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Integrated Strategies In Desalination Process Combining Thermoelectric Generation, And Phytoremediation

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Abstract

Water scarcity is a significant global issue that is exacerbated by factors like increasing populations and global warming. Even though, innovative strategies that combine ecological solutions and technological advances are needed to address this problem. However, this study investigates an extensive approach to addressing water scarcity using a multimodal method that includes phytoremediation and desalination processes. The study is structured into three distinct phases aimed at optimizing water management practices across various environmental contexts. The initial phase is to use iron and copper triangular fins to increase the effectiveness of desalination. The purpose of selecting these materials is to increase the efficiency of heat transfer during desalination. The desalination process interacts with a thermoelectric generator (TEG) in the secondary phase to transform surplus heat into electrical energy. This dual-purpose concept improves sustainable water treatment practices while enhancing energy efficiency. Finally, Phytoremediation, a biological technique that uses plant-based systems to analyze and reduce water contaminants, is introduced in the third phase. When compared to conventional desalination methods, the process produces 65% water production efficiency and 27% in electricity production through conduction. The main goal of this study is to find ways to integrate modern desalination methods and sustainable alternatives like phytoremediation may operate synergistically. This study intends to offer insights into practical water management techniques that may be scaled for worldwide application by analyzing water contaminants throughout the experimental assessment.

Keywords: *Desalination, thermoelectric generator (TEG), Phytoremediation, triangular fins*

1. INTRODUCTION

The worldwide issue of water scarcity has become increasingly due to several interrelated factors, such as the world's fastest population growth, increasing urbanization, and the widespread effects of climate change. Conventional approaches to water source and treatment are not satisfying the growing demands for freshwater. In this regard, major progress has been made in resolving the issues raised by water shortage with the development of desalination technology and the use of ecological strategies such as phytoremediation. Desalination is the process of turning salt and minerals from brackish or saltwater into freshwater suitable for industrial uses, agricultural irrigation, and human consumption. Reverse osmosis (RO), electrodialysis, and distillation are among the desalination techniques. The main goals of technological developments are to minimize environmental effects, increase efficiency, and use less energy. Hybrid systems integrate various desalination techniques to maximize water quality and energy efficiency. Worldwide, desalination is utilized for industrial, agricultural, and municipal water supply. Research and development must continue in order to address issues including high costs, energy usage, and environmental effects.

However, a natural and eco-friendly method of treating water is provided by phytoremediation. Phytoremediation is a technique that can be used in conjunction with typical chemical-based treatments to lessen the environmental impact of agricultural and industrial operations on water quality. It does this by utilizing the inherent capacities of specific plant species to absorb and accumulate contaminants. The goal of recent developments in desalination technology has been to increase sustainability and efficiency.

Moreover, the use of thermoelectric generators (TEGs) signifies a noteworthy technological progression in the desalination domain. TEGs are apparatuses that transform waste heat produced by the desalination process into electrical energy that can be used. This dual-purpose strategy produces more electricity while also lowering the desalination plants' overall energy usage. Numerous environmental and sustainable advantages can be obtained by combining ecological strategies like phytoremediation with desalination techniques. These technologies lessen the strain on naturally occurring freshwater supplies, which are already stressed by overexploitation and climate unpredictability. Furthermore, implementation obstacles include high initial capital expenditures, complex technology, and the requirement for specialist knowledge in plant design and operation. In addition, desalination's negative environmental effects such as brine outflow and disruption of marine ecosystems need to be carefully managed and mitigated.

Qi and leepei (2016) focused on using Ipomoea aquatica in aquaponics systems for phytoremediation and desalination of heavy metals in brackish water. The findings demonstrated a drop in Na, Mg, K, and Ca in the field water between Days 0 and 30, demonstrating the capacity of Ipomoea aquatica to absorb important components that contribute to salinity and possible desalination. Additionally, the study discovered that as metal ions were absorbed by plant biomass and fish scales, conductivity, total dissolved solids, and salinity decreased from Day 0 to Day 35. Angrish et al., (2015) addressed technique for clearing soil contaminated with metal ions is called phytoextraction, which takes advantage of plants' special capacity to accumulate large concentrations of metal ions in their above-ground tissues, especially leaves. It also includes phytodegradation, which is the process by which plants remove organic chemicals from the soil, and phytoaccumulation, which is the process by which plants extract and accumulate toxic metals or ions.

