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Enhancing efficiency in solar non-intrusive desalination: Solar still prototype optimization in Southwest Europe

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HIGHLIGHTS

- Solar desalination system to produce freshwater for non-potable uses for small islands
- Over 99 % salt removal achieved in both prototype and pilot-scale experiments
- The pilot-scale unit shows 6.24 L/day·m^2 productivity in peak summer.
- Innovative design options significantly enhanced solar desalination efficiency.

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ABSTRACT

Access to freshwater is a pressing global challenge. Despite being irreplaceable freshwater is an increasingly scarce resource, especially in regions as Southern Europe, due to high human pressure and climate change. Solar desalination presents a low impact solution to produce freshwater from seawater, particularly in sun-rich regions. The main goal of this study was to develop a modular solar desalination system based on a non-intrusive approach, with simple assemblage, installation, and maintenance, to produce freshwater for non-potable purposes. The modular design was chosen to allow scalability and adaptability, enabling effective response to variable water demands in small island communities. The case study is a small island from Algarve, Portugal (Southwest Europe). The study evaluates the performance enhancements accomplished by transitioning from an initial prototype solar desalination unit, smaller and with a simple design, to an enhanced pilot-scale system designed to improve efficiency and water output. The research showed that both systems exhibit a high conductivity removal (higher than 99 %), demonstrating the potential of this technology to produce freshwater from seawater, delivering high-quality desalinated water, across different seasons. Prototype 1 demonstrated limited productivity, around 0.45 L/day.m^2, while pilot-scale unit presented a productivity of approximately 6 L/day.m^2 in summertime. This substantial improvement reflects the design modifications implemented in the pilot-scale unit, positioning it as a valuable option for water desalination in regions with abundant solar resources. These findings confirm the strong potential of solar desalination as a non-intrusive and effective solution and lays the groundwork for future advancements, focusing on maximising efficiency by exploring innovative materials to enhance solar energy absorption and optimizing operational conditions.

1. Introduction

The increasing water scarcity for human activities and biodiversity support highlights the need to improve water resources management. We are living through both climate and biodiversity crises driven by the unsustainable use of our planet's resources, namely water [1]. The number of city inhabitants lacking safely managed drinking water has increased by >50 % since 2000 [2]. Water use efficiency and unconventional water sources, mainly for non-potable purposes, can make all the difference particularly in the cities where we will have an increase of

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2.2×10^9 residents, from 56 % in 2021 to 68 % in 2050 [3]. The water scarcity will result on the growth of severe problems regarding food production, water-borne illnesses, biodiversity losses, access to education and climate refugees all around the world.

Water in the environment follows a natural circular model. However, in urban water context, the water resources are managed by human decisions following an anthropogenic water cycle, where water is extracted from different primary sources (e.g., surface water, groundwater, and seawater) to meet urban water demands. This strategy is no longer sustainable due to its resource's imprudent consumptions and environmental contamination [4].

The oceans can be an alternative water source for human activities, mainly to islands and other coastal urban areas, allowing the pressure reduction on natural freshwaters, surface and groundwater. Under these communities' seawater desalination (or brackish water) to obtain freshwater can be a crucial alternative source for water supply. Desalination systems require significant energy to remove salts from seawater, making them unaffordable for many worlds' water-scarce areas. Gulf countries are leading the World in terms of installed desalination capacity since they combine arid climate and fossil fuel abundance. In 2019, there were 15,906 operational desalination plants, producing around 95 million m^3/day of water for human consumption, of which 48 % are in the Middle East and North Africa region [5].

Desalination can be mostly achieved by two types of technology, membrane systems that use mechanical energy, and thermal systems supported by thermal energy. Membrane desalination through reverse osmosis (RO) is the most productive technology and accounts for 3/4 of global desalination capacity and 85 % of the total worldwide number of desalination plants [5]. However, desalination environmental impacts are a problem and depend on the technology in use, feedwater type, and management of the brine produced [6]. Although over the last few decades RO membranes underwent significant improvements, allowing lower energy consumption and substantial water production at a reasonable cost [6,7], the disposal of the toxic brine remains a threat to coastal and marine ecosystems, and the consumption of fossil energy is expensive and linked with climate change [8,9]. Desalination is expanding particularly in regions with severe water scarcity as Mediterranean, and RO plants are discharging at sea large amounts of toxic hypersaline brines, with direct and indirect impacts, affecting the primary productivity in sediments and benthic fauna [10,11]. Brine toxicity is mainly due to the accumulation of acids, disinfectants and antiscalants (namely phosphonates and synthetic organic polymers or co-polymers), which are added during feedwater pre-treatment, to increase system productivity and lifespan of membranes [12,13].

Solar desalination has been used since the time of Aristotle, and different desalination methods have been developed using solar energy. Solar based desalination is economical, reliable, and has low ecological impact also. Setting up, running and maintenance of a solar desalination plant is easier as compared to other desalination plants [14]. However, the major limitation of these systems remains their low productivity [15]. Solar stills are devices that use solar thermal energy to distil water, constituting a less expensive solution, especially for developing countries that receive high solar irradiation. These solar systems can collect the solar energy to produce distillate directly, or can present two subsystems, one for solar energy collection and one for desalination. Furthermore, solar stills can distil water using only solar thermal energy being considered passive devices for solar desalination or can be active solar stills if use additional heating sources besides the sun [15–17]. Several factors condition the solar stills performance and productivity namely, the location, design, shape, and basin water depth [18,19].

