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# Optimization of a Hybrid Solar Still-HDH System via Parametric Study for Lightweight Desalination in Remote Areas

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## Abstract

Freshwater scarcity in remote and arid regions necessitates desalination systems that are not only productive but also lightweight, low-cost, and easy to deploy. In this study, a transient numerical model of a hybrid solar still-humidification-dehumidification (SS-HDH) desalination system is used to perform a comprehensive parametric analysis aimed at minimizing system weight while maintaining a target freshwater productivity. Key operational parameters (basin water depth and air mass flow rate) and design parameters (basin material and thickness, glass thickness and material, and absorber material) are systematically investigated under summer and winter climatic conditions. The results show that reducing basin water depth to 0.5 cm and air mass flow rate to 0.1 kg s<sup>-1</sup> increases total freshwater productivity by up to 15% compared to the baseline configuration while enabling operation under natural convection. Replacing a stainless-steel basin with black-coated cotton reduces the total system mass from 486.6 kg to 131.7 kg ( $\approx 73\%$ ) with negligible impact on productivity, while minimizing basin and glass thickness further decreases weight without affecting thermal performance. Using aluminum fins and glass covers remains preferable to preserve high productivity, whereas plastic covers and cotton absorbers cause productivity reductions of 10–15%. An optimized configuration increases freshwater production by 31% in winter and 26% in summer relative to the reference case. These results demonstrate that selecting optimal parameters can significantly enhance portability and efficiency, enabling practical deployment of hybrid solar desalination units in off-grid and resource-limited communities.

**Keywords:** Humidification-dehumidification (HDH), Parametric Study, Solar Desalination, Solar Still, System Optimization

## 1. Introduction

Freshwater is essential for life, supporting domestic, industrial, agricultural, and social needs. Although water is abundant globally, 97% is saline and less than 1% of freshwater is accessible for human use [1, 2]. This scarcity is especially severe in remote and desert regions, where over a billion people lack access to clean drinking water, predominantly in rural areas [3]. The problem is acute in regions like the Mediterranean basin, Middle East, and North Africa (MENA), where many communities face extreme freshwater shortages [3]. As a result, desalination of saline water has become a critical alternative to address freshwater scarcity, particularly in underserved rural areas [4, 5]. Solar desalination offers a practical solution for freshwater scarcity in sunny, remote regions like the MENA, leveraging abundant solar energy [6, 7]. While photovoltaic (PV)-powered reverse osmosis (RO) plants are common for larger applications, they tend to have higher capital costs. In contrast, direct solar desalination systems, such as solar stills, are ideal for small-scale, remote setups (up to 100 L/day) due to their simple design and low operation and maintenance requirements. Recent advancements focus on integrating solar stills with other technologies to boost freshwater productivity. One such innovative approach is the integration of solar stills with humidification-dehumidification (SS-HDH) systems [8, 9]. Several contemporary studies have further expanded the design space of solar desalination systems. Elminshawy et al. (2025) numerically investigate a solar still combined with external energy storage and Fresnel lens concentrators, demonstrating enhanced freshwater yield and energy efficiency through integrated storage and optical concentration strategies [10]. Ziauddin et al. (2025) introduce an innovative humidification-dehumidification configuration powered by direct solar energy with an ultrasonic atomizer, achieving increased evaporation rates and highlighting the potential of droplet atomization in HDH performance enhancement [11]. Contemporary reviews also underscore hybrid desalination trajectories: a 2025 state-of-the-art overview outlines advances in solar-driven hybrid desalination systems, including HDH and adsorption integrations, and

their implications for sustainability and energy utilization [12]. Experimental work on solar HDH units with pressurized humidifiers by Easa et al. (2025) offers empirical data on productivity under varied operational conditions, providing context for model validation and comparison [13]. These recent developments complement and motivate the present parametric optimization study, which uniquely emphasizes minimizing system mass while maintaining productivity under realistic climatic conditions. In this context, our previous study developed a transient model of a solar still integrated with an HDH system, providing detailed analysis of its dynamic performance and demonstrating potential improvements in freshwater yield and system efficiency for decentralized desalination applications [14].

In our previous work, a solar still integrated with a two-stage humidification–dehumidification (HDH) system and a finned absorber was modelled and simulated using MATLAB, with climatic data from Abu Dhabi. The primary objective was to enhance freshwater production by recovering waste condensation heat from the still. The system was evaluated under forced convection conditions and showed promising results; achieving a basin productivity of  $6.3 \text{ kg/m}^2$  in winter and  $8.5 \text{ kg/m}^2$  in summer, while the dehumidifier produced  $13 \text{ kg/day}$  and  $16.6 \text{ kg/day}$  respectively. In both seasonal cases, the target of 50 liters of daily production was met. The performance of solar stills is highly dependent on a broad range of design, material, and operational parameters. Although solar distillation systems appear simple in construction, their thermal behavior is influenced by coupled heat and mass transfer processes that respond sensitively to changes in geometry, cover properties, basin materials, water depth, and auxiliary enhancement techniques. As demonstrated across the literature, even minor modifications can significantly alter evaporation rates and overall freshwater yield, thereby establishing the need for a systematic parametric investigation.