Kamyab et al. (2020) focused on producing valuable byproducts by phytoremediation palm oil mill effluent (POME) with algae. This method improves water quality and aids in resource recovery by taking advantage of algae's capacity to absorb and reduce contaminants in wastewater. It is consistent with sustainable environmental practices. Su et al. (2012) exploited transgenic Arabidopsis plants that overexpress a Populus glucosyltransferase enzyme to investigate phytoremediation of trichlorophenol. The work shows how genetic engineering may improve metabolism in plants, allowing toxins like trichlorophenol to be broken down in contaminated environments more effectively. Siregar and Damanik (2020) evaluated the energy efficiency of single slope solar stills and their suitability for desalination procedures. The study provides insights into designing solar still designs to increase freshwater production while decreasing energy usage by examining energy inputs and outputs.

Esfe et al. (2021) optimized the geometrical parameters of single slope solar stills fitted with thermoelectric devices. The goal of this research is to increase the efficiency and sustainability of solar-driven desalination devices by optimizing heat transfer processes through geometric modifications. Alwan et al. (2020) assessed the output of a recently created single-slope solar still at different saltwater depths. Through an analysis of the relationship between freshwater yield and water depth, the study offers actionable advice on how to maximize solar still efficiency under various environmental circumstances. Mohammed et al. (2021) enhanced the efficiency of solar stills with a single slope by employing phase change materials (PCMs). The goal of the research is to improve water yield and energy efficiency in solar desalination processes by utilizing PCMs, which store and release thermal energy during phase transitions.

Altarawneh et al. (2017) performed out computational and experimental assessments to maximize the performance of solar stills with pyramidal, double, and single slope shapes. The goal of the study is to determine the optimal configuration for solar-driven water desalination by evaluating several configurations.

Al-Mezeini et al. (2023) examined single slope solar still for water desalination are the focus of this study. The study advances the use of solar energy in freshwater production by evaluating the solar still's effectiveness in real-world circumstances. Gholizadeh and Farzi (2020) investigated single slope solar stills that helps solar desalination systems operate more efficiently and produce more freshwater by improving heat absorption and retention qualities. Akkala and Kaviti (2023) evaluated how various fin designs affect solar still desalination systems' performance. The study offers insights into improving heat transfer mechanisms to raise overall system efficiency by examining different fin designs. Mevada et al. (2020) explored fin setup options affect solar still performance. The goal of the study is to enhance heat transfer mechanisms and boost freshwater output in solar desalination systems by assessing variables like fin geometry and material. Shaabani and Kargar Sharifabad (2020) explained common and porous fins in desalination systems numerically. Through the use of heat transfer rate simulations and distilled water production modeling, the study assesses how well various fin forms contribute to improved thermal performance and freshwater yield. Setyawan et al. (2020) analyzed the effectiveness of fin geometry in low-temperature condenser tubes of vacuum desalination systems. The study helps to optimize condenser performance for effective water desalination by examining how various fin designs affect heat exchange processes.

Several recent studies have explored advancements in fin configurations and material applications to enhance the performance of solar desalination systems. Septiyanto et al. (2024) examined the effect of hollow circular fins on the efficiency of solar stills used for seawater desalination, aiming to improve both freshwater output and heat transfer processes. In a similar context, Hadi et al. (2024) utilized SS302 hollow circular fin absorbers at different heights in single-slope desalination systems to determine optimal configurations under varying environmental conditions. Velmurugan et al. (2008) conducted earlier investigations into fin-type solar stills for wastewater desalination, providing valuable insights into the influence of fins on evaporation and system productivity.

Expanding on this, Mevada et al. (2020) analyzed multiple fin geometries and materials, highlighting the impact of design choices on thermal efficiency and freshwater yield. Mohammed et al. (2021) further evaluated solar stills equipped with angled rectangular perforated fins attached to absorber panels, identifying the role of fin shape in optimizing system performance. Mohammed et al. (2022) conducted a comparative study incorporating hollow cylindrical perforated fins, inclined rectangular perforated fins, and nanocomposites into pyramidal solar stills, demonstrating substantial improvement in desalination efficiency. Alawee et al. (2021) also investigated absorber panels with slanted perforated rectangular fins, combining experimental and financial analyses to assess the feasibility of such enhancements for large-scale deployment.