In recent years, the effects of some variables on solar stills productivity have been studied, including glass cover material, thickness and its inclination, wind velocity, solar input, ambient temperature, the heat capacity of the still, the basin water temperature, the use of various energy storage materials, the application of advanced materials to improve the efficiency of solar desalination units, the use of multi-effect distillation aided by latent heat of vaporization, regenerative effects, or water-film cooling [16,18,20–23]. Even under optimized operating conditions, the reported efficiency of the single basin solar still is in the range of 30–45 %, with <5 L/m^2 day of freshwater production [21,24,25]. Some attention is being given to renewable energy resources (RES) as sustainable solution to optimize the productivity of solar stills increasing the freshwater production. A recent work also compared the performance of a conventional solar still, a horizontal wick solar still with flat plate collector and basin tilted wick solar still at 30° integrated with flat plate collector. The performance of solar with tilted wick at 30° coupled with flat plate collector was found better as compared with the other options because the basin water of tilted wick still gains more heat from flat plate collector, showing the importance of design modifications for efficiency improvements [26].

The aim of this study was to develop a modular desalination solution using a non-intrusive process, with simple installation and maintenance to produce water for non-potable uses for a small island community, Culatra Island, located in Algarve, the southernmost region of Portugal. Focused on developing, installing, testing and optimizing a pilot-scale system in Culatra Island using real conditions, this work went further with its main novelty being a design and technical improvement, which increased productivity by over 60 %. This innovation represents a significant achievement, particularly since one of the solar desalination main limitations is low productivity. It concludes by addressing how the set experiment not only enhances solar desalination feasibility but also sets a new benchmark for more sustainable and efficient water solutions, mainly in islands, which frequently face severe water scarcity issues. Moreover, the technology could be replicated in other coastal areas worldwide, providing a viable contribution to water issues globally. Additionally, the concept of modularity was chosen for its scalability, adaptability, and ease of maintenance. In regions like small islands, where seasonal population variations significantly impact water demand, modularity allows for flexible expansion or contraction of the system.

2. Case study – pilot site location

Culatra Island (Fig. 1), is a small island (approximately 7 km in length and a maximum width of 1.2 km, comprising a total area of 4.34 km^2) located in the barrier islands that compose the Ria Formosa Natural Park in Algarve region, South of Portugal. With a Mediterranean Csa climate (Köppen-Geiger classification), Algarve region is characterised by mild and short winters and long, hot and dry summers, average temperature is 16 °C. Yearly rainwater precipitations are around 550 mm and 97 % of those are concentrated in 8 months, which leaves only 3 % of the already low precipitations for the 4 summer months. However, even these values have been decreasing and are mainly concentrated in short and extreme events which makes rainwater harvesting more difficult.

The main village, Culatra, has around 1000 habitants and the main economic activities are fishing and tourism, both of which are highly linked to Ria Formosa. The village faces big challenges in terms of energy efficiency and self-sufficiency, water scarcity, waste management and localized contamination. During the summer from June to September the population triples, as also the water consumption. Since 2010 the Culatra Island has been supplied with sanitation services and safe drinking water, pumped from the mainland, meaning high energy consumption and carbon emissions. In turn, the wastewater is pumped out through a collector back to the mainland to be treated in a wastewater treatment plant. To face these constraints and the local effects of climate change, Culatra needs to implement a sustainable management of water and energy. There are several challenges to be faced such as: decrease the energy consumption to water and wastewater transportation; increase the water availability to irrigate green areas in the island; improve the efficiency of water usage; engage the community in the sustainable water management; and face the seasonal fluctuation of