Material-related studies show substantial productivity variations arising from cover thickness, cover type, and basin liner selection. For

example, a reduction in glass cover thickness from 6 mm to 3 mm increased production by approximately 16.5% [15]. Similarly, using asphalt basin liners elevated productivity by 51% due to enhanced absorptivity [16]. Several researchers have shown that alternative cover shapes, such as semi-spherical and arch designs, yield different performance outcomes, with the conventional inclined flat cover outperforming the rest [17]. These findings highlight the sensitivity of solar still output to optical and thermal properties of construction materials. Geometric modifications, such as transitioning from single- to double-basin or single- to double-slope designs, have also been shown to significantly affect productivity. Karaghoulis and Alnaser [18] reported a 40% increase in output for a double-basin still compared to a single-basin design, while Rajaseenivasan et al. [19] observed up to an 85% gain in freshwater production when employing a double-slope configuration. These variations are also influenced by climatic conditions, with single-slope designs outperforming double-slope designs in cold climates and the reverse being true in warm regions [20]. Additional enhancements such as internal and external reflectors yielded productivity improvements ranging from 70% to 100% [21], reinforcing the role of solar concentration on thermal performance. Chemical and thermal enhancement techniques have been extensively explored, further expanding the parameter space. Previous studies have shown that adding dye-based materials into solar still basin water can enhance solar absorption and increase evaporation rates. Rajvanshi (1981) reported that using different dyes significantly improves water heating and distillate production [23]. Similarly, Akash et al. (2000) confirmed that basin-type solar still productivity can be improved under local climatic conditions through enhanced thermal absorption techniques such as dye additives [24]. Overall, additives such as black naphthalene and potassium permanganate were found to increase distillate yield by approximately 18–29%. In addition to dyes, incorporating thermal energy storage materials has been widely investigated to improve heat retention and extend productivity into night-time hours. Sakthivel and Shanmugasundaram (2008) demonstrated that using black granite gravel

as a storage medium improves distillation performance [25]. Likewise, the use of phase change materials (PCM) was shown to stabilize basin temperature and significantly enhance freshwater production [26]. Depending on the storage approach, productivity gains in the range of 17–85% have been reported. Active solar still designs provide even higher performance improvements by supplying additional external heat sources. Coupling a still with a flat-plate collector was found to enhance water temperature and increase productivity compared to conventional passive designs [29, 31]. Furthermore, photovoltaic-thermal (PV/T) integrated active solar stills achieved substantial performance improvements due to combined thermal and electrical energy benefits, with productivity increases exceeding 200% in some configurations [34, 35]. Overall, these studies confirm that both passive enhancements (dyes and thermal storage) and active configurations (collectors and PV/T systems) can significantly improve heat input, thermal retention, and overall solar still productivity. These wide-ranging results highlight the influence of supplementary heat sources on daily yield and the need to quantify their specific contributions. Given the broad spectrum of modifications and the variability of outcomes reported, conducting a structured parametric analysis is essential for developing optimized and context-appropriate solar still designs. Despite the extensive body of work on improving solar still productivity through geometric, material, and thermal enhancements, most existing studies focus primarily on maximizing freshwater yield or thermal efficiency, with limited consideration of system mass, portability, and practical deployment in remote environments. Moreover, parametric investigations of hybrid solar still-HDH systems remain scarce and are typically restricted to performance evaluation rather than design optimization. In this context, the present study offers several novel contributions:

- (i) it performs the first comprehensive parametric optimization of a hybrid SS-HDH system with system weight as a primary design objective alongside productivity;

- (ii) it quantitatively evaluates productivity-mass trade-offs for key operational and material parameters using a validated transient model;
- (iii) it assesses optimal configurations under both summer and winter climatic conditions representative of arid regions; and
- (iv) it proposes a lightweight, high-productivity system configuration suitable for decentralized desalination in remote and resource-limited areas.

These contributions extend prior solar still and HDH studies by shifting the design focus from performance alone to practical deployability and structural feasibility. These material and design optimizations not only improve performance but also hold promises for reducing lifecycle emissions and capital costs, as discussed in the conclusion.

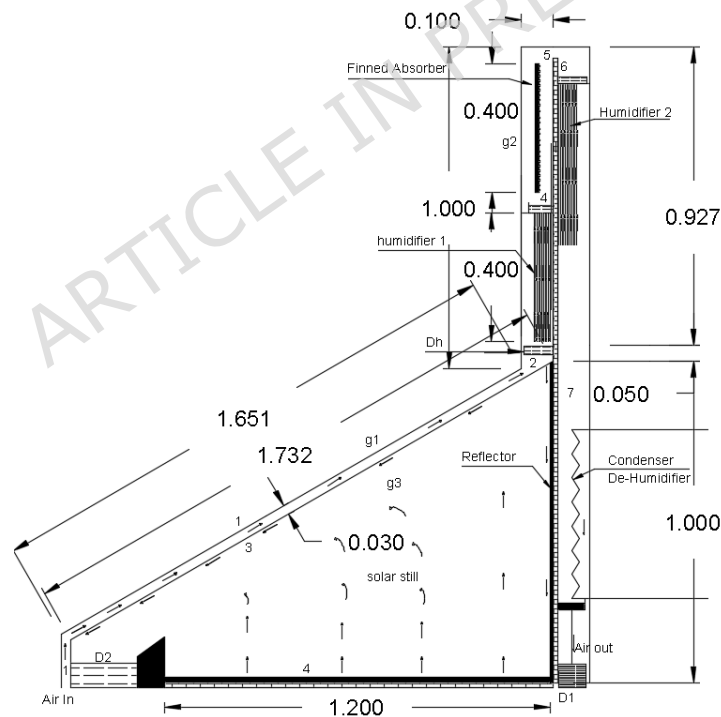
## **2. Methodology**

### *2.1. Base Model Description*

The proposed solar desalination unit consists of a single-sloped solar still (SS) integrated with a two-stage humidification-dehumidification (HDH) system and a finned solar absorber. This integrated system is designed to improve freshwater productivity by effectively recovering and reusing thermal energy from both solar radiation and condensation. The system configuration is illustrated in Figure 1. Solar radiation enters the unit through two transparent glass covers (components 2 and 3). The transmitted radiation is absorbed by the saline water in the insulated basin (component 4), which initiates the evaporation process. Water vapor rises and condenses on the cooler interior surface of the upper glass cover (3). The resulting condensate (D2) is collected and represents the primary distilled water output (PW1) of the solar still.