In terms of advanced materials, Seyednezhad et al. (2020) explored the incorporation of nanoparticles within solar heat exchangers, revealing a significant increase in heat transfer efficiency and overall desalination performance. Hafs et al. (2023) focused on the seasonal behavior of solar stills utilizing rectangular channels and phase change materials (PCMs), aiming to enhance thermal energy storage and utilization throughout the year. Li et al. (2023) evaluated the impact of gas presence in saltwater desalination systems, suggesting practical strategies for improving operational efficiency. Hoseinzadeh et al. (2018) carried out simulation studies on rectangular cross-section porous fins to validate their thermal performance, offering insights into design improvements for increased freshwater productivity. Finally, Subramaniyan et al. (2021) conducted a numerical and experimental investigation on triangular solar stills equipped with rectangular fins, optimizing basin design parameters to maximize drinking water production.

2.METHODOLOGY

This research explores a novel approach to desalination processes in 2024, focusing on efficient water management techniques for future generations. The experimental setup is divided into **three phases**, each integral to the production of desalinated water and electrical energy.

Phase 1, the phytoremediation process, involves the collection of wastewater from diverse sources such as AC runoff, bathroom drainage, kitchen effluents, and rainwater from a 1000 sq. ft. commercial house was utilized for experimentation. This wastewater was stored in a container situated atop the house and placed near the desalination equipment. The collection of this wastewater is part of the phytoremediation process, which was then advanced to Phase 2. This phytoremediation method effectively removes pollutants, making the water more suitable for subsequent treatment and ensuring cleaner output.

Phase 2 incorporates the use of advanced desalination technology through a specially designed experimental setup. The prototype, with dimensions of 1×1 m^3, is fabricated using 1.2 mm thick galvanized steel and coated with black powder to enhance solar heat absorption. The structure is square in shape and includes an innovative interior configuration, featuring an internally mounted glass reflector positioned at an 11° angle, optimized for solar capture. The main framework comprises a steel box with a surface area of 1.2×1.2 m^2 and variable heights of 0.59 m and 0.6 m. To minimize heat loss through conduction, sawdust insulation is provided at the base. This thoughtful design improves the thermal efficiency of the stepped tray desalination system, utilizing a single-sided solar still prototype. The top surface of the solar still, measuring 1.2 m^2, is covered with 5 mm thick transparent glass, also inclined at 11 degrees facing north, corresponding to the latitude of Madurai, Tamil Nadu. This alignment ensures optimal solar exposure throughout the day.

Distilled water collection was carried out in two operational modes:

a) Day Mode: from 6:00 AM to 6:00 PM

b) Night Mode: from 6:00 PM to 6:00 AM

Continuous water distillation and collection were observed during both modes, highlighting the system's ability to function effectively under varying ambient conditions, thereby demonstrating its potential for sustainable, round-the-clock freshwater production.

Phase 3 introduces a thermal energy generation system using thermoelectric generators (TEGs) to convert thermal energy into electrical power for lighting. This setup, mounted on four-point pins, integrates solar and electrical energy: the solar panel captures energy during the day, stores it in a battery, and converts it to AC with an inverter. The combined energy, along with that from the TEG, powers a helium bulb lantern at night to support desalination. The desalination process relies on solar energy for continuous water purification. Key components include a solar panel, DHT11 sensor, solar basin, and heating element (lightbulb). The solar panel powers the system and charges the battery, while the DHT11 sensor monitors temperature and humidity within the solar basin. The basin heats commercial wastewater, ensuring evaporation and condensation into purified distilled water, which is collected and stored. The system maintains effective heat in the basin and undergoes regular testing to ensure the distilled water is safe for consumption.

The system comprises several critical components working together to ensure efficient operation. The DHT11 sensor plays a key role by measuring and monitoring the temperature and humidity inside the solar basin, thereby optimizing the evaporation process. A 100-watt solar panel, with dimensions of 1200 x 540 x 30 mm, converts solar radiation into DC electricity, powering the system. This electricity is stored in 12V, 12Ah/20HR lead-acid batteries, which provide a reliable power source for nighttime use. The PWM controller for solar charge regulates the voltage and current from the solar panel to prevent overcharging the batteries and ensure their safe operation. To maintain the heating and evaporation process during the night, a 100-watt light bulb serves as a substitute for solar energy. Additionally, a 1000-watt solar inverter converts the stored DC electricity into AC power, enabling the operation of AC equipment when necessary. Red and black 2.5 mm cable wires are used to connect these components, with red indicating positive connections and black for negative terminals, ensuring the correct and efficient flow of electricity throughout the system