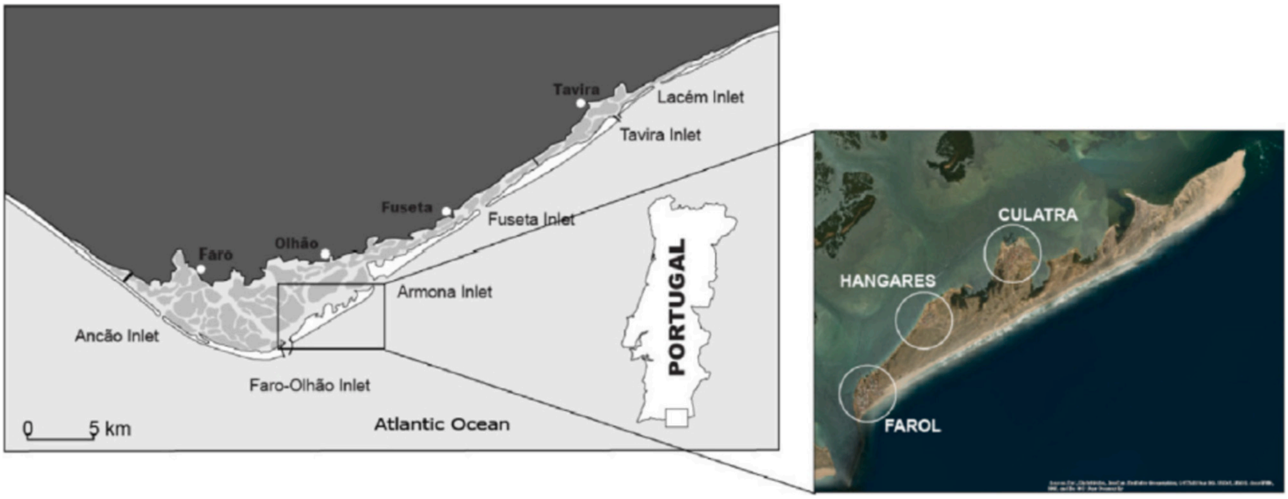

Fig. 1. Culatra Island location (36.9937°N; −7.839793°W). Culatra Island has three settlements: Farol, Hangares and Culatra, the latter standing as the case study for this paper.

water consumption due to the tourism seasonality.

On 2019, and to promote sustainable development, the University of Algarve launched to the islanders the initiative "Culatra2030 - Sustainable Energy Community", supported by the Clean Energy for EU Islands (CE4EU). The Culatra2030 initiative is a demonstration project covering multiple aspects of green transition. It implements the ambitions of the Smart Specialisation Strategy (S3) in Algarve, using a novel Entrepreneurial Discovery Process (EDP) to create a living-lab for green transition, focusing on the island specific needs and capitalising on its assets [27].

3. Material and methods

3.1. Solar desalination unit development and test (Prototype 1)

Prototype 1 was developed based on the simplest form of operation as showed in Fig. 2. Evaporation, condensation and freshwater collection is crucial for the productivity and efficiency of the system. In this case desalination relies on simultaneous evaporation and condensation, which rates are depending on parameters such as water and glass cover temperature.

Initially, three solar stills of different heights 40 cm, 80 and 160 cm (with width and length, both of 1 m in the three cases) were designed, built and tested to assess productivity as a function of dimension (Supplementary material). Due to the lower productivity of bigger systems, the small unit was chosen as Prototype 1 and further experiments were carried out only with this one (Figs. 3 and 4). Prototype 1 is a passive solar still, where the salt water is in the tank bottom, evaporates and condenses on the cover inner side, flows down to a freshwater collection gutter, and enters into the reservoir placed next to the solar still (Fig. 3). The unit was constructed using fiberglass-reinforced by polymeric composite material due to the high resistance to traction, flexion, and impact. The tank walls were painted black to enhance sunlight absorption. The glass cover had 3 cm of thickness and a 37° inclination angle corresponding to the latitude of Algarve, i.e., 37°N. The reservoir to collect the desalinated water were built also using fiberglass reinforced. Conductivity (μS/cm) (Mini Conductivity Probe K 1.0, Atlas Scientific Environmental Robotics) and temperature (°C) (PT100, Atlas Scientific Environmental Robotics) sensors were installed inside the tanks. The air temperature was monitored at three different heights, 10 and 40 cm (mid-height) above the water surface, and 10 cm underneath the glass cover, and glass cover temperature was measured with a sensor pressed against the glass inner side.

In order to assess system efficiency, Prototype 1 was installed, between May and December 2021, in a salt rock mine (TechSalt, Campina de Cima, Loulé, Algarve) to treat a hypersaline water with a salinity ten times higher than seawater, about 320 $g.L^{-1}$.

After these experiments under extremely inflow conditions, Prototype 1 performance to produce freshwater for non-potable uses from seawater desalination, was evaluated. The unit was relocated, installed, and tested at the pilot site on Culatra Island during August 2022 (Fig. 4). A set of sensors was installed on a common axis originating from the centre of the basin: (1) Salty water's temperature and conductivity are measured at the bottom of this axis; (2) Air's temperature is measured 10 and 40 cm (mid-height) above the water surface, and 10 cm underneath the glass cover; (3) Glass cover's temperature is measured with a sensor

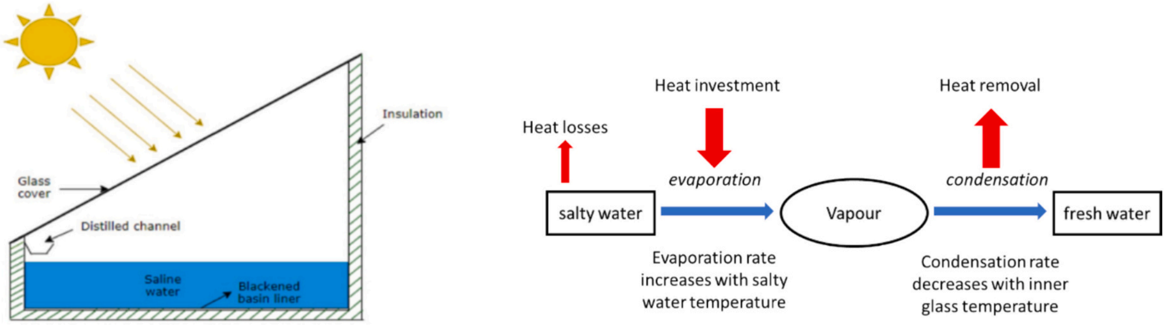

Fig. 2. Solar still functioning basis, desalination process and key parameters. (Adapted from [28].)