To utilize the condensation heat, air is circulated through a lower air channel (from component 1 to 2), where it absorbs thermal energy and moisture. This preheated and partially humidified air then rises to the first-stage humidifier (component 4), composed of cotton ropes with high surface area to enhance heat and mass transfer. After humidification, the

air flows upward through the thermal chimney and over the solar finned absorber (component 5), which further increases the air temperature through convective heat exchange. The heated air subsequently passes over the main humidifier (component 6), where it picks up additional moisture. It then moves into the secondary dehumidifier (component 7), where condensation occurs and additional freshwater is recovered. The humidifiers are designed with large surface areas and flexible materials to promote efficient humidification and airflow. Additionally, the vertical slope of the SS incorporates a wick-type absorber that preheats incoming saline feed water before it enters the basin. This enhances energy recovery and reduces thermal losses. This integrated system, previously validated under UAE climatic conditions, serves as the base model for the current parametric study. The study investigates the influence of varying design and operational parameters on the system's freshwater output, thermal efficiency, weight, and overall feasibility for remote-area applications.



**Fig.1.** Proposed System [10]

## 2.2. Parametric Study Setup

This study performs a detailed parametric analysis of a hybrid solar still-HDH desalination system using a validated transient numerical model

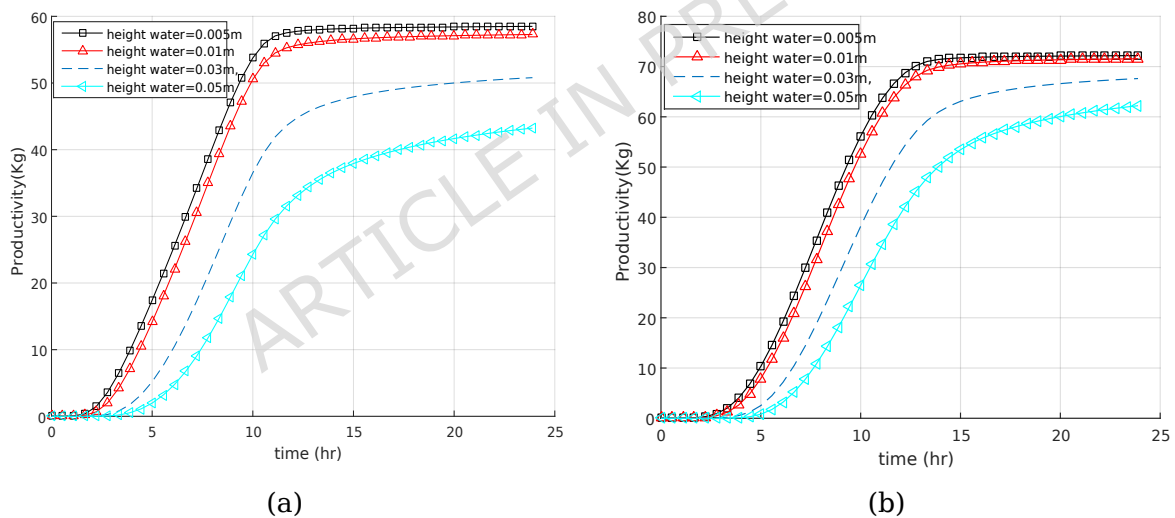
developed in MATLAB. The goal is to determine optimal design and operational configurations that maximize freshwater productivity while minimizing the system's structural weight and capital cost. The simulation framework includes dynamic energy and mass balance equations for each component, solar still basin, dehumidifiers, humidifiers, and the solar finned absorber, under realistic environmental conditions. Climatic input data, including hourly solar radiation, wind velocity, and ambient temperature, were obtained from Masdar Institute in Abu Dhabi and used to simulate both winter and summer scenarios, which feature approximately 11 and 14 sunlight hours per day, respectively. The study focuses on two main categories of parameters: (1) operational parameters, which include the initial basin water height and the mass flow rate of circulating air, and (2) design parameters, which include basin material (stainless steel or black-coated cotton), basin thickness, glass thickness, glass cover material (glass vs. Plexiglas), absorber material (aluminum fins vs. cotton ropes), and the temperature difference across the dehumidifier. Each parameter was varied independently while maintaining baseline values for the others, enabling the evaluation of individual impacts on system productivity, thermal performance, and total system weight.

### **3. Results and discussion**

#### *3.1. Operational Parameters*

Various research investigated the effect of water depth on productivity. Ahsan et al. [36] and Zurigat et al. [37] evaluated water productivity with various depths of 1.5, 2.5 and 5 cm and concluded that water production is inversely proportional to the depth of water. Similarly, Suneja et al. [38] investigated the effect of water depth on double basin solar still and it was also found that productivity increases with decreasing water depth. Tiwari et al. [39] found the overall efficiency of water produced based on the water depth. It was found that at a depth of 4cm, efficiency of output distillate output was high. It was concluded that at a minimum water depth, higher productivity is obtained due to an increase in water temperature and evaporation rate. Among the operational parameters evaluated, the initial mass, or height, of water in the solar still

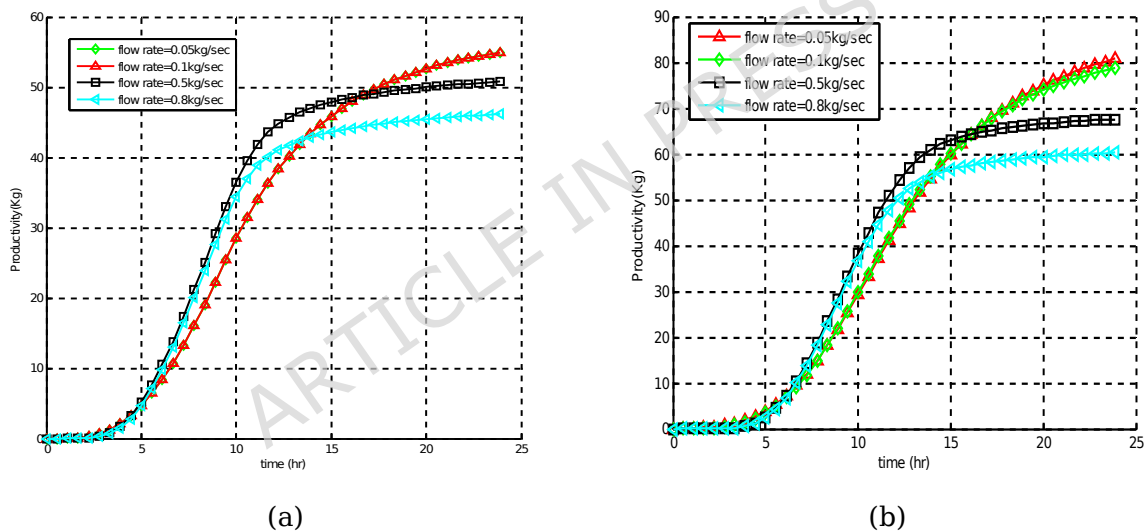
basin demonstrated a significant influence on system productivity in both winter and summer conditions. Lower water heights resulted in improved productivity and reduced basin weight, making the system more efficient and portable. In the winter case, a water height of 0.5 cm led to a 15% increase in total productivity, while 1 cm yielded an 11% increase compared to the 3 cm reference. Conversely, increasing the water level to 5 cm resulted in a 15% decrease in productivity. In the summer, a water height of 0.5 cm improved productivity by 7.5%, and 1 cm led to a 6% increase. While the gains in summer were slightly less pronounced than in winter, the overall trend remained consistent: lower water levels enhance thermal response due to reduced thermal mass, leading to faster temperature rise and more efficient evaporation as shown in Figure 2. These findings support the selection of shallow water levels in the basin to maximize freshwater output while minimizing system weight.



**Fig.2.** Effect of water height on still productivity (a) Winter (b) Summer

The mass flow rate of circulating air was found to significantly impact the performance and operational economy of the SS-HDH system across both winter and summer conditions (Figure 3). In the winter scenario, increasing the air flow rate from 0.5 kg/s to 0.8 kg/s resulted in a 10% decrease in productivity, whereas decreasing the flow rate to 0.1 kg/s and

0.05 kg/s led to an approximate 11% increase. This behavior is attributed to the fact that higher flow rates rapidly increase the moisture-carrying capacity of air but also induce a higher rate of heat extraction from the glass cover (g3), thereby reducing the temperature gradient between the basin and the glass. This diminishes the evaporation rate and increases convective and radiative losses. Similarly, in the summer case, reducing the flow rate from 0.5 kg/s to 0.1 kg/s increased productivity by 12%, while further reduction to 0.05 kg/s yielded no significant additional benefit. These findings suggest that a flow rate of around 0.1 kg/s is optimal for both seasons. Moreover, operating at such low flow rates opens the possibility for natural convection-driven airflow, eliminating the need for forced circulation fans and thereby reducing system complexity, energy consumption, and capital costs.



**Fig. 3.** Effect of mass flow rate (a) Winter (b) Summer

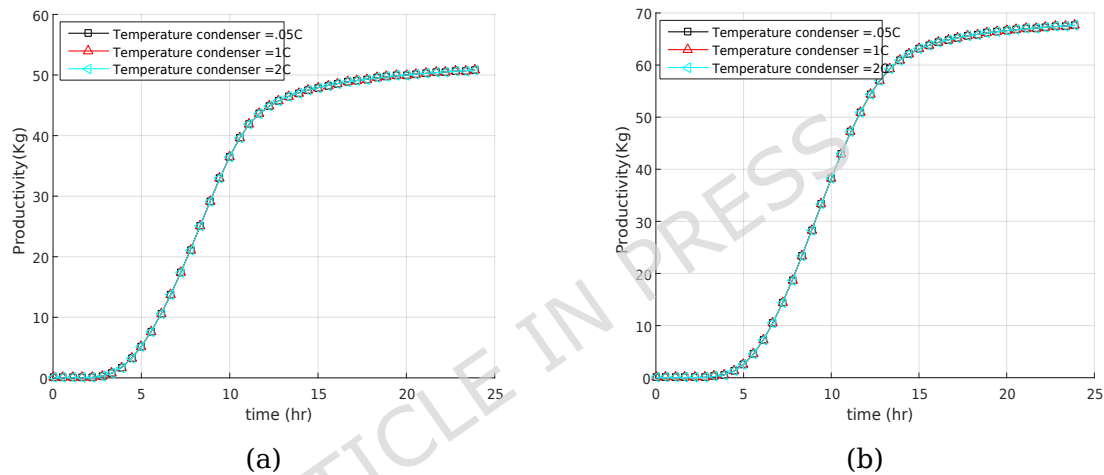
### 3.2. Effect of Design Parameters

Design parameters help in better still configuration in terms of materials usage, which helps to optimize the design weight and cost. Several parameters were studied such as basin materials, glass thickness, glass type, solar absorber materials and the temperature difference between the inlet and outlet water across the dehumidifier. The impact of alternative

parameters like the absorptivity of the basin and basin insulation thickness has already been reported within the literature to be insignificant.

### 3.2.1. Temperature Difference in the Dehumidifier

Temperature difference between the inlet and outlet of cooling water determines the amount distillate produced in the condenser. This factor hardly had any significant effect on the productivity as shown in Figure 4. Temperature difference between the inlet and outlet of cooling water had insignificant effect on the productivity.

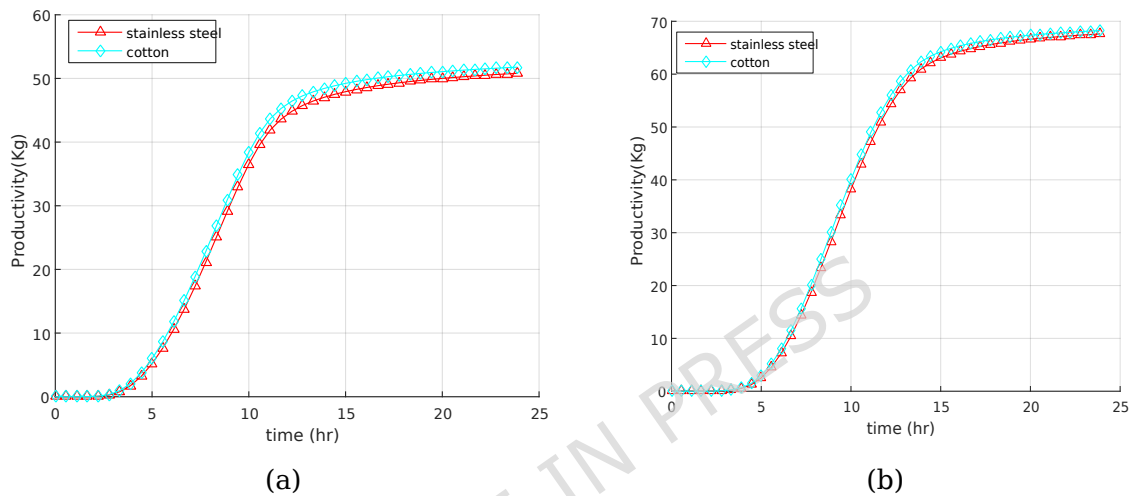


**Fig. 4.** Effect of temperature difference in condenser (a) Winter (b) Summer

### 3.2.2. Basin still material

The choice of basin material had a substantial impact on the overall weight of the SS-HDH system while causing only minimal variation in productivity across both winter and summer conditions. The conventional stainless-steel basin, though structurally robust, contributed significantly to the unit's mass, making it less suitable for deployment in remote or portable applications. To address this, a lightweight alternative using black-coated cotton was investigated. In the winter case, replacing stainless steel with cotton increased productivity slightly from 50.8 kg to

51.8 kg while reducing the total system weight from 328.3 kg to 181.6 kg; an impressive 81% reduction (Figure 5). Similarly, during the summer, cotton material yielded nearly the same productivity as stainless steel, confirming its suitability without sacrificing performance. These results indicate that using black-coated cotton as a basin material provides a cost-effective and lightweight alternative, making the system easier to transport and install, especially in off-grid and rural settings.

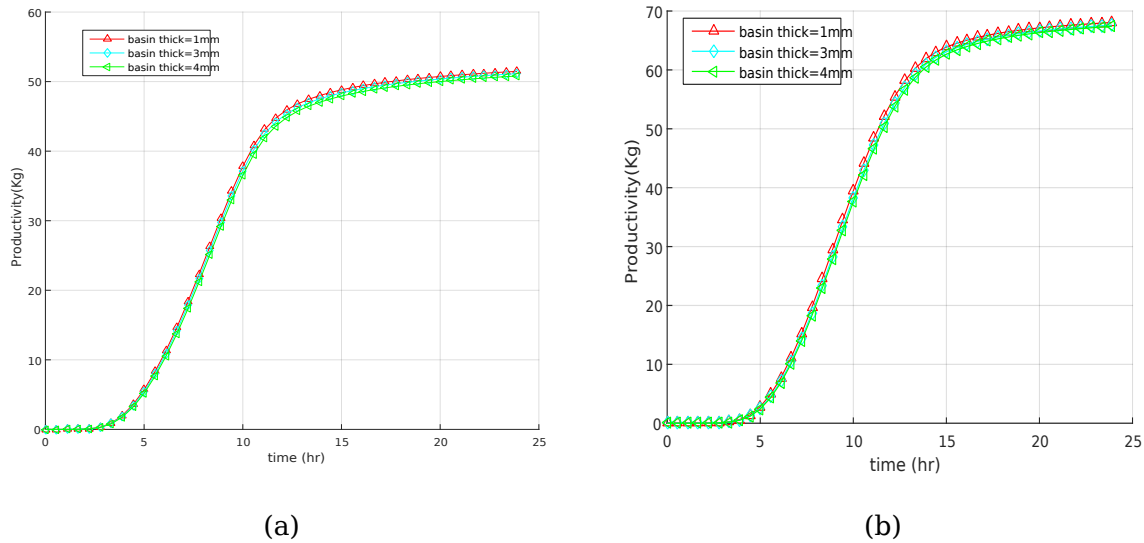


**Fig. 5.** Effect of different materials in solar still (a) Winter (b) Summer

### 3.2.3. Stainless steel basin thickness

The effect of basin thickness on the performance of the SS-HDH system was found to be negligible in terms of productivity but significant in terms of weight reduction. Across both winter and summer scenarios, varying the thickness of the stainless-steel basin between 1 mm, 2 mm, and 3 mm did not result in any notable changes in freshwater output. However, the impact on system mass was substantial. For instance, a 1 mm basin thickness reduced the total system weight to 229.4 kg, compared to 278.9 kg and 328.2 kg for 2 mm and 3 mm thicknesses, respectively (Figure 6). These findings highlight that minimizing basin thickness is an effective strategy for reducing system weight without compromising desalination

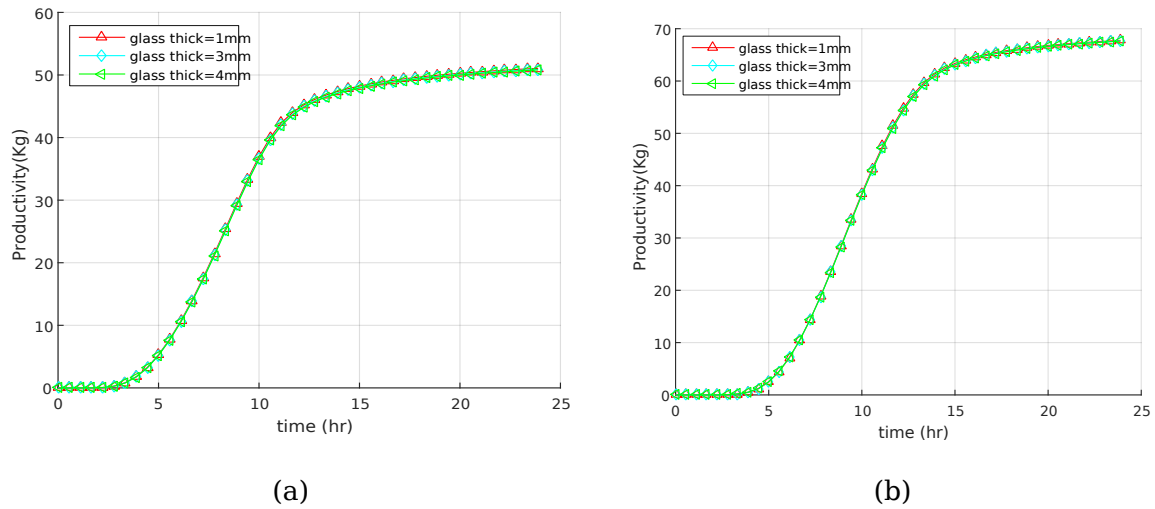
performance, making it advantageous for portable or cost-sensitive deployments.



**Fig. 6.** Effect of basin thickness (a) Winter (b) Summer

#### 3.2.4. Glass thickness as parameter

Varying the thickness of the glass cover showed an insignificant effect on the overall productivity of the SS-HDH system in both winter and summer conditions, but it had a notable impact on system weight. In the winter case, reducing the glass thickness from 3 mm to 1 mm resulted in a substantial decrease in total glass weight, from 272.2 kg to 68.1 kg, without affecting the distilled water output (Figure 7). Similar trends were observed in the summer case, confirming that glass thickness does not influence thermal performance. These findings suggest that thinner glass should be preferred in the system design to reduce total weight and facilitate easier transportation and installation, particularly in remote or off-grid applications.

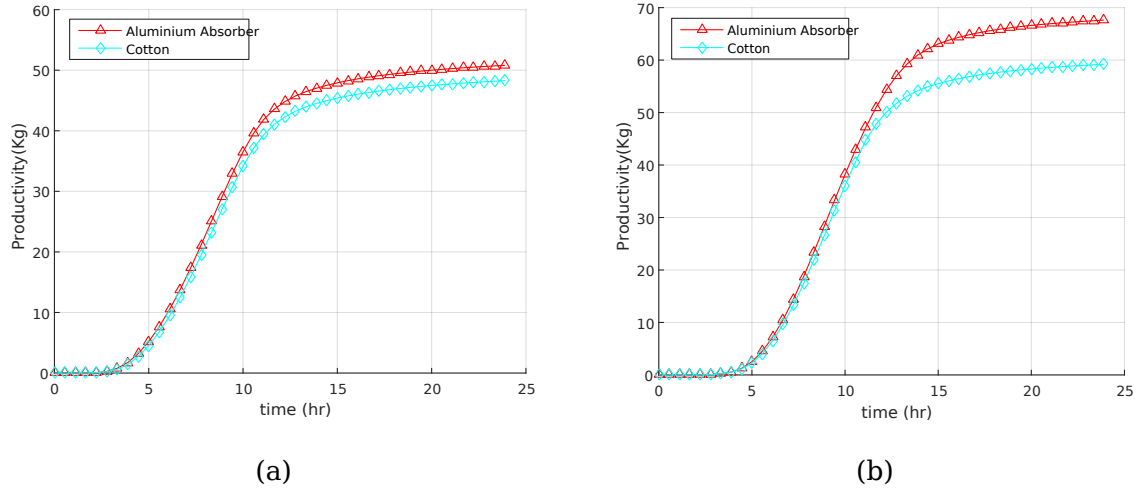


**Fig. 7.** Effect of glass thickness (a) Winter (b) Summer

### 3.2.5. Absorber material

The choice of material for the solar finned absorber significantly influenced both the weight and productivity of the SS-HDH system. Two materials were compared: the conventional aluminum finned plate and a lighter alternative made from cotton rope. In the winter case, replacing the aluminum with cotton rope reduced the absorber weight from 16.2 kg to just 2.6 kg, a significant reduction, while causing only a modest 4% decrease in productivity. However, in the summer case, the productivity drop was more pronounced, with a 15% decrease observed when using cotton rope instead of aluminum (Figure 8). While the lightweight nature of cotton improves system portability and reduces material costs, the corresponding loss in thermal performance, especially in high solar intensity conditions, makes aluminium the more favorable choice for consistent year-round productivity. Therefore, the use of aluminium fins is

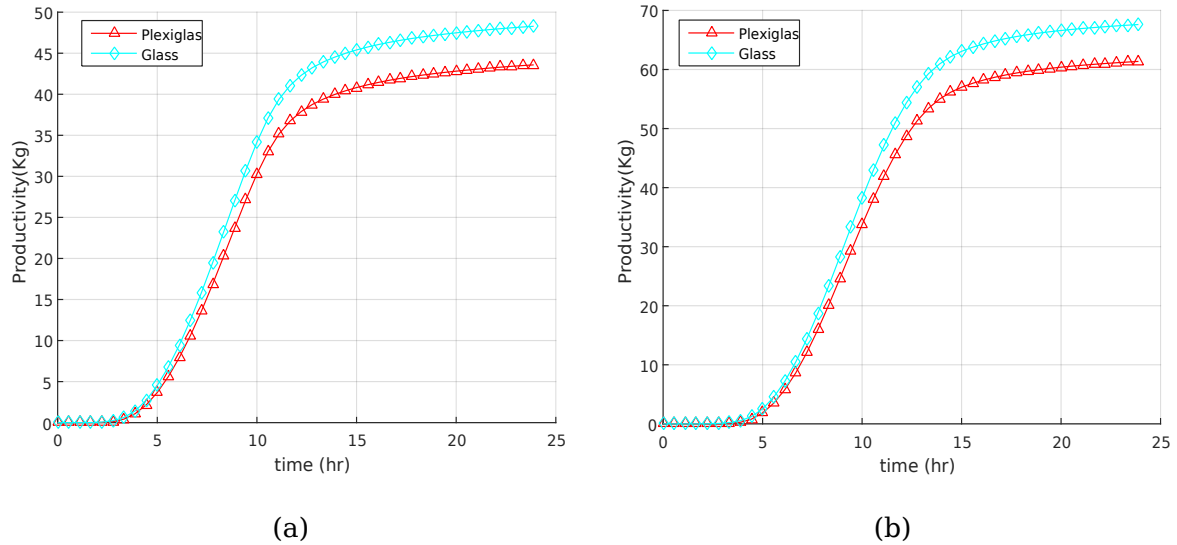
recommended to ensure high efficiency, particularly in summer conditions where thermal demand is greater.



**Fig. 8.** Effect of different materials on absorber plate (a) Winter  
(b) Summer

### 3.2.6. Glass cover material

The impact of glass cover material on the SS-HDH system was evaluated by comparing conventional glass with Plexiglas (plastic). As illustrated in Figure 9, across both winter and summer cases, replacing glass with Plexiglas resulted in a reduction in system weight but also a measurable decline in productivity. In the winter case, productivity dropped from 48.2 kg to 43.5 kg, a reduction of approximately 10%, when using Plexiglas. Similarly, the summer analysis showed an 11% decrease in productivity with the plastic cover. Despite this performance trade-off, the weight of the glass covers decreased substantially from 271 kg to 115 kg. While Plexiglas offers the advantage of reduced weight, its lower solar transmittance negatively affects thermal performance. Therefore, conventional glass remains the preferred material for applications where maximizing freshwater output is prioritized over minimizing system mass.



**Fig. 9.** Glass cover material (a) Winter (b) Summer

### 3.3. Combine System- Optimum case study

In this section, based on parameters study results, optimum factors were taken to maximize the productivity, as well as, to ensure cost effective design by ensuring light weight design. Table 1 shows the combined parameters that were taken for the combined system of winter and summer.

Table 1: Combine parameters

<b>WINTER &amp; SUMMER OPTIMUM PARAMETERS</b>	
<b>Operational Condition</b>	
Mass flow rate	0.1kg/sec
Water height	0.005m
<b>Design Condition</b>	
Basin still material	cotton
Basin thickness	1 mm
Glass thickness	1 mm
Finned absorber material	Aluminium
Cover	Glass

Aforementioned are the factors that were chosen for the combine system. Dehumidifier inlet and outlet temperature has no effect on productivity. Optimum flow rate and water height of 0.005m and 0.1kg/sec chosen had significant increase in productivity. For the design factors, basin still material of cotton shows almost insignificant change in total productivity while reducing the mass of the system greatly. Hence, cotton was chosen. Basin thickness and glass thickness have no effect on total productivity. Hence 1mm is the ideal for reducing the weight of the unit for the same productivity. As for the solar absorber material, the conventional aluminium was favorable as compared to cotton, because using cotton materials, the mass of SS-HDH unit was reduced, but productivity reduced dramatically. Also, the change in overall mass using cotton as absorber was also less. Cover should be made of glass as plastic decreases penetration of solar radiation.

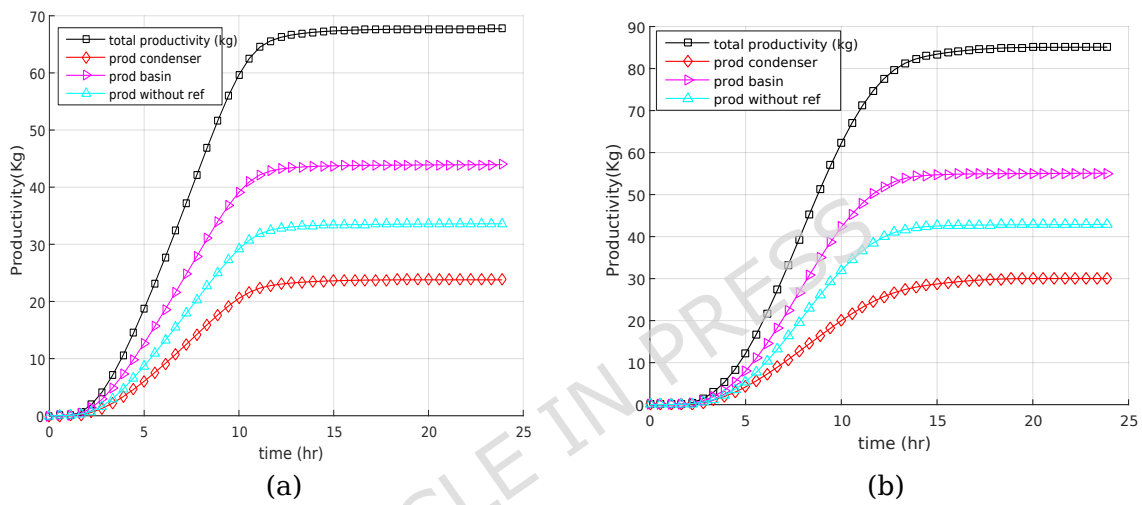
### *3.3.1. Combine winter and summer system*

Choosing the optimum parameters resulted in significant increase in total productivity and decrease in weight of the total SS-HDH unit. Figures 10 show the total productivity of winter and summer combine parameter results respectively. For winter, it can be observed that the total productivity increased case from 51kg to 67.7kg i.e. increased by 31%. And for the summer case, productivity increased from 67.6 to 85.1kg i.e. increased by 26%. Table 2 shows the change in total mass for the SS-HDH unit. From the table we can see that the total mass of SS-HDH unit reduced to 131.8kg from 486.6kg for without water, showing a dramatic decrease of 73%. The usage of cotton material and smaller thickness also ensures reduced capital cost of the system. Therefore, based on the parametric study, we were able to figure out best possible combination for enhancing productivity and low weight.

Table 2: Comparison of mass

	<b>Conventional mass (kg)</b>	<b>Parameter mass (kg)</b>

Mass of glass 1	109.2	26.5
Mass of glass 2	56	14
Mass of glass 3	110	27.6
Mass of basin (No water content)	148.3	0.48
Mass of absorber	18.4	18.4
Mass of humidifier ropes (No water content)	44.8	44.8
Total Mass	486.6	131.7



**Fig. 10.** Combined parameter results (a) Winter (b) Summer

#### 4. Conclusions and Future Recommendations

This study conducted a comprehensive parametric optimization of a hybrid solar still-humidification-dehumidification (SS-HDH) desalination system using a validated transient numerical model, with particular emphasis on achieving high freshwater productivity while minimizing system weight for remote-area deployment. The results demonstrate that operational parameters strongly influence system performance. Reducing the basin water depth from 3 cm to 0.5 cm increased total freshwater productivity by approximately 15% in winter and 7.5% in summer, while simultaneously reducing basin mass. Likewise, lowering the air mass flow rate from  $0.5 \text{ kg s}^{-1}$  to  $0.1 \text{ kg s}^{-1}$  enhanced productivity by 11–12% and enables the possibility of natural convection operation, thereby eliminating

the need for auxiliary fans and reducing energy consumption and system complexity. Design parameters were found to play a decisive role in minimizing structural weight. Replacing the stainless-steel basin with black-coated cotton reduced the total system mass from 486.6 kg to 131.8 kg, corresponding to a 73% reduction, while maintaining nearly identical freshwater yield. Furthermore, decreasing basin and glass thickness from 3 mm to 1 mm resulted in substantial weight savings without any measurable impact on thermal performance or productivity. In contrast, replacing aluminium fins with cotton absorbers or glass covers with plastic reduced system mass but caused productivity losses of 10–15%, rendering conventional aluminium absorbers and glass covers preferable for year-round operation. By combining the optimal operational and design parameters, the integrated system achieved a productivity increase from 51.0 kg to 67.7 kg per day in winter (31%) and from 67.6 kg to 85.1 kg per day in summer (26%), while maintaining the reduced structural mass of approximately 132 kg. These results confirm that substantial gains in both efficiency and portability can be realized through systematic parameter selection.

Several limitations of the present study should be acknowledged. First, the analysis is based on numerical simulations and has not yet been experimentally validated under field conditions. Second, the long-term mechanical durability, fouling behavior, and thermal stability of lightweight materials such as cotton basin liners were not investigated. Third, the model assumes forced convection airflow, whereas natural convection operation, although promising based on the low optimal flow rate, was not explicitly simulated. Finally, system performance during nighttime remains limited due to the absence of thermal energy storage.

Future research should therefore focus on:

- (i) experimental validation of the optimized SS-HDH configuration under real climatic conditions.
- (ii) long-term reliability testing of alternative lightweight materials.
- (iii) detailed modelling and experimental assessment of natural convection airflow regimes;

(iv) integration of thermal storage media such as phase change materials to enhance nocturnal productivity, and

(v) techno-economic analysis and life-cycle environmental assessment to quantify the cost savings and emission reduction potential of the proposed lightweight SS-HDH system. By significantly reducing system mass and simplifying operational requirements, the optimized design has the potential to lower capital expenditure, transportation costs, and embodied carbon, thereby enhancing its viability for sustainable deployment in rural and off-grid communities. Established performance-evaluation and techno-economic assessment frameworks reported in recent floating desalination and solar still studies can be directly adopted to support such analyses [40, 41]. These developments would further strengthen the practical feasibility of lightweight hybrid solar desalination systems and accelerate their deployment in off-grid and water-scarce regions.

**CRedit authorship contribution statement:** Muhammad Mustafa Muhammad Iqbal: Conceptualization, Methodology, Software, Visualization, Validation, Writing - original draft. Muhammad Saad Javed: Writing - review and editing. Serter Atabay: Writing - review and editing. Hasan Fath: Supervision, Writing - review and editing. Mehmet Fatih Orhan: Conceptualization, Visualization, Supervision, Writing - review and editing.

**Declaration of competing interest:** The authors declare no competing interests.

**Data availability:** The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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