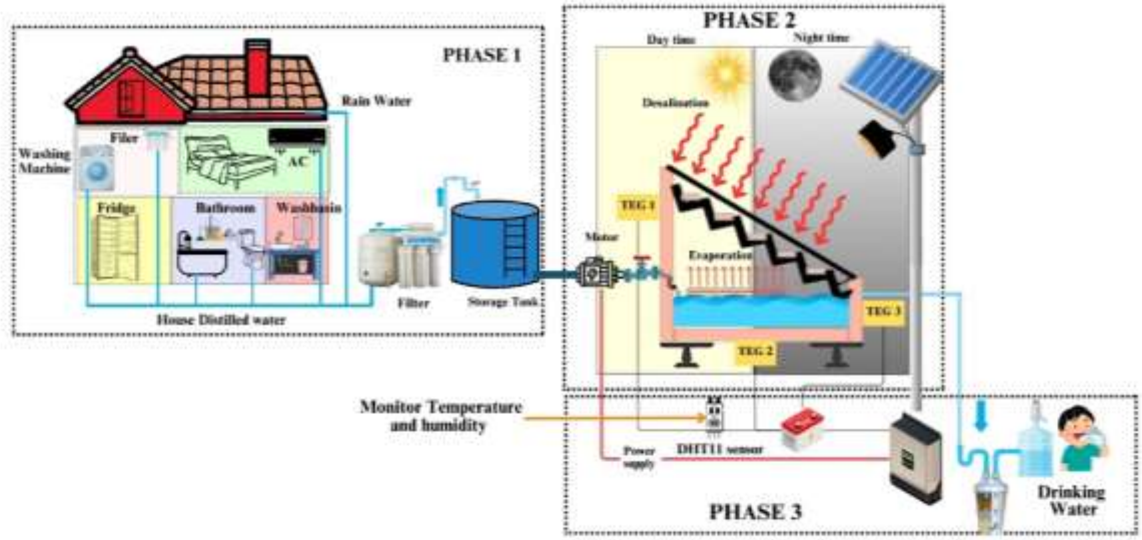


Figure 1. Methodology

The process of evaporation during the day is seen in Fig. 2, where the water evaporates and then condenses into clean water on the glass surface due to heat from the sun. This method produces comparatively pure distilled water by efficiently eliminating contaminants and salts. On the other hand, Fig. 3 shows evaporation during the night with a 100W incandescent lightbulb serving as the heat source. Even while the lightbulb produces heat, the evaporation that results is not as effective as it would be during the day. In comparison to the more efficient daylight method, this inefficiency arises from the heat from the bulb only sufficiently warming a section of the glass surface, which results in less condensation and worse water purity.

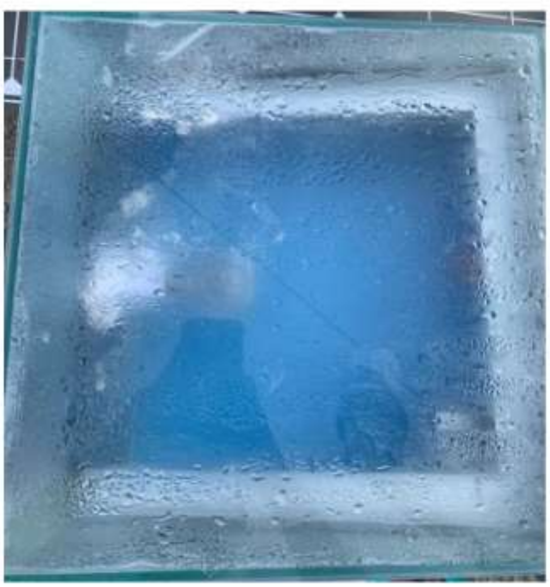


Figure 2: Distilled water at day time

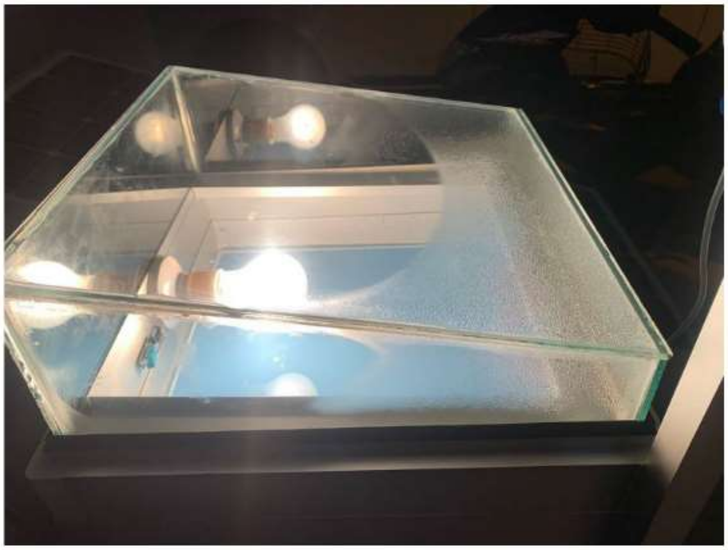


Figure 3: Distilled water production at night time

2.1 Working Process At Day:

To assess water evaporation, the desalination system was tested for seven hours during the day in direct sunshine. Time, temperature (°C), humidity (%), and evaporated water volume (ml) are among the variables that were recorded. The volume of water that evaporates directly correlates with temperature, as Fig. 4 illustrates. Since greater temperatures give water molecules more energy, higher temperatures inside the solar basin result in higher rates of evaporation. Because of the high temperature, evaporation peaked at 520.35 ml at noon. Later in the day, as the temperature dropped, so did the rate of evaporation. As a result, the highest temperature attained and the volume of water that evaporates are directly related.

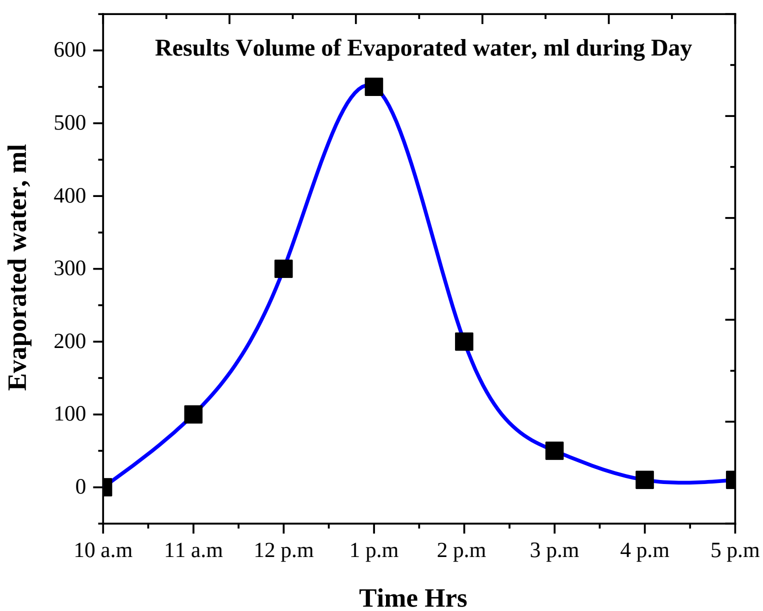


Figure 4: Daytime Water Evaporation Volumes vs. Time

2.2 Working Process At Night

The water evaporation process throughout the night, when a lightbulb takes the place of sunlight as the heat source, are shown in Figure 5. The graph shows that during this time, the amount of water that evaporated reached 632.74 ml. The lightbulb acts as a constant heat source during testing at night, keeping the temperature steady to promote evaporation. Longer times result in more evaporation, as the graph illustrates, with the volume of evaporated water increasing as the experiment carries on. This is because the heat from the lightbulb steadily raises the water's temperature, enabling more water molecules to absorb enough energy to turn from liquid to vapor. The longer heating time increases the overall amount of water that evaporates, supporting the idea that higher heat exposure times result in higher evaporation rates.