Fig. 3. (a) Prototype 1 solar still unit, with temperature and conductivity sensors, and the reservoir for desalinated water storage; (b) detail of the gutter placed inside of the solar still for desalinated water collection.

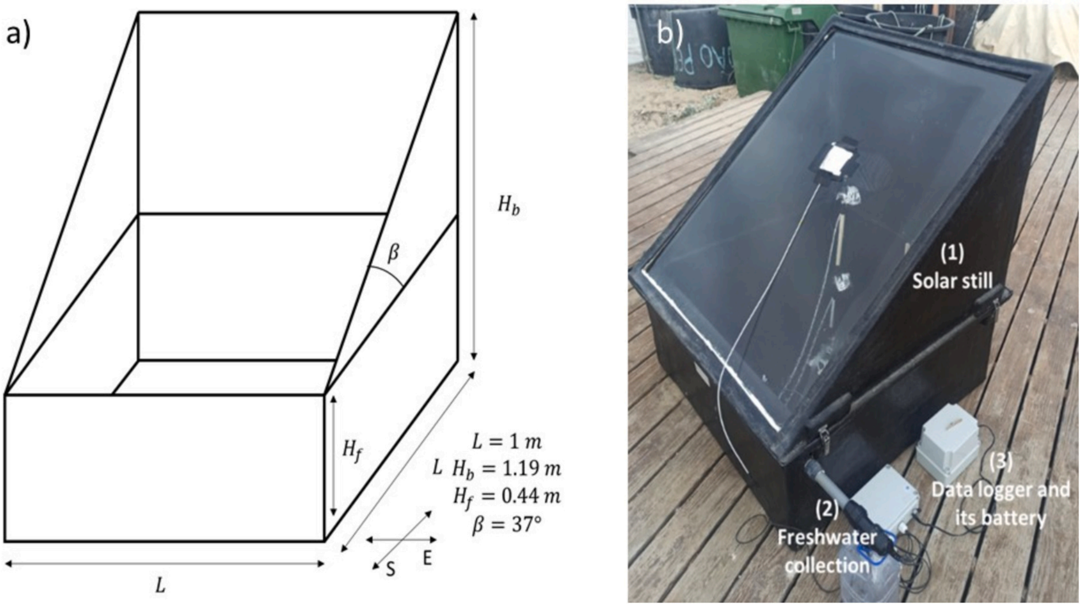

Fig. 4. (a) Prototype 1 design with dimensions; (b) Prototype 1 (1) with the pipe for freshwater collection (2) and the data logger (3).

pressed against the inner side of the glass. The temperature sensors used are PT100 thermometers and the conductivity sensor is referred to as "Mini Conductivity Probe K 1.0". All sensors were bought from Atlas Scientific Environmental Robotics. Temperatures are read in °C and conductivities in μS/cm. Water samples were collected periodically and analysed for conductivity at laboratory conditions.

3.2. *New solar desalination system development (pilot-scale unit)*

The pilot unit was developed based on the lessons learned from the experiments conducted with Prototype 1 to enhance system productivity. The main conditions to develop the pilot unit were: (1) to ensure a steady state for solar irradiation, liquid water and steam flows; (2) to achieve and maintain a homogeneous temperature in the salt water tank; (3) to guarantee an efficient freshwater recovery in vapor phase; (4) to ensure no heat losses and no steam accumulation; and (5) to guarantee that deposit of salts closes on the surfaces over time, as well as a simple way to be cleaned, maintained, and restored. Therefore, the pilot unit evolved from a passive to a semi-passive system, where a complementary thermal solar system powered by the sun was added. Fig. 5 summarises the process.

The complementary heat from the steam allows heating a coil placed under the seawater. The panel will be able to operate solely on solar energy. However, can also use additional heat to enhance productivity when there is a surplus of photovoltaic (PV) generation on the island. To achieve this, the device integrates a heat exchanger that collects heat from an external solar collector. The steam is used to accelerate the seawater evaporation, thereby enhancing solar still productivity. The thinning of the water film increases the temperature of both water and the steam, which improves the evaporation and condensation processes.

