of the solar still for both cases.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Without vacuum** | **Time (hours)** | 10:30 | **11:30** | **12:30** | **13:30** | **14:30** | **15:30** | **16:30** |
| | M ml | 70 | 153 | 280 | 320 | 344 | 272 | 208 |
| **With vacuum** | Time (hours) | 10:30 | 11:30 | 12:30 | 13:30 | 14:30 | 15:30 | 16:30 |
| | M ml | 151 | 163 | 284 | 326 | 349 | 245 | 202 |

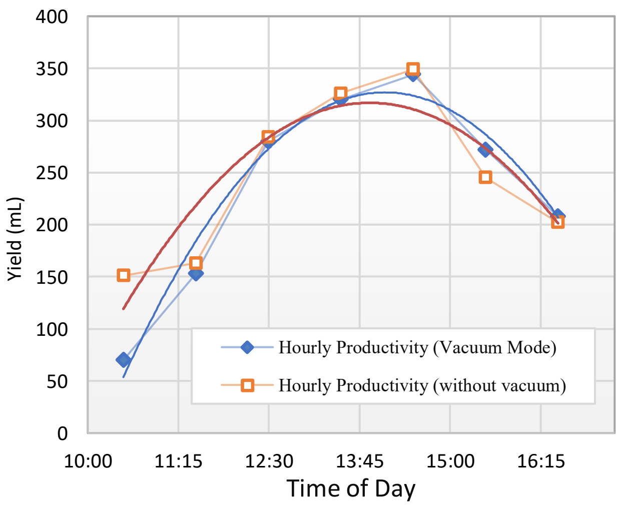


**Fig. 7.** Hourly Productivity under Atmospheric and Vacuum Conditions.

**Discussion**

The integration of the passive vacuum system led to significant performance improvements across all tested variables. By lowering the internal pressure, the boiling point of water was reduced, enabling earlier and more efficient evaporation. The system exhibited:

- Faster thermal response in morning hours.
- Enhanced sensitivity to moderate solar radiation.
- Improved condensation due to reduced vapor saturation temperature.
- Stable operation under varying ambient conditions.

In summary, the vacuum-assisted solar still consistently outperformed the conventional design, especially during early hours of the day and under moderate solar and wind conditions. These findings validate the effectiveness of low-cost vacuum enhancement in boosting solar distillation efficiency for application in arid and off-grid regions.

## 4. Conclusions

This study evaluated the performance of a solar still enhanced with a passive vacuum-assisted system, comparing it to conventional atmospheric operation. Experiments under varying conditions—basin water depth, ambient temperature, wind speed, and time of day—demonstrated that vacuum integration significantly increased freshwater productivity by lowering the boiling point and accelerating evaporation. These improvements were especially evident during early hours and with deeper water levels. While higher ambient temperatures enhanced output, increased wind speeds reduced condensation efficiency, particularly under vacuum conditions.

In addition to confirming the technical feasibility and robustness of the system, the study recommends further improvements: optimizing vacuum generation using solar-powered components, maintaining optimal shallow water depths, utilizing corrosion-resistant and thermally efficient materials, and adopting low-cost, modular designs for scalability. These steps can enhance the practicality, sustainability, and real-world applicability of vacuum-assisted solar stills, particularly in remote or resource-limited regions.

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