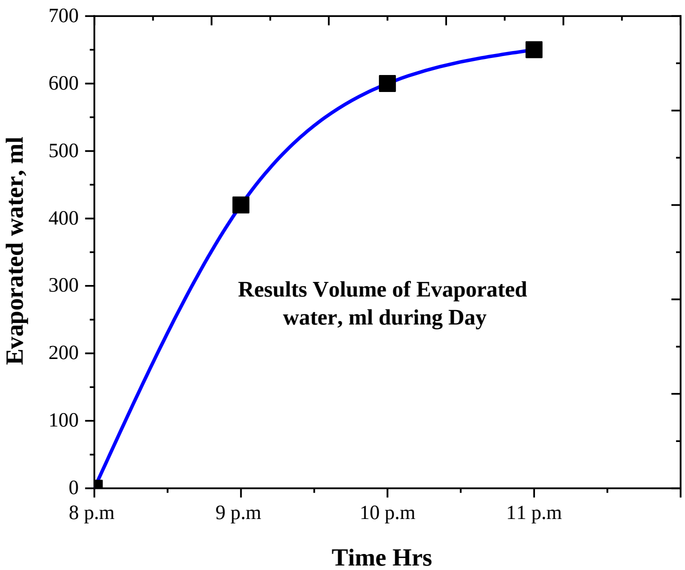


Figure 5: Nighttime Water Evaporation Volumes vs. Time

This innovative setup promises significant benefits for future water management and sustainability. The experimental setup aims to demonstrate how these phases work together to enhance desalination efficiency and energy recovery.

3. RESULTS

This section delves into the analysis of productivity patterns and the hourly variations observed during both day and night. By examining the productivity rates alongside the atmospheric and environmental conditions, significant insights are gained into how different times of the day and night influence overall efficiency and performance. The findings highlight distinct trends in productivity that correlate closely with the variations in temperature and solar radiation, offering a comprehensive understanding of the temporal dynamics affecting productivity

3.1 Results Of Productivity During Day And Night

Figure 6 shows the productivity rate during the Night starts lower but increases rapidly after 5 hours, peaking at around 13 hours, where it reaches approximately 600 ml/0.5m^2/hr. After peaking, the Night productivity rate decreases steadily until 20 hours. The Day productivity rate also begins at a lower level and rises, but it peaks later, around 14 hours, at about 300 ml/0.5m^2/hr. The Day rate then gradually declines, mirroring the general trend seen in the Night productivity rate, but at a lower magnitude.

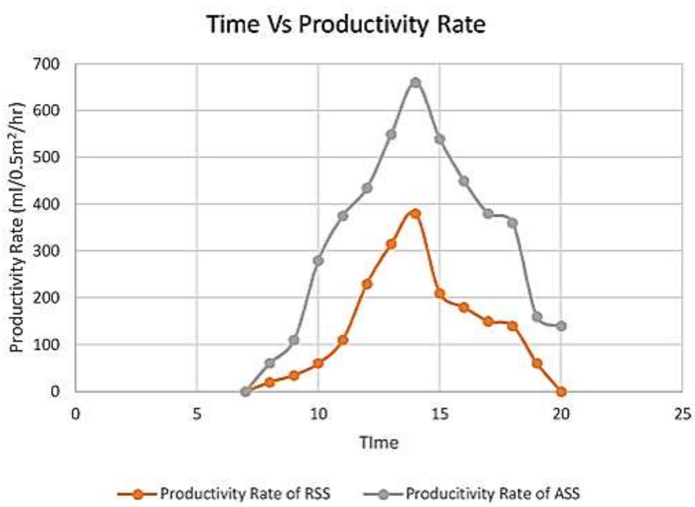


Figure 6: results of productivity during Day and Night

3.2 Effect Of Temperature On The External Components:

In this study, a prototypical stepped solar still was employed to measure water depth and compare its performance under two distinct conditions *(refer to Figure 7)*. The research was extended through the implementation of three innovative design variations: a plain tray, a round fin configuration, and a square fin configuration. These configurations were evaluated under two case studies — Case Study 1 with a water depth of 6 mm, and Case Study 2 with 24 mm.

To assess the thermal efficiency and environmental influence, air temperature readings were recorded and analyzed *(see Figure 4)*. The experiment included comparative analysis with and without the use of internal and external reflectors, allowing a deeper understanding of their impact on system performance and overall heat gain.

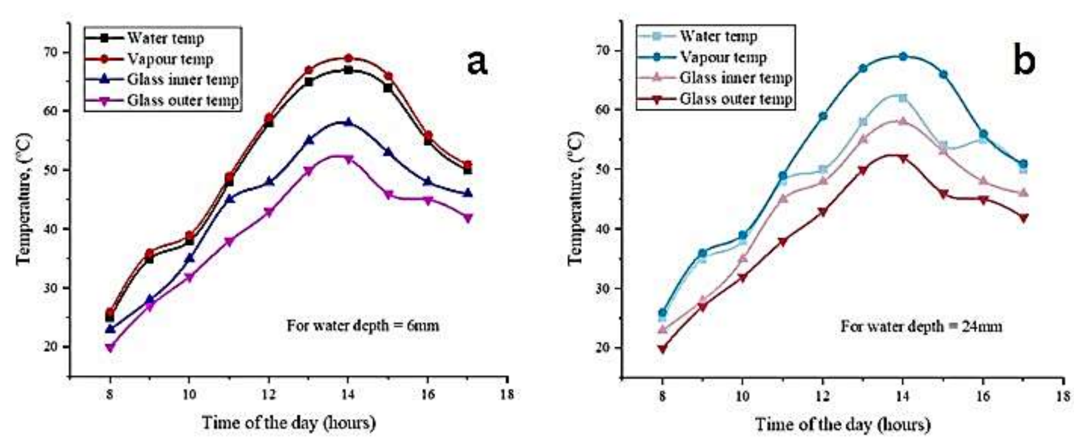


Figure 5.2 Hourly observation of temperature variations (1)[Internal components] vs. time of the day (B)with water depth = 6 mm and 26mm

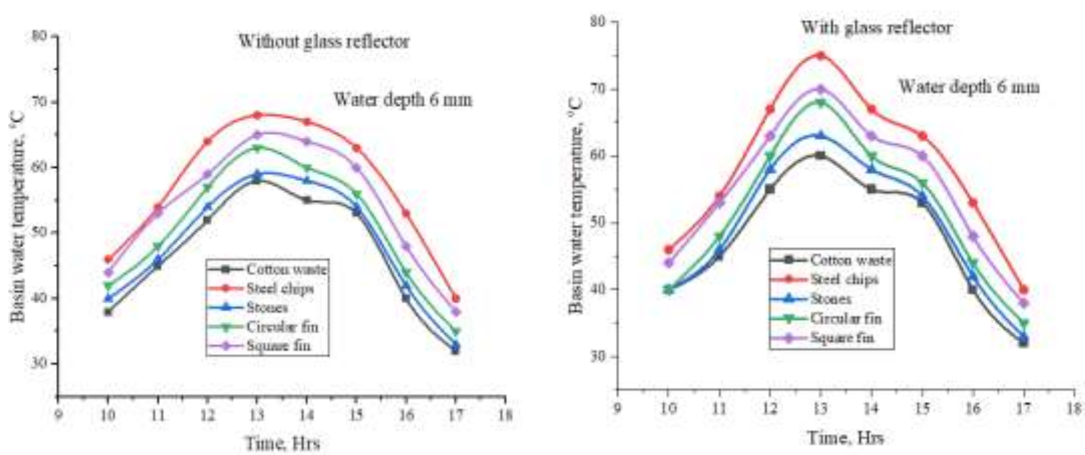
3.3 Temperature Enhancement With Glass Reflector And Without Glass Reflector

In the stepped solar still system, key variables such as water temperature, rate of temperature change, and material temperature play a significant role in the desalination process. Data collection was primarily focused during the period between 12:30 PM and 2:30 AM, during which time the outer glass reflector's temperature showed noticeable variations. During these hours, although solar intensity gradually decreased, the vapor temperature within the still increased, contributing to the efficiency of the desalination process.

The surplus solar energy observed in the system is effectively utilized through the transfer of heat from the borewell water to different components, including the inner and outer reflectors, the basin, and the trays. These elements facilitate improved thermal distribution and evaporation.

In the experimental setup, the internal components of the stepped solar still were enhanced using absorbent and conductive materials such as cloth, stones, and iron scraps placed in the basin. The presence of stones and pebbles within the basin and step trays aids in increasing the overall water temperature and enhances the rate of evaporation due to their high thermal mass.

To maximize the surface area for evaporation, cloth materials are strategically placed within the basin. These materials exploit capillary action, thereby increasing the water retention and allowing a more sustained and efficient evaporation process. Furthermore, the productivity of the system is enhanced by increasing the absorber surface area, which is achieved through the addition of fins to the plates.



(a) (b)

Figure 5.3 Temperature enhancement with (a) without glass reflector (b) with reflector

3.4 Hourly Variation Of Atmospheric Temperature At Day And Night Time

The graph illustrates the hourly variation of atmospheric temperature and solar radiation during the daytime, showing a clear correlation between the two. Starting from 8:00 AM, both solar radiation and ambient temperature increase steadily, with solar radiation reaching its peak between 12:00 PM and 2:00 PM at around 900 W/m^2, and ambient temperature peaking at approximately 30°C during the same period. After the peak, both parameters gradually decrease as the day progresses, with solar radiation and temperature both declining towards evening, indicating the typical daily pattern of heating and cooling driven by the sun's position and intensity.

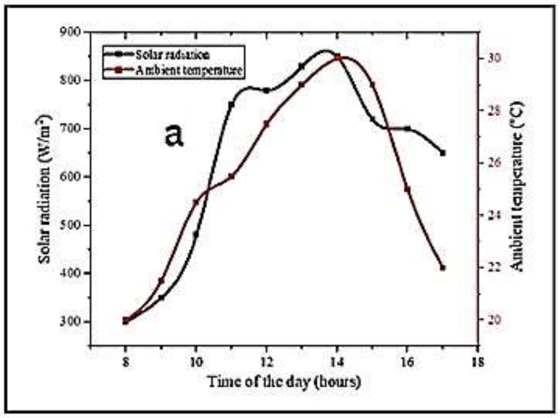


Figure 6. Hourly variation of atmospheric temperature and sun radiation during daytime

Figure 7 illustrates the hourly variation of atmospheric temperature and solar radiation during the nighttime, showing distinct patterns as the night progresses. Starting from 6:00 PM, solar radiation is minimal and remains low, reflecting the absence of sunlight, with a slight peak around 9:00 PM before gradually decreasing further as the night continues. In contrast, the ambient temperature begins at a higher level and steadily decreases throughout the night, stabilizing after midnight, indicating the cooling effect that typically occurs as night falls and continues until early morning.

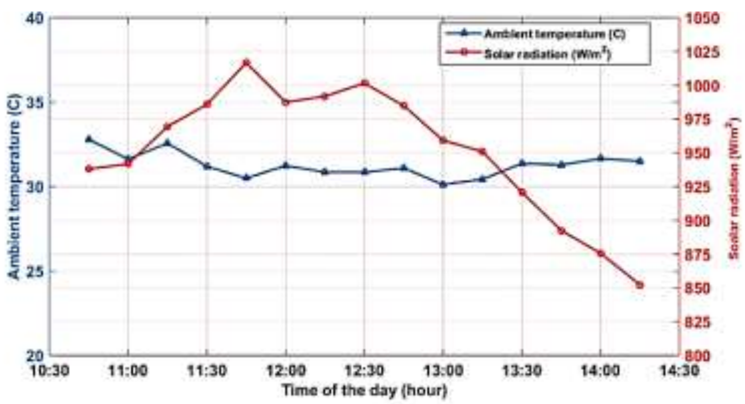


Figure 7. Hourly variation of atmospheric temperature and sun radiation at night time

These findings highlight the significant impact of environmental conditions on productivity. Cooler nighttime temperatures appear to enhance productivity, while higher daytime temperatures and solar radiation may limit it. Understanding these dynamics is crucial for optimizing the productivity of environmental factors.

4. CONCLUSION

In conclusion, this study represents a significant advancement in water treatment technology, with potential global implications due to its reliance on sustainable energy sources. Through the use of a lightbulb and sunshine as heating components, this system effectively generates clean water with minimal environmental impact. This strategy is especially beneficial for underprivileged areas with limited access to infrastructure for water purification. The project's dedication to using renewable resources is demonstrated by the usage of solar energy, and even though the lightbulb produces heat, it does not add to waste or environmental toxicity. As a result, the idea provides a useful and environmentally responsible way to supply clean water for everyday usage. The successful design and implementation of the solar desalination system attests to its potential to produce evaporated water efficiently. The addition of a DHT11 sensor improves the system by providing precise measurements of the sun basin's temperature and humidity—two critical elements affecting evaporation rates. This all-encompassing strategy ensures that the desalination process is not only efficient but also flexible enough to adjust to different environmental circumstances, increasing its usability and advantages for a wide range of communities across the globe.

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