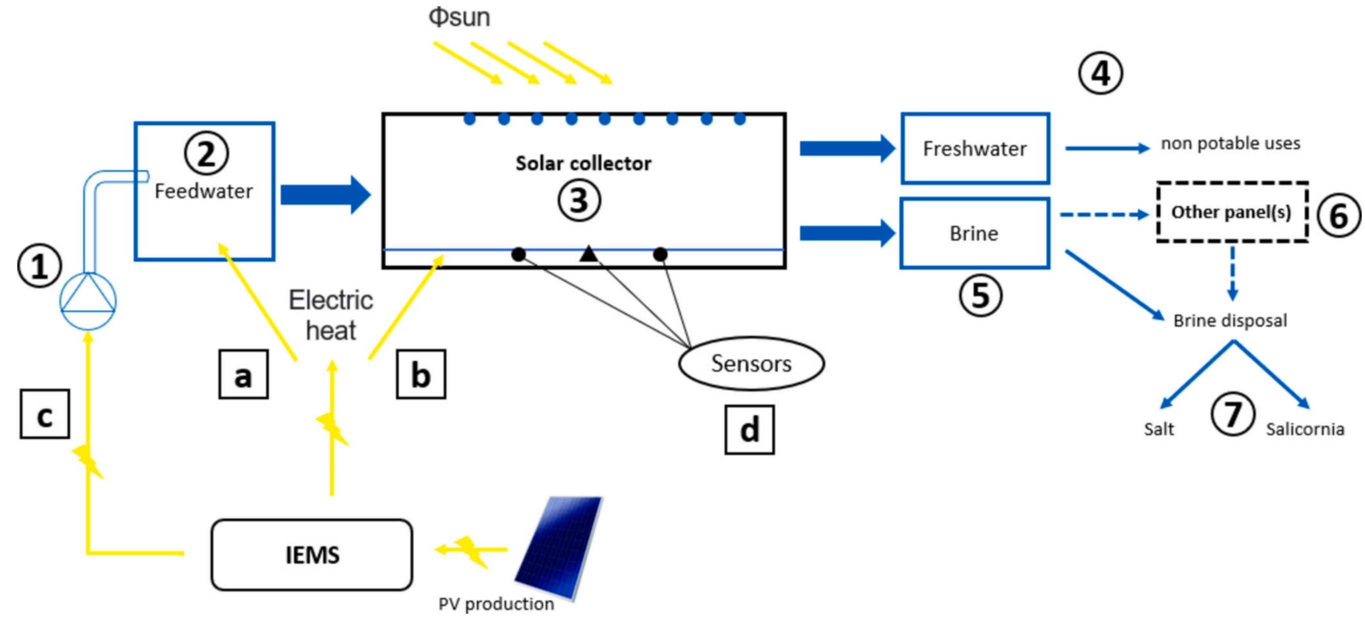

Fig. 5. a) New solar still prototype - the water is fed to the top; it flows down and evaporates while receiving heat from the Sun; it then condenses and runs off on the cover to be finally collected at the bottom; (b) functioning scheme of the news solar still desalination system adapted to Culatra and connected to the Integrated Energy Management System (IEMS) and PV panels. Water is pumped from the sea (1) and stored at the seawater tank (2). The water then flows through the solar collector with a small depth; steam condensates and pours on the cover (3). The freshwater (4) is collected and used for non-potable uses such as watering green spaces and brine is collected separately (5), which can be fed to another panel (6) to concentrate it even more in salt. The brine is then disposed for valorisation through salt production (open air evaporation) or Salicornia culture (7). The IEMS can provide supplementary heating to the seawater storage to study the influence of feedwater temperature or supplementary heating to the main tank to study the influence of total heat provided. The IEMS also powers the pumps that fill the seawater storage. If possible, this energy comes from surplus PV production. The sensors allow monitoring the temperature and salinity all along the solar collector.

The higher internal temperature increases the temperature difference with the glass, leading to enhanced water condensation.

A new desalination panel was designed using corrosion-resistant materials e.g. stainless steel, and small copper tubes were installed to house temperature and conductivity sensors for studying the desalination process at different temperatures (Fig. 6).

Cooper tubes were placed beneath the desalination panel, forming a coil to facilitate heating and accelerate the desalination process (Fig. 6b). A staircase structure was added to allow seawater to descend very slowly, enabling its condensation on the glass panel (Fig. 6d). Exposure to solar energy causes the water to evaporate, leaving behind salt in the stairs. The water condensed droplets of distilled water run down the cover and are collected in a separate container, becoming freshwater. The salt deposited on the stairs can be cleaned by removing the sliding glass panels.

After the technical improvements, the experiments using the pilot

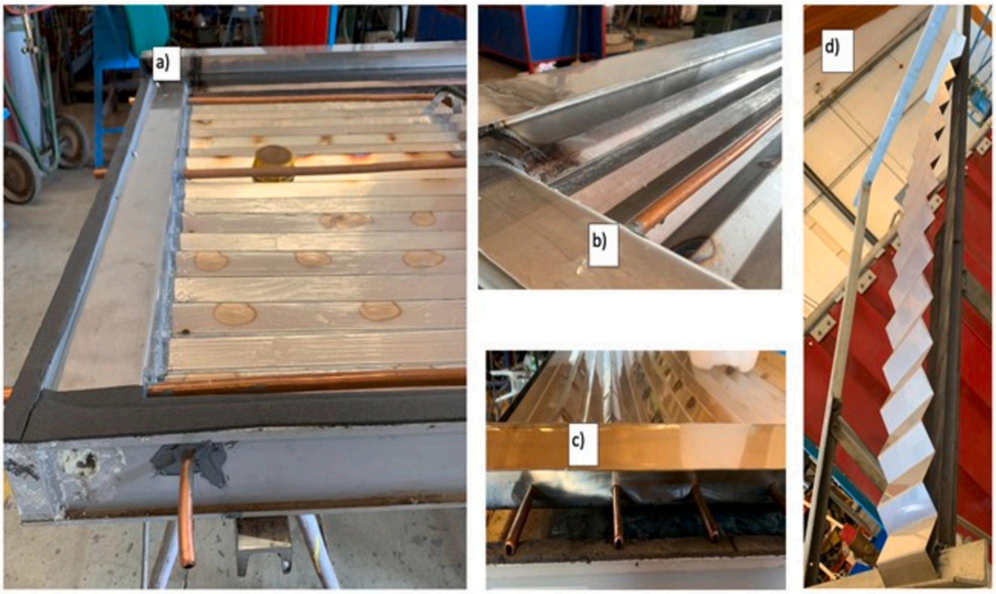

Fig. 6. New desalination panel construction (a), with anti-corrosion treatment (b), small copper tubes for sensors installation (c) coil beneath the desalination panel to promote the heat: and (d) small stainless-steel steps to allow a very slow descent seawater inside the panel. The heated seawater goes down these small stairs inside the panel inclined and covered with a transparent cover (glass).

unit were firstly carried out (February and March 2023) on the construction site to system optimization. During July 2023 the pilot unit was tested under real conditions at Culatra Island. The final Pilot-scale unit installed at the rooftop of Culatra Social Centre is showed in Fig. 7. The unit was strategically positioned facing east for optimal solar exposure. The system was strategically oriented eastward for optimal solar exposure, mainly during the morning, which is typically the most favourable period for efficient operation [20].

An adjacent meteorological station (Fine Offset, WH2650) was installed at the experimental site to monitor atmospheric temperature, solar radiation, and wind direction and speed (Fig. 8).

3.3. Analytical methods

Water samples were characterised for electric conductivity and salinity before and after treatment from solar desalination units. Laboratory water analyses were carried out according to the internationally standardised analytical methodologies [29], presented in Table 1. Samples were collected in the solar still on different days, i.e., at different levels of the process and therefore different brine concentration. Sea water was collected as another sample as a marker for the beginning of the desalination process. Fresh water was also collected in the output of the solar still. Their salinity is measured with the conductivity meter of a laboratory aggregated with the national IPAC label at a controlled temperature, i.e., 20 °C. To obtain more intermediate points to better establish the correlation, additional samples have been derived by dilution from the collected ones. The uncertainty related with the electric conductivity measurements is 3 %, as reported in Table 1. Regarding salinity, its measurement uncertainty is challenging. But refractometer is considered by many to be a more accurate way to measure salinity. In general, many uncertainty sources related to the measurement conditions, external from the refractometer, can play a major role in the total uncertainty of measurements.

4. Results and discussion

4.1. Conductivity removal efficiency

The conductivity of the final water is a critical indicator for assessing the desalination system performance, as it directly indicates the ability to remove dissolved salts the water.

Table 2 shows the conductivity removal of the initial prototype (Prototype 1) and pilot-unit under various conditions and feed waters.

The initial experiment was conducted with Prototype 1 using hypersaline water during the summer of 2021. This hypersaline feed water, characterised by an extremely high initial conductivity (227,000 μ/cm), set a significant challenge for the desalination system. Despite this, Prototype 1 reduced the final conductivity to 5200 ± 0.30 μS/cm, corresponding to a conductivity removal of 97.71 %, demonstrating a high ability to remove salts from water and other dissolved minerals. Although the final conductivity, is not under the limits for typical freshwater, being considered a moderately saline water [30] it could be used to salt tolerant crops irrigation. At the end of the experiment, the precipitated salts remain at the desalination system bottom, as show in Fig. 9. A mass of approximately 5.6 kg of salts was recovered.

In the summer of 2022, Prototype 1 was further evaluated at real conditions in Culatra Island and using seawater (48,000 μS/cm). A final conductivity of 450 ± 14 μS/cm was achieved, resulting in a

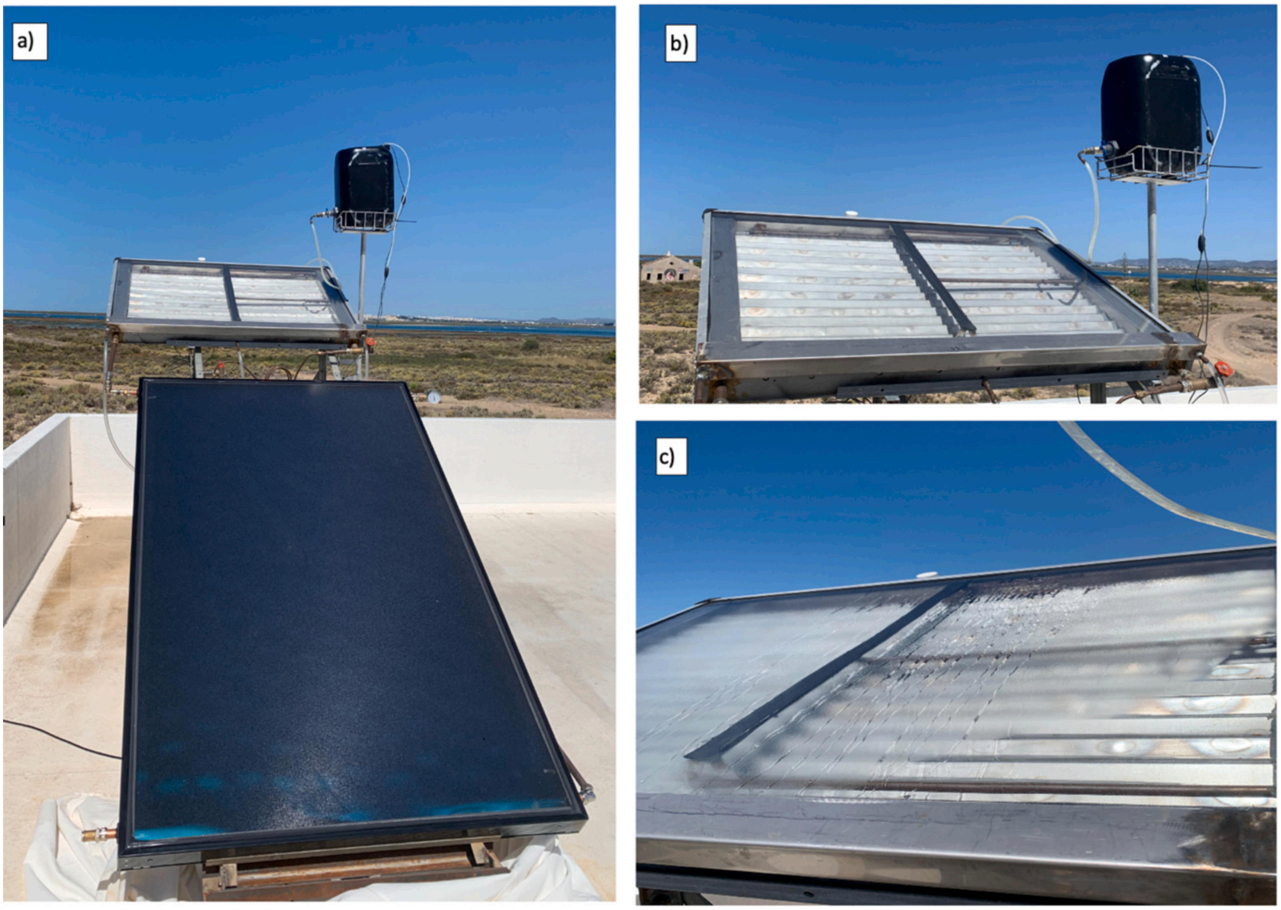

Fig. 7. (a) Final pilot-scale unit at Culatra Island, (b) desalination module with the innovative staircase structure and (c) detail of the water condensation on the glass cover.

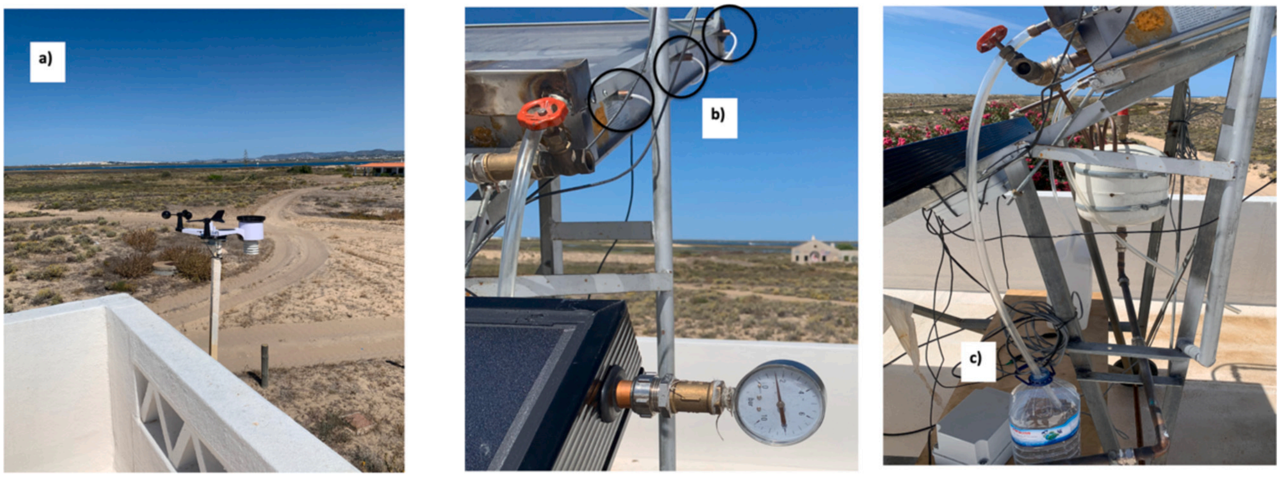

Fig. 8. (a) Weather station, (b) temperature and conductivity sensors at the desalination panel and (c) control box connections for online monitoring via GSM.

Table 1
Analytical methodology used in water characterization.

Parameter	Units	Methods	Uncertainty
Electric conductivity	μS/cm	Electrometry SMEWW 2510B[a]	3 %
Salinity	g/L	Refractometry	ND

ND Not determined.

[a] [29].

Table 2
Removal efficiency of conductivity for Prototype 1 and pilot-scale unit using different feed waters and different times of the year.

		Initial conductivity (μS/cm)	Final conductivity (μS/cm)	Conductivity removal (%)
Prototype 1				
Hypersaline water	Jun–Sept 2021	227,000	5200 ± 0.30	97.71
Seawater	Aug 2022	48,000	450 ± 14	99.06
Pilot-scale unit				
Seawater	Feb 2023	48,500	80.2 ± 2.4	99.83
	Mar 2023	48,000	80.1 ± 2.4	99.83
	Jul 2023 (7th)	48,500	435 ± 13	99.10
	Jul 2023 (24th)	48,000	440 ± 13	99.08

significantly improved removal efficiency of 99.06 %. This result highlights the effectiveness of the solar still technology in standard scenarios. The low conductivity of the final water corresponds to freshwater (freshwater <700 μS/cm) [30], within the limits even for drinking water, indicating that could be used to all non-purposes uses, being considered suitable for irrigation.

The promising results from Prototype 1 regarding conductivity removal, provided the foundation to scale up the technology to the pilot-scale level. The Pilot-scale unit was tested exclusively with seawater as feed across the year of 2023, providing insights into its performance under different seasonal conditions. In February and March 2023, the unit achieved a remarkable conductivity removal of 99.83 %, reducing the initial seawater to a final conductivity of approximately 80 μS/cm (Table 2). These results demonstrate a high effectiveness even under cooler seasonal conditions. During the summer months, a slight increase in the final water conductivity was observed, reflecting a decrease in the system performance. However, conductivity removal was still very high, approximately 99 %, with a final water conductivity below 450 μS/cm (Table 2). These slightly reductions may be related to the increase of temperature and solar irradiance during summer, which can affect the desalination process' thermal dynamics.

Conductivity (or salinity removals) using solar desalination systems varies between approximately 85 to 99.9 % in the literature [31–34], indicating that the pilot-scale unit develop in the present study ranging from 99.08 % to 99.83 % is positioned at the upper end of the reported efficiencies.

Fig. 9. Precipitated salts after the Prototype 1 experiment using hypersaline feed water.

4.2. Freshwater productivity

Freshwater productivity, measured as the water produced per square metre of desalination panel per day (L/day.m^2), is a key indicator of the system's efficiency and operational capacity. Table 3 shows the productivity of both Prototype 1 and Pilot-scale unit under different feed and seasonal conditions.

Prototype 1 productivity was relatively low, with values of 0.45 L/day.m^2 for hypersaline water and 50 L/day.m^2 for seawater. These low productivity values, reflect the operational limitations of the initial prototype. The slightly difference between the two feed waters suggests that the system can operate in extreme salinity conditions. But, overall, productivity is constrained by design limitations, possibly due to ineffectiveness of evaporation and condensation processes. Regarding conductivity data presented in Table 2, the higher final conductivity values observed for the hypersaline water (5200 μS/cm), shows that the system is less efficient under more challenging feed conditions. However, despite the lower productivity, the lower final conductivity in the experiment fed by seawater (450 μS/cm), shows that Prototype 1 was effective in the salt's removal, but the overall efficiency was limited.

The productivity results (Table 3) clearly show a substantial improvement from Prototype 1 to Pilot-scale unit, across all experimental periods. Regarding seawater experiments, the Pilot-scale unit demonstrated a high increase in productivity, starting at 1.77 L/day.m^2 in the wintertime and increasingly to 6.24 L/day.m^2 by late July (Table 3). This notable improvement reflects the enhanced design, clearly demonstrating that the Pilot-scale unit benefited from the optimizations described under the Methodology section, which allowed for a higher throughput and more efficient operation under variable weather conditions. The steady rise observed for the pilot unit productivity (Table 3), indicates that system performance improve as the operational parameters are fine-tuned and environmental conditions became more favourable, as during the summer where solar radiation is higher.

The increase productivity observed for the pilot unit from winter to summer (Table 3 and Fig. 10), highlights the impact of seasonality on the solar still performance. The higher productivity (6.24 L/day.m^2) in late July corresponds to the highest solar radiation average during the experiments period (Fig. 10a), which increases the evaporation and condensation, critical processes for the solar desalination technique. This finding aligns with previous works, which highlighted the direct correlation between solar energy availability and desalination output [35] This direct correlation is observed in Fig. 10a, as also supported by Eq. (1), where a correlation of 0.92 was obtained between the productivity of the pilot-scale unit and the solar radiation.

$$Correl\,(X,Y) = \frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}} \tag{1}$$

This result shows a strong positive correlation, suggesting that the productivity of the system significantly increases with the increase of solar radiation. At higher solar radiation, more energy is available for the desalination process, leading to higher rates of evaporation and condensation, resulting in greater output of desalinated water [25].

Table 3
Freshwater productivity for Prototype 1 and pilot-scale unit using different feed waters and different times of the year.

Feed waters		Freshwater productivity (L/day·m^2)
Prototype 1		
Hypersaline water	Jun–Sept 2021	0.45
Seawater	Aug 2022	0.50
Pilot-scale unit		
Seawater	Feb 2023	1.77
	Mar 2023	3.51
	Jul 2023 (7th)	4.42
	Jul 2023 (24th)	6.24

Despite the higher productivity, a slