JJMIE

Volume 20, Number 1, March. 2026
ISSN 1995-6665
Pages 59– 70
https://doi.org/10.59038/jjmie/200106
Editor-in-Chief: Prof. Faris M. AL-Oqla

Jordan Journal of Mechanical and Industrial Engineering

Performance Enhancement of Double-Slope Solar Still Using Evacuated Tubes under Jordanian Climate Conditions

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Received 21 Aug 2025 *Accepted 1 Feb 2026*

Abstract

This study presents an experimental investigation of a double-slope solar still integrated with an evacuated tube collector under the real climatic conditions such as scarcity, particularly in arid and semi-arid regions in Jordan. The system was designed to enhance thermal performance and freshwater productivity while maintaining simplicity and low cost. A key novelty of this work lies in the combined assessment of water pH and water depth as operational parameters in an evacuated-tube-enhanced solar desalination system, introducing a chemical dimension that has received limited attention in previous studies. A double-slope solar still with a 1 m² basin area and an evacuated tube solar collector to raise basin water temperature and evaporation rate made up the experimental setup. Both saltwater and greywater were used to evaluate the system at different pH levels (5.0, 6.5, and 9.0) and water depths (2, 4, and 6 cm). The findings show that basin temperature and hourly distillate yield are greatly improved by incorporating evacuated tubes. At a water level of 2 cm, maximum productivity was reached at 5.8 L/day for greywater and 5.0 L/day for saltwater, which is an improvement of 36–52% over deeper water layers. With peak outputs of 7.8 L/day for greywater and 6.5 L/day for saltwater, raising the pH to 9.0 further increased productivity. The energy efficiency and exergy efficiency ranged from 5.2% to 16.2% and 0.8% to 2.5%, respectively, demonstrating the significant impact of operational parameters on thermal performance. Under the same circumstances, the output of greywater was found to be 21.4% greater than that of saltwater. The findings also demonstrated that solar radiation is essential to the desalination process and that productivity is directly increased by higher irradiance. This work offers fresh insight into operational optimization techniques by combining evacuated tubes with a double-slope solar still and concurrently investigating the linked effects of water pH and depth under outdoor settings. The results provide useful recommendations for the development and implementation of effective, affordable, small-scale desalination systems appropriate for areas with limited water resources.

Keywords: Desalination, Solar Panel, Wind, Grey Water, Salt Water.

1. Introduction

Freshwater scarcity has become a critical global challenge for the general population, particularly in countries which suffer from water availability, energy resources, and economic capacities. Conventional Freshwater production methods require a lot of energy, especially when dependent on fossil fuels-based energy sources. Growing environmental concerns, coupled with accelerating energy costs, have therefore driven increased interest in alternative and renewable energy sources such as wind, hydro, geothermal, solar, and others.

Water demands have been significantly increased over the last decade. However, an estimated 800 million people still do not have access to safe drinking water, and nearly 4 billion people experience water scarcity for at least one month per year. Moreover, several regions are also rapidly depleting their available freshwater resources. Many major rivers in both developed and developing countries are experiencing severe water stress as mentioned in [1]. Although saltwater constitutes almost 97 % of the Earth's total water resources, freshwater accounts for less than 3%. The majority of the world's freshwater is trapped in glaciers, ice caps, and aquifers, leaving only about 1% of Earth's water readily accessible for human use. This limited fraction is primarily replenished by precipitation, which is a key component of the hydrological cycle that sustains ecosystems and human activities worldwide [2].

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Solar still desalination systems have been the subject of numerous studies worldwide, with an emphasis on integration with auxiliary solar collectors, thermal upgrades, and geometric alterations. Although conventional solar stills are well known for their affordability and ease of use, their productivity is still constrained under typical operating circumstances. Several studies have investigated using evacuated tube collectors to raise basin temperatures and improve evaporation rates to get over this restriction. Because of decreased thermal losses and increased heat transfer efficiency, these investigations consistently show increased freshwater output.

The impact of operational factors such water depth, feedwater salinity, and weather on solar still performance has been studied in several studies. It has been demonstrated that shallow water depth speeds up heating and evaporation, and environmental elements like ambient temperature and sun radiation have a significant impact on daily productivity. Despite these developments, most of the current research concentrates on thermal or geometric optimization and saltwater desalination, paying little attention to the combined effects of operating parameters and chemical characteristics like pH in actual outdoor settings.

Jordan is currently confronting several environmental challenges related to water scarcity. Water represents a critical factor in the country's population/resource equation, as limited water availability concurs with continuous population growth. This imbalance has been exacerbated by the increase of the population rate and significant inflows of migrants. In the light of the impending water and energy crises, as well as their interactions, the potential of solar-powered water treatment technologies are increasingly being explored as promising and sustainable solutions to alleviate water shortage in Jordan.

Jordan is considered one of the world's poorest countries in terms of water resources. More than 90 % of its land area receives less than 200 millimeters of annual precipitation per year, while over 70% receives less than 100 millimeters of annual precipitation per year. The country suffers from severe lack of renewable freshwater supplies, with an annual average of approximately 680 million cubic meters, equivalent to about 135 m^3 per capita for all uses. As a result, Jordan's water supplies are among the world's lowest per capita. Jordan gets its water from three sources: groundwater (about 60 %), surface water (about 28%), and treated wastewater (around 12 %) [3].

Jordan is experiencing significant depletion of both groundwater and the surface water. Consequently, desalination has become a necessary approach for securing additional fresh water. Among all the water desalination technologies, solar desalination represents one of the suitable and cost-effective solution for Jordan, owing to the country's high solar potential. This advantage is further facilitated by the widespread deployment of the solar panels, making Jordan as a leading producer of solar energy in the Middle East. Desalination is a technique for extracting dissolved minerals from seawater, brackish water, or treated wastewater. It has become increasingly important in addressing the ongoing decline in freshwater availability. Moreover, the researchers in [4] mentioned that another serious reason for water wastage is water leakage which is caused by the distribution system, which prompts an extensive loss of water assets and energy.

Previous studies have highlighted the growing importance renewable energy in addressing global energy challenges. The researchers in [5] examined the importance of the global renewable energy landscape, progress, and status, and found out that it focused on increasing the RE share in the energy mix. Moreover, the integration of renewable energy into desalination control system has been recognized as a key component of smart and intelligence which are expanded worldwide [6-8]. These studies reported that challenges remain in data management, data accuracy, efficiency and cooling requirements.

Recent research has also focused extensively on smart cities applications aimed at minimizing energy consumption, reducing operational cost, and optimizing system lifespan. For instant, author in [9] proposed semi-dynamic real-time task scheduling algorithm that effectively assign jobs and improves system efficiency. Solar desalination driven by renewable energy resources is considered one of the major important technologies for distilling fresh water from salty, brackish water using solar energy.

In this context, researchers in [10] developed a solar-powered irrigation system with a real-time monitoring system for okra cultivation demonstrating the feasibility of renewable energy-based water systems. Solar desalination systems are generally classified into two main types: passive solar still and active solar still. In general, Passive solar still depends solely on solar energy, while active solar still uses additional energy sources such as solar thermal collectors, solar concentrators, or PVs. Active solar still uses additional energy sources including solar energy and mechanical sources.

The authors in [11] designed a single basin and concluded that solar productivity is strongly influenced by the collector's surface area, which maximizes absorption of both direct and diffuse solar radiation. This enhancement led to significant increases in the evaporative and convective heat transfer coefficients. Additionally, the researchers in [12] tested two single-slope single-basin solar still units: the conventional and the modified solar still. For the modified solar still, they used V-shaped black cloth floating wicks at the bottom of the basin. Moreover, it was discovered that the modified solar still increased the evaporation surface area by 26% due to the V-shape profile of the floating wick, resulting in increasing the distillate water productivity in both summer and winter.

In [13] the authors conducted a comparison between the double basin and single basin. Their findings showed that although the addition of an extra basin increased the total system cost, it resulted in significant enhancement in distillated yield. The maximum distillate production for both SB and DB configurations occurred at a low basin water depth of2 cm. It is also observed that the presence of a wick or porous or energy-storing substance in the basin boosts distillate production. The presence of extra basins boosts daily productivity by around 75% as compared to a single basin. The passive double basin improved night production by 49.2 %.

In [14], the effect of the water basin depth (40, 30, 20, and 10 mm) on the productivity of a double basin single-slope (DBSS) solar still was experimentally investigated.

The results indicated that a water depth of 10 mm produced a yield approximately 13% higher than the achieved at depth of 40 mm, confirming that desalinate yield decreases with increasing water depth. To reduce thermal resistance between the basin and collector, the researchers in [15] employed evacuated tubes as combined solar collectors and basin elements. Their results demonstrated on overall productivity of 0.83 kg/m^2 h.

Many experiments have been carried out to enhance the distillate production of solar still. For instance, the performance of conventional double basin solar still was compared with that of system integrated with evacuated tubes, both with and without black granite gravel. In a double basin solar still, it was discovered that adding vacuum tubes enhanced distillate production by 56%, while adding vacuum tubes and black granite pebbles boosted distillate production by 65%. In Reference [17], the author focused on freshwater production through the utilization of solar energy to heat saline water ponds. In this approach saline water was heated and evaporated, and the resulting condensate was collected in dedicated basins to obtain distilled water. Double basins with specific dimensions were employed, and the basins were painted black and thermally insulated to maximize solar radiation absorption and minimize heat loss to the surrounding atmosphere.

The researchers in [18] evaluated the performance of two single-slope solar stills; a conventional configuration and a modified design incorporating a partition at the base plate. Similarly, in [19], the effect of a reticular porous insert (black sponge rubber) on the efficiency of a single slope solar still was experimentally investigated. Both studies were carried out in the Semnan, Iran. From an economic perspective, the cumulative freshwater production cost level (CPL) of the still equipped with partition was found 8.3 % more than for traditional solar stills.

For the modified solar stills incorporated with reticular porous insert, efficiency enhancement of approximately 15.6%, 24%, 26.9%, 20%, and 15.8%, respectively were reported in 30/08/2016, 3/10/2016, 5/10/2016, 14/12/2016, and 1/3/2017, respectively. Furthermore, as compared to conventional still, the CPL/m2 for modified solar still (reticular porous insert) was 12.03 % lower. In [20] the researchers studied the effects of water surface-cover distance (WCD) and water depth on the productivity of a single solar still basin double slope. Each parameter was varied independently while keeping the other constant to measure their system impacts on productivity. Most researchers who worked on active solar stills used a single-slope solar still with a flat plate collector or concentrating collector as mentioned in [21].

Another important addressed in the literature review is the treatment and reuse of greywater. The authors in [22] conducted an evaluation on the human health risk of greywater reuse. They used a three-tiered approach to investigate the potential health risks associated with the presence of micropollutants in greywater and they found that most of the compounds presented pose no risk to human health, even if the reclaimed greywater is used for drinking purposes for the rest of one's life. The authors in [23] explored and utilized a converter with various applications in smart grids, specifically in the context of renewable energy systems where much of the research is forcing in the future applications.

The researchers in [24] reported that Solar desalination provides a viable long-term solution to freshwater scarcity in arid climatic deserts, such as the upper part of Egypt. However, the large-scale application of solar desalination systems in these areas remains limited due to their relatively low productivity. Several initiatives have been made internationally, primarily to improve productivity and performance. The evaluation included solar stills with horizontal and inclined absorbers, which could be operated passively or aggressively. These changes are intended to improve evaporation and/or condensation processes (e.g., metallic fins, black coating, nanoparticles, sensible and latent heat storage materials, internal and exterior reflectors, wick absorbers, magnets, cover cooling, and the integration of various types of solar collectors. According to [24], pyramid solar stills exhibit superior performance under passive operation due to their relatively high production. Adding a corrugated absorber covered with black paint and zeolite crystals to a pyramid solar still can increase daily yield from 3 to 5 L/m2 (standard flat absorber) to 8-13 L/m2. Additionally, integrating an evacuated tube solar collector with different solar still can enhance productivity by up to 175%. Such hybrid configurations are therefore considered critical for mitigating freshwater scarcity in arid places.

The authors in [25] found that a solar-still's productivity is determined by its water and glass temperatures. The authors examined a double-slop, double-basin solar-still with evacuated tubes. The investigation found that reducing heat loss increases productivity. Eight double-walled hard borosilicate glass tubes were used. The experiments were conducted on the still during daylight hours (9 a.m.-5 p.m.) with tap water as feeder. The outer tubes of evacuated tubes were transparent. Inner tubes were coated with a selective Al-Ni/Al compound to enhance solar radiation absorption and reduce emittance. The tubes added thermal energy to the system, increasing the water temperature which leads to increase evaporation and productivity of distillate water.

The researchers in [26] designed, constructed, installed, and tested a multi-effect desalination (MED) system with a production capacity of 10 m^{3}which used to convert seawater into potable water using solar energy system. In this system, hot water generated by a solar flat plate collector field was initially flashed in the desalination plant's flash chamber before being fed to the first stage of the multi-effect evaporator. The average hot water temperature generated by the collector field was 75°C.In the multi-stage evaporator, sea water was sprayed parallel to vacuum pressure to produce water vapor while also condensing the water vapor flashing through the tube from the flash chamber/previous effects. The brine and condensate were transported to the final stage of the multi-effect desalination (MED) system using a manometric head. During the experiment, the largest temperature differential between the intake and outflow of condenser cooling water was 13°C. The ejector maintained vacuum pressure during the operation of the MED system, which included the flash chamber.

Experimental investigations on the MED system were conducted for better understanding of the performance and the thermal behavior when it powered entirely by solar energy.

Table 1. Comparison of Solar Still Techniques

Technique	Productivity	Cost	Complexity
Single Basin	Low (2–5 L/m²/day)	Low	Low
Double Basin	Moderate (up to 85% higher than single basin)	Moderate	Moderate
Multi-Effect (MESS)	High (10–15+ L/m²/day)	High	High

The main objective of this study is to experimental investigate the impact of integrating evacuated tubes with solar still basins in desalination productivity, with particular emphasis on reducing basin water depth and increasing the PH value. As demonstrated in [27] that the basin water depth plays a critical role in enhancing solar-powered desalination systems. In arid and off-grid regions, including remote areas in Jordan, solar-powered desalination of brackish groundwater offered a sustainable and practical solution for freshwater production. By Leveraging abundant solar radiation and locally available water resources, small-scale solar still have been developed and experimentally tested.

Building on this foundation , the present study aims to enhance the system's productivity by systematically evaluating key operational parameters, particularly basin water depth and water pH. Experiments were conducted using varying water depths ranges from 0.5 to 4 cm and total dissolved solids (TDS) concentration of 5000 ppm, under consistent climatic conditions. The results confirmed that reducing water depth significantly enhances freshwater yield, while productivity was also found to be strongly influenced by solar radiation intensity and improved condensation performance achieved through effective glass cover cooling.

The key innovation lies in integrating evacuated tubes with a double-slope solar still, a combination that enhances thermal efficiency and remains underexplored. Additionally, the study uniquely investigated the impact of water pH alongside depth, introducing a novel focus on water chemistry in solar desalination research.

Moreover, while many of earlier studies have examined the effectiveness of evacuated-tube collectors and traditional solar stills, there has been little attention in the literature to hybrid systems that combine both technologies for the treatment of various types of water under actual climate circumstances. Greywater reuse received very little attention in most previous studies, which exclusively looked at saltwater. Furthermore, the combined effects of pH and water depth on an evacuated-tube-enhanced double-slope solar still's thermal behavior, productivity, energy efficiency, and exergy efficiency have not yet been thoroughly examined.

In order to fill this gap, the current study quantifies energy and exergy performance metrics while experimentally analyzing a hybrid desalination system using both saltwater and greywater under various operating conditions. This allows for a better understanding of the system's thermal enhancement and possible uses.

The examined literature indicates that there is still a significant research gap in the systematic evaluation of the combined effects of water depth and pH on the performance of evacuated-tube-enhanced solar stills, especially in local climates. Furthermore, there has not been much experimental focus on using these hybrid systems for greywater treatment and saltwater desalination. By experimentally examining a double-slope solar still integrated with evacuated tubes and measuring productivity, energy efficiency, and exergy efficiency under various pH levels and water depths in the climate of Amman, Jordan, the current work fills this gap.

The combined impact of operational factors like water depth and water chemistry, notably pH, has received little consideration, especially in actual outside climate settings. Consequently, there is a glaring research gap in the methodical assessment of how these linked factors impact the productivity, efficiency, and thermal behavior of evacuated-tube-enhanced solar stills. By experimentally examining a double-slope solar still integrated with evacuated tubes and concurrently examining the combined impacts of water pH and water depth, the current work fills this gap and enhances the uniqueness and usefulness of the suggested method.

Evacuated tube collectors, solar still desalination systems, and the impact of operating parameters on freshwater productivity have all been thoroughly studied in recent years; a significant number of these research have been published. Most of these studies concentrate on structural changes or thermal performance under fixed water characteristics, even though they offer insightful information about thermal enhancement methods and design enhancements.

2. EXPERIMENTAL SET-UP AND INSTRUMENTATION

2.1. System Components

The experimental setup employed in this study comprises two primary components: evacuated tube collectors and a double-slope solar still basin. The system was designed and installed on the campus of the University of Jordan in Amman, Jordan. The key element of the setup includes a dual-basin solar still and an array of evacuated tubes. The inner basin of the still was constructed with dimensions of 1.0 m × 0.33 m. Thermal insulation was provided using polyurethane foam (PUF) with a thickness of 10 cm, to ensure maximum retention of solar energy within the basin. The top of the solar still was sealed with 6 mm thick glass, measuring 51 cm × 119.5 cm, and inclined at angle of 45° relative to the horizontal to enhance solar radiation absorption and facilitate condensate collection as shown in Figure1.

To improve thermal efficiency, the absorber plates within both basins were coated with matte black paint, to increase heat absorption capability. The entire structure of the solar still was fabricated using galvanized iron, selected for its durability and high thermal conductivity to support elevated water temperatures during operation.

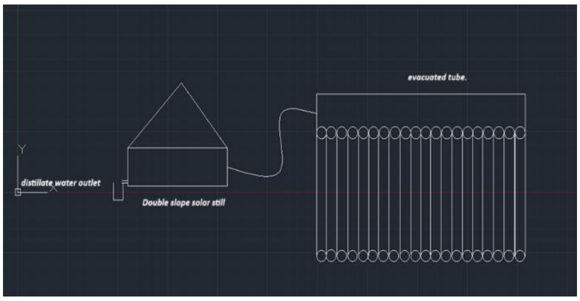

Figure 1. Solar desalination system.

The basin contains the following essential components: Two plate glass condensing covers for condensation and distillate collection; distillate collection channels for gathering the condensed fresh water; a black-painted solar collector to maximize heat absorption; thermal insulation to minimize heat losses to the surroundings, and an external water container used to feed the basin. A schematic representation of the system is provided in Figure 2.

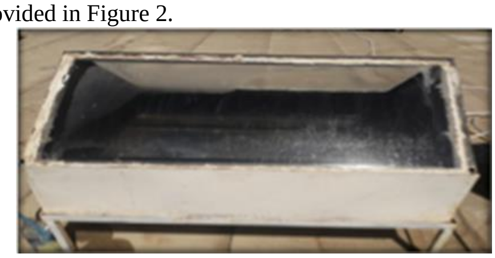

Figure 2. Double Slope Solar still basin

When the hot water enters the basin in the system, the incident solar energy is transmitted through the glass cover and transferred to the water. Simultaneously, the blackened basin absorbs the majority of the transmitted radiation. As a result, the basin water temperature increases, initiating the evaporation process. The generated water vapor rises and comes into contact with the cooler inner surface of the glass cover, where it condensed. The condensed water runs then flows downward along the inclined cover and is collected in the distillate trough due to gravity and the provided slope. The second major parameter of the experimental setup is the evacuated tubes, which contains a storage tank, heat pipe fin, and heat exchanger (condenser).

The evacuated tube collector system consists of 20 individual tubes, each with a diameter of 5.8 cm and a length of 1.8 m. These tubes are made of concentric borosilicate glass tubes and are inclined at a 45° angle from the horizontal, as depicted in Figure 3. The evacuated tube solar collectors (ETSCs) comprise two concentric glass tubes with one open end. The inner absorber tube is positioned inside the outer clear glass tube, creating a vacuum between them. This vacuum significantly enhances thermal efficiency by minimizing heat loss.

Figure 3. Evacuated tube collector

The evacuated tube is a vacuum-sealed cylindrical structure featuring a selectively coated solar-absorbing surface. These selective coatings are engineered to absorb the majority of incident solar radiation while maintaining low emissivity, thereby maximizing heat absorption. The vacuum surrounding the absorber tube further minimizes thermal losses through conduction and convection. The absorbed heat is transferred either to a heat pipe or to circulating water inside the tube. The heat pipe, which contains a refrigerant, is a sealed copper pipe attached to a black copper fin. This assembly occupies the interior of the tube, functioning as the collector absorber plate, and is designed to transfer the captured solar energy to a working fluid or heat sink for subsequent utilization or storage.

Evacuated tubes were directly connected to the inner basin of a solar still to enhance the distillate output of the double basin solar still. In addition to this configuration, researchers have explored other approaches to improve distillate production.

For instance, the authors in [28] investigated a single-slope solar still coupled with an evacuated tube collector (ETC) operated under forced circulation conditions. A comprehensive thermal model of the integrated system was developed to evaluate its performance under the climatic conditions of New Delhi, India. For a basin water depth of 0.01 m and a mass flow rate of 0.006 kg/s, the system achieved a daily distillate output of 3.47 kg. Optimal performance was observed at a higher mass flow rate of 0.06 kg/s and a basin water depth of 0.03 m, resulting in a maximum daily yield of 3.9 kg. Under typical summer conditions, the corresponding energy and energy efficiencies were calculated to be 33.8% and 2.6%, respectively. Furthermore, the estimated annual average yield per unit area of the solar collector exceeded that of systems operating in natural circulation mode.

The thermal efficiency of the evacuated tube collector is optimized by reducing thermal losses, through the vacuum surrounding the absorbed tube, which minimizes energy dissipation. The key components of the evacuated tube system include storage tank for holding preheated water, heat pipe for transferring thermal energy, a heat absorbing fin to enhance heat capture, and heat exchanger (condenser) for transferring heat to the working fluid.

2.2. Experimental Procedure

The experimental setup was first prepared by installing the system and thoroughly cleaning both the basin and the evacuated tube collectors. The storage tank connected to the evacuated tubes was filled with water, which was then preheated for a duration of 2 to 3 hours. Once the water inside the evacuated tubes reached a desired temperature, it flowed into the solar still basin via thermal circulation. The key variables investigated during the experiments were the pH value and the water depth inside the basin. Water depth was adjusted to three levels: 2 cm, 4 cm, and 6 cm. For pH variation, the water was initially set at pH 6, then increased to pH 9 using a basic solution (NaOH) and later decreased to pH 5 by adding an acidic solution (HCl). These adjustments were made to study the effect of pH variation on desalination performance and water productivity.

The glass cover temperature, chamber temperature, water temperature, and ambient-air temperature were measured using thermocouples in both stills. GRWS100 weather station, consisting of an array of equipment and sensors was employed to monitor atmospheric, and soil conditions. Commonly observed environmental parameters included solar radiation, air temperature, wind speed, and light intensity. A Total Dissolved Solids (TDS) Meter was used to measure the TDS levels in both the inner and outer water samples. Additionally, graduated cylinders were utilized to measure water production as summarized in Table 2.

Two types of feed water were tested over the four-week experimental period: greywater in the first week and saltwater in the second. The water depth inside the basin was manually regulated using ruler markings placed on the interior surface. As evaporation occurred, the water level decreased by approximately 1–2 cm every 1–2 hours on hot days. Additional water was manually added as needed to maintain the target depth. Data collection was performed at 30-minute intervals throughout the experiment to accurately monitor changes in water pH and depth. For the saltwater experiment, 100 grams of coarse table salt (NaCl) were added to the water in the basin every hour to simulate seawater conditions. As sunlight struck the basin surface, the grey or saline water evaporated and condensed on the inner surface of the glass cover, forming droplets. These droplets trickled down into a dedicated channel and were collected in bottles placed beside the basin. Additionally, the collected distilled water was measured hourly using a graduated cylinder to determine the output volume. Throughout the experiment, various parameters were recorded hourly, including ambient temperature (T_a), glass surface temperature (T_g), evacuated tube inlet temperature (T_{ei}), evacuated tube outlet temperature (T_{eo}), basin inlet temperature (T_{bi}), basin outlet temperature (T_{bo}), pH value, total dissolved solids (TDS), and the volume of distilled water in milliliters.

Table 2. Measurement Devices and Solar Panel Details

Component	Serial Number	Description
pH Meter	PHM-110	Measures the pH level of water to assess acidity or alkalinity.
TDS Meter	TDS-210	Measures total dissolved solids in water to estimate salinity or mineral concentration.
GRWS100 Weather Station	WS-300-GRWS	A compact weather station that measures: - Air Temperature - Solar Radiation - Wind Speed - Light Intensity (Lux)
Thermocouple Sensor	TC-401	Measures the temperature of water or other substances using thermoelectric principles.

3. RESULTS AND DISCUSSION

A simplified thermal model was considered to interpret heat transfer within the evacuated-tube-enhanced solar still, thereby increasing the system's engineering rigor. The primary sources of heat gain are the basin water are convection from the hot water supplied by the evacuated tubes and solar radiation transmitted through the slanted glass covers. To understand the temperature distribution and identify locations of thermal irreversibility, convective losses to the surrounding air and conductive losses through the basin walls were conceptually evaluated. This thermal analysis demonstrates how evacuated tubes enhance the thermal driving force for evaporation and validates the observed increases in basin temperature. From an engineering design perspective, the incorporation of 20 evacuated tubes, the glass covers' 45° inclination of the glass covers, and the 10-cm polyurethane insulation layer are intentional design choices aimed to minimizing thermal losses and optimize energy utilization. By calculating the useful thermal gain relative to the total solar input and identifying sources of inefficiency, the subsequent energy and energy evaluations provide deeper engineering information. The metrics are essential for system optimization, as they assess how successfully the system transforms available solar energy into evaporation potential. The findings have direct implications for technical and industrial applications. Decentralized water treatment in arid and semi-arid areas, agricultural irrigation support, and small-scale desalination units for remote communities can all benefit from the demonstrated productivity improvement under optimal water depth and pH conditions. A scalable and energy-efficient solution that may be modified for inexpensive industrial deployment is provided by the hybrid design that combines evacuated tubes with a double-slope solar still. This engineering-focused interpretation emphasizes the system's potential practical value and increases the work's relevance to audiences in mechanical engineering. To improve the productivity of single basin solar still, evacuated tubes were directly coupled with the still. Furthermore, water depth and pH values were varied to assess their influence on performance. The experimental data were analyzed by systematically comparing the productivity of the solar still under different water depth and pH levels. For each set of parameters, the amount of distilled water produced was recorded at regular intervals throughout the day, and the average daily productivity was calculated. This analysis identified the optimal water depth and pH level that yielded the highest water output, enabling a clear evaluation of how each variable affected the overall performance of the desalination performance.

Water depth in the basin plays a critical role in influencing both thermal dynamics and system productivity. A shallow water layer heats up more rapidly under solar radiation, resulting in a higher evaporation rate and, consequently, greater freshwater yield. Conversely, a greater water depth requires more energy to reach the evaporation temperature, reducing efficiency and delaying the distillation process. Additionally, an increase in the pH level of the feed water was observed to correlate with a higher distillate yield, indicating improved distillation performance within the optimal pH range.

Graphical analysis was employed to illustrate the impact of variations in water depth and pH level on the quantity of distilled water produced, as well as to assess the relationships among the experimental variables.

3.1. Effect of PH Value.

Three different pH values (5.0, 6.5, and 9.0) were tested using greywater and saltwater samples. The results revealed a clear dependence on distillation performance on the pH level as shown in Table 3. The average daily distillate production increased significantly as the pH increased from 5.0 to 6.5, with over 2000 mL gain in volume for both water types. This trend is attributed to a reduction in acidity, which diminishes corrosive interactions and promotes better thermal and crystallization dynamics. Beyond pH 6.5, the increase in yield became marginal due to salt precipitation and changes in ionic behavior that hinder evaporation. At pH 9.0, greywater produced ~7500 mL and saltwater ~5500 mL of distillate.

Table 3. Average Daily Distillate Production at Different PH Values

pH Value	Greywater (mL)	Saltwater (mL)
5.0	5300	3500
6.5	7300	5200
9.0	7500	5500

The effect of the pH level on system productivity was evaluated by adjusting the water's pH to 5, 6.5, and 9 using controlled additions of acidic (HCl) and basic (NaOH) solutions. The resulting water output was recorded throughout the day for each pH level. The average daily distillate production was calculated, and comparative graphs were developed to analyze the observed trends. This analysis clarified how variations in water acidity or alkalinity influence the evaporation and condensation processes within the still, thereby identifying the optimal pH for maximum desalination efficiency.

Figure 4 aligns with the findings reported by researchers in [29], confirming that an increase in pH values facilitates salt crystallization at the bottom of the basin. This phenomenon accelerates the desalination process, resulting in improved water productivity.

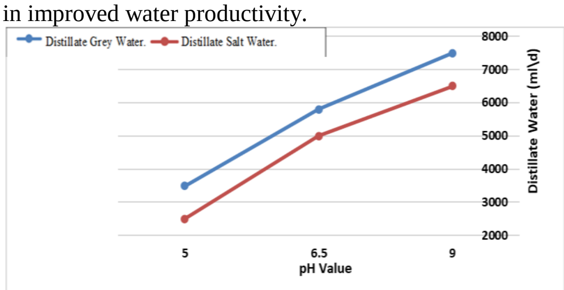

Figure 4. Variation of daily production as pH value in greywater and saltwater.

The findings demonstrate a clear increase in distillate production with raising PH, with both seawater and greywater producing their maximum output at PH 9.0. Numerous thermophysical mechanisms account for this phenomenon. Water's surface tension is lowered by higher PH values, which makes it easier for water vapor to develop and escape at the air–water interface. Alkaline conditions also allow for faster evaporation under the same thermal input because they marginally reduce the enthalpy needed for phase shift. Additionally, higher PH increases molecular diffusivity, which makes it easier for vapor molecules to leave the liquid phase. When paired with the high temperatures attained by the evacuated tubes, these actions increase the rate of evaporation inside the basin. A novel operational parameter for enhancing solar still performance is introduced by this mechanistic explanation, which explains why productivity increased with PH. This feature was rarely examined in earlier evacuated-tube desalination experiments.

3.2. Accumulative Distillate Water.

Under constant conditions (pH 6.5 and 2 cm water depth), hourly distillate output was recorded from 10:00 AM to 6:00 PM. Initial yields were modest- approximately 5000 mL for greywater and 2500 mL for saltwater- due to gradual heat accumulation. Maximum yields occurred between 3:00 PM and 6:00 PM, reaching 20,000 mL and 35,000 mL for greywater and saltwater, respectively. These trends reflect the time-dependent nature of solar energy absorption, heat transfer, and phase change dynamics.

As shown in Figure 5, a comparison between grey and saltwater was conducted. The accumulative distillate of both water types increased steadily over time. From 10:00AM to 3:00PM, the figure indicates a gradual rise. with saltwater reaching approximately 2500 mL and greywater about 5000 mL. However, both curves exhibited a sharp increase during the next three hours (3:00PM to 6:00PM), with accumulative saltwater exceeding 35000 mL and accumulative grey water reaching 20000 mL. This figure confirms that accumulative distillate from greywater is higher than that from saltwater, because saltwater has a higher TDS content and salinity, which delays the desalination process.

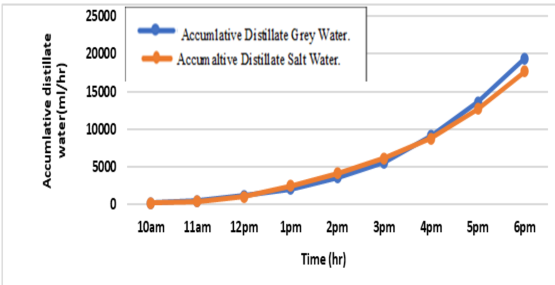

Figure 5. Accumulative distillate water every hour.

3.3. Effect of water depth on productivity of distilled water

The distillate output of solar still is strongly influenced by the depth of water in basin. Water depth plays a critical role in determining freshwater production. In reference [30], the authors investigated the effect of varying water depths (40 mm, 30 mm, 20 mm, and 10 mm) on the yield of a double basin single-slope (DBSS) solar still. Their findings indicated that a water depth of 10mm produced a 13% higher yield compared to a depth of 40 mm, confirming that as the depth increases, distillate output decreases.

Water depths of 2 cm, 4 cm, and 6 cm were tested and the results indicate an inverse relationship between water depth and productivity. At 2 cm, greywater and saltwater produced 5800 mL and 5000 mL, respectively, while at 6 cm, production dropped to 3900 mL and 3000 mL. Shallower depths promote faster heating, enhancing evaporation rates due to reduced thermal mass, as shown in Figure 6 and Figure 7.

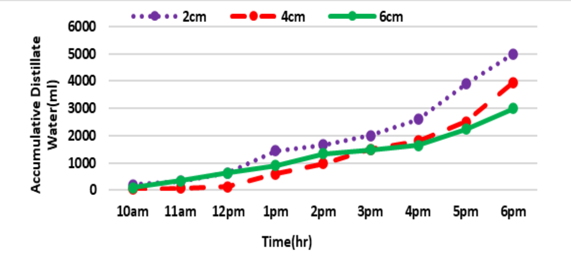

Figure 6. Accumulative distillate saltwater with variable depth

Across all depths, greywater consistently yielded more distillate than saltwater which aligns with the previous findings reported in [30]. It was observed that increase in distillate water was slow between 10:00AM to 12:00PM,with all curves remaining below 1000 mL during the first two hours. This can be attributed to the gradual temperaturerise, which is a major factor influencing the desalination process. Once the temperature stabilized between 1:00PM to 4:00PM, distillate water output began to increase steadily. From 4:00PM to 6:00PM, a substantial rise was recorded across all curves. For instance, the 6 cm greywater curve doubled during this period, reaching 3900 mL,while the 4 cm curve increasedto approximately 3950 ml.

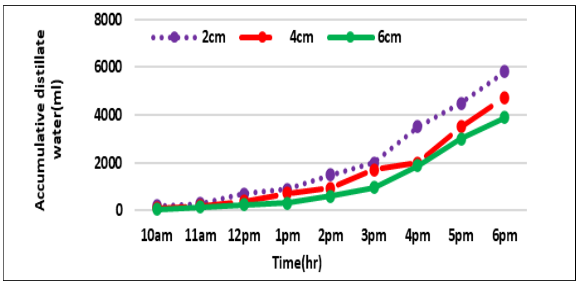

Figure 7. Accumulative distillate greywater with variable depth

Distillate yield and water depth showed a strong negative relationship, with the maximum output coming from the shallowest depth (2 cm). Established thermal concepts are in line with this behavior. The basin may reach greater working temperatures faster when the water depth is less since it takes less energy to raise the water's temperature. Furthermore, shallow water improves the condensation process by maintaining a greater temperature difference between the water's surface and the glass cover.By collecting more heat and releasing it more slowly, deeper water layers serve as thermal storage, lowering the rate of evaporation during the hottest parts of the day. Rapid evaporation is made possible by the combination of shallow depth and the constant heating supplied by the evacuated tubes. These results validate that a crucial design factor for optimizing performance in small-scale desalination systems is water depth.

The researchers in [31] studied the effect of water depth on productivity enhancement of fouling-free non-contact nanostructure desalination system (NCNS).They reported that nanocoated absorber's topsurface exhibited an absorptivity of 90% and an emissivity of 85%. Experiments were conductedusing synthetic saline water over six days, both with and without a reflector, at varying water depths (0.5 cm, 1 cm, and 1.5 cm). The results showed that increasing water depth did not significantly improve production due to the NCNS's interfacial heating effect. In addition, to productivity test, analytical modeling, fouling studies, accelerated corrosion assessments, and water quality evaluations were all performed. The findings were highly promising confirming that the freshwater obtained was safe to drink.

To guarantee the accuracy of the experimental measurements, an uncertainty analysis was carried out for the main study instruments, such as thermocouples, the solar power meter, and the graduated cylinders used for distillate collection. The root-sum-square (RSS) approach, which takes into consideration both statistical and instrumental uncertainties, was used to estimate the combined uncertainty. The solar power meter showed an inaccuracy of ±5%, whereas the thermocouples used to measure basin, glass, and tube temperatures had an accuracy of ±0.5°C. There was a ±2% margin of error in the distillate volumetric measurement. For sun desalination studies carried out in outdoor climates, the overall uncertainty of the computed energy and exergy values was determined to be within ±6–9%. The published thermal performance and productivity results are strengthened by this uncertainty analysis.

Table 4. Distillate Yield for Different Water Depths

Depth (cm)	Greywater (mL)	Saltwater(mL)
2	5800	5000
4	4700	3900
6	3900	3000

3.4. Comparison of Evacuated Tubes Inlet and Outlet Temperature

The authors in [17] reported that the evacuated tube temperature was 39°C at 9:00AM and reaches its peak 77°C at 2:00 PM, coinciding with the highest ambient temperature, before gradually declining. Similarly, the study in [32] examined the performance of a solar-powered desalination system integrated a single-slope solar still with an evacuated tube solar collector. The system operates by capturing solar energy through evacuated tubes, which heat saline water that is subsequently transferred to the solar still, where additional solar energy enhances the evaporation process. Two configurations wereanalyzed: a conventional solar still (Still-I) and a modified still integrated with an evacuated tube collector (Still-II). Both systems are simulated under identical environmental conditions in Tanta, Egypt, using a detailed theoretical model developed in FORTRAN to explore heat transfer dynamics in each component. A comparative energy performance analysis revealed that Still-II significantly outperformed Still-I, producing 8.02 kg/m²·day of freshwater -a 31.26% increase over Still-I's 6.11 kg/m²·day- at a constant water depth of 2.0 cm. Additionally, the daily energy efficiency of Still-II reached 46.72%, compared to 36.00% for Still-I.

Table 5 presents the measured temperatures at the intel and outlet. At 10:00 AM, the intel water temperature was 40.2 C° . By 1:00PM, when the ambient air temperature reached its peak, the evacuated tube temperature rose to 59 C°, after which it gradually declined for both greywater and saltwater. Across all days, Tei consistently increased from 10:00 AM to 1:00 PM before decreasing in the following hours.For example, on 1st day rose from 52 C° to 59 C°, then dropped to 51 C° by 4:00 PM. On third day, it increased from 44 C° to 59 C°, then fell to 56 C° , while in the last day it climbed from 56 C° to 66 C°, before declining to 65 C°.

However, Teo values are quite different. They increased slightly at the end of the day. On the 2nd day and the 4th day, Teo enhanced from 10:00AM to 1:00 PM to reach 79 C° and 68 C° respectively. Nevertheless, they began to decline in the next hours to reach 60 C° and 58 C° on the same days.

The ETC-enhanced double-slope solar still demonstrated superior productivity and thermal efficiency compared to traditional designs, due to better insulation and heat retention. Experimental results confirmed that water depth and pH significantly influence system output. Although the system entails a higher initial cost, it offers strong potential for future water desalination with further development. The integration of evacuated tube collectors resulted in a substantial performance boosts, with experimental data showing up to 65% increase in distillate output compared to a traditional solar still as shown in Table 6. The ETC system reached basin water temperatures as high as 79°C (inlet) and 68°C (outlet), ensuring sustained high thermal input for efficient evaporation. The integration of evacuated tube collectors into a single-basin solar still significantly enhances water distillation performance. Experimental results confirmed that variables such as pH, water depth, and solar radiation critically influence productivity.

Table 6. Productivity Comparison Between Conventional and ETC-Integrated Solar Stills.

Configuration	Daily Output (mL)	% Increase
Without ETC	4800	—
With ETC	7920	65%

The ETC system achieved a 65% improvement in distillate yield over conventional setups. The enhancements observed are supported by underlying heat transfer and phase change mechanisms. Additionally, the system produced water of acceptable quality for both potable and non-potable uses. These results support the adoption of ETC-enhanced solar stills as a viable solution for freshwater generation in water-scarce regions.

3.5. The temperature at Various Points of the Distillation Unit

The hourly fluctuations of various temperatures obtained during the experiment are depicted in Figure 8. It demonstrates that all temperatures rise in the same direction from morning to midday due to the increase of solar energy at different times of the day. The results show that the greatest temperature was found in the outlet evacuated tube, followed by the inner basin water temperature, inlet evacuated tube water temperature, outer basin glass temperature, outer basin water temperature, and ambient temperature, respectively.

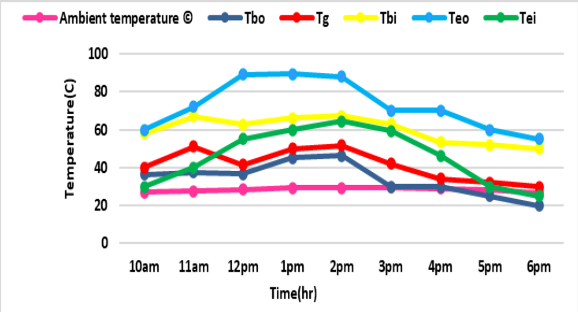

Figure 8. Temperature at various points of a distillation unit.

These temperatures are the main factors that affect the desalination process. This is agreed with the study in [16] which discovered that the temperature of the outlet evacuated tube is the highest, followed by the temperature of the inlet evacuated tube, the inner basin water temperature, the outer basin water temperature, the ambient temperature, the outer basin glass temperature, and the inner basin glass temperature.

3.6. The variation of solar radiation with time.

Another important factor that can have a major effect on solar still efficiency is solar radiation. The current study used a pyranometer to monitor solar radiation on an hourly basis, and the data are shown in Figure 9. The solar radiation outgoing the instrument is measured in W/m^2. The variation of solar radiation and ambient temperature on 23/8/2021.

Table 5. Temperature input and output water in an evacuated tube

Sr.no.	hour	1st day evacuated tube (c)		2nd day evacuated tube (c)		3rd day evacuated tube (c)		4th day evacuated tube(c)		5th day evacuated tube(c)	
		Tei	Teo	Tei	Teo	Tei	Teo	Tei	Teo	Tei	Teo
1	10 am	52	75	50	70	44	59	50	60	56	65
2	11 am	53	77.8	54	83	45	60	55	62	59	70
3	12 pm	55	78.8	60	88	54	68	59	66	60	80
4	1 pm	59	80	59	79	59	69	60	68	66	88
5	2 pm	53	79	55	70	54	68.7	58	65	60	80
6	3 pm	51	77	53	71.8	56	60	55	63	56	75
7	4 pm	50	70	50	72.9	50	74	53	61	54	69
8	5 pm	45	67	46	66	45	72	50	60.2	50	65
9	6 pm	40.2	62	30	60	40	70	45	58	48	60

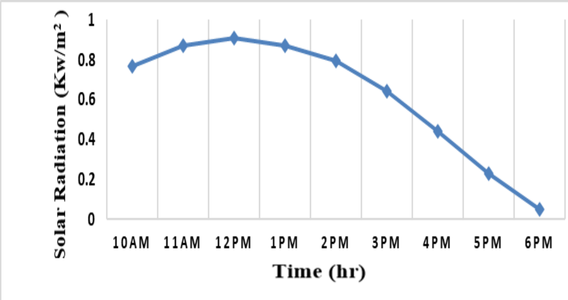

Figure 9. solar radiation at different times of the day

Solar radiation gradually increases from early morning to 2 pm due to bright sunlight and then decreases towards evening due to low sunlight. These results didn't match with the previous study by the researchers in [33], where the maximum solar radiation at 12 pm equals 0.7 kw\m^2. Solar radiation was recorded concurrently with component temperatures. Peak irradiance occurred around 12:00 PM, reaching 907 W/m², coinciding with the highest temperature differentials across system parts. Evaporation rates closely followed the radiation trend, highlighting the dependency of distillate yield on solar input. The sequence of temperature gradients (ETC outlet > ETC inlet > basin water > glass cover > ambient air) underscores the system's efficient thermal coupling.

The output of distilled water was tested in the laboratory. The parameters tested in a lab were color, odor, TDS, and pH as mentioned in Table 7 and 8.

Table 7. Quality of greywater after the desalination process

	Parameters	Result
1	Color	not objectionable; acceptable.
2	Odor	not objectionable; acceptable.
3	TDS	(500-1500) mg\l.
4	PH	Around 7.5.

Table 8. Quality of saltwater after the desalination process

	Parameters	Result
1	Color	not objectionable; acceptable.
2	Odor	not objectionable; acceptable.
3	TDS	(50-100) mg\l.
4	PH	Around 6.5.

A statistical consistency analysis was carried out on the hourly distillate measurements gathered over several days to increase the dependability of the experimental results. Due to variations in sun irradiation, wind speed, and ambient temperature, the variability between repeated observations stayed within a margin of ±8–12%, which is common for outdoor solar desalination experiments. The indicated trends, especially the impacts of pH and water depth, are statistically significant because the standard deviation of distillate output for each operating condition was found to be minimal in comparison to the mean. Additionally, all experimental days consistently showed a monotonic rise in productivity with higher pH values and lower water depths, offering compelling evidence that the stated performance improvements are not the result of random variation but rather reflect repeatable system behavior.

As shown in Tables 7 and 8 the quality of salt water after the desalination process for color, odor, TDS, and PH value. The quality parameters are set for drinking water which must be met as per the International Standards for drinking water, while the grey water quality may not be suitable for drinking. may be marginally suitable for some agricultural applications. Post-treatment water quality was evaluated using TDS, pH, and sensory properties. Saltwater distillate had TDS values between 50–100 mg/L, suitable for drinking. Greywater distillate had higher TDS (500–1000 mg/L) but was acceptable for irrigation. Both distillates were odorless, clear, and exhibited near-neutral pH. Finally, by comparing to traditional single-slope solar stills, which show only modest gains (~13%) from water depth optimization, the ETC-integrated design demonstrated superior performance (up to 65% improvement). This substantial gain is attributed to efficient thermal energy transfer and sustained high-temperature operation enabled by the ETCs.The useful energy obtained from water evaporation was compared to the total solar energy incident on the evacuated-tube array to determine the system's energy efficiency (η). The mass of distillate produced multiplied by the latent heat of vaporization (2.45 MJ/kg) yielded the usable energy output. Depending on the water type, pH, and depth, the energy efficiency varied from 5.2% to 16.2%. Temperature gradients and system irreversibility had a significant impact on energy efficiency, which ranged from 0.8% to 2.5%. These performance metrics verify that adding evacuated tubes greatly increases the thermal driving force for evaporation, especially at higher pH levels and shallow water depths.

4. CONLUSION

The effects of water depth and pH on desalination performance were the focus of this study's experimental investigation of an evacuated-tube-enhanced double-slope solar still operating in Amman, Jordan's actual climate. The findings demonstrate that incorporating evacuated tubes considerably raises distillate productivity and basin temperature. It was discovered that the ideal water depth was 2 cm, yielding up to 5.8 L/day for greywater and 5.0 L/day for saltwater—a 36–52% improvement over deeper layers. Performance was further improved by raising the pH to 9.0, which resulted in daily distillate yields of 6.5 L for saltwater and 7.8 L for greywater. Exercise efficiency varied between 0.8% and 2.5%, while energy efficiency ranged from 5.2% to 16.2%, demonstrating the significant impact of operational factors on overall system efficacy. These results show that basic operational changes like water depth and pH can also increase performance in addition to structural improvements. In arid and semi-arid areas, where access to sustainable freshwater solutions is becoming more and more important, the system exhibits great potential for small-scale, inexpensive desalination applications. To further maximize system output, future research should examine seasonal fluctuations, long-term performance stability, and the incorporation of automatic pH control modules.

Double solar slope still connected with an evacuated tube and the influence of water depth and PH value in two types of water (grey, and saltwater) was also investigated. The water depth changed to (2,4,6cm) and the PH value to (5,6.5,9). However, accumulative distillate greywater was 21.4 % higher than accumulative distillate saltwater. When the water depth decreases the productivity increases, the higher productivity was in water depth 2cm then 4cm then 6cm which was the productivity for saltwater (5000,3950,3000ml) and for greywater (5800,4740,3900 ml), respectively. When the PH value increases the productivity increases, the higher productivity was at PH 9 then 6 then 5 was the productivity for saltwater (6500,5000,2500 ml) and for greywater (3500,5900,7800 ml) respectively. Solar radiation was a factor that affected the desalination process when solar radiation increased productivity. the quality of salt water after the desalination process for color, odor, TDS, and PH value. The experimental findings show a great deal of practical significance for the installation of small-scale desalination plants in dry areas. For hybrid solar still systems improved with evacuated tubes, engineers have access to trustworthy performance indicators thanks to the precise quantitative data collected in Jordan's actual climate. The significant positive link between water pH and distillate productivity, a factor that was rarely looked at in earlier research, is one of the most significant discoveries. To improve freshwater output without raising energy consumption, this presents a new operational parameter that can be tuned. Additionally, the results demonstrate that evacuated-tube connection and shallow water depth significantly increase evaporation and overall efficiency, providing useful design recommendations for field applications. These observations aid in the creation of decentralized, reasonably priced desalination methods appropriate for areas with limited water resources.

To ensure compatibility with the experimental dataset, all figures showing temperature profiles, distillate production, and system performance were cross-checked. The graphical findings accurately depict the recorded measurements because the temporal fluctuations in tube outlet temperature (Teo), basin water temperature, and distillate yield show synchronized trends across multiple days. While the late afternoon fall is consistent across all plots, production peaks are precisely correlated with periods of highest solar radiation. Rather than being the result of inconsistent measurements, any slight visual variations between figures are caused by natural climatic variability. Overall, the results visually demonstrate the impact of water depth, pH, and evacuated-tube integration on the system's performance and corroborate the study's primary conclusions. The experimental results were evaluated using an energy and exergy performance framework, which provided quantitative insight into system efficiency and thermal losses and increased the work's engineering relevance. The evacuated-tube-enhanced double-slope solar still's heat transfer mechanisms, including solar energy absorption, convective heat transfer to basin water, and conductive and convective heat losses to the environment, were explained using a simplified thermal modeling approach.

In addition to highlighting potential for system modification, such as enhancing thermal insulation, regulating water depth, and modifying operating pH levels, this engineering-oriented study makes it possible to identify performance-limiting components. Furthermore, experimentally validated performance metrics establish a clear link between the system design and its potential engineering applications, particularly in small-scale, decentralized desalination units for industrial water reuse, remote communities, and agricultural support in arid and semi-arid regions. The work enhances its contribution to mechanical engineering design and offers a useful basis for scaling and practical implementation by combining experimental findings with energy and exergy assessments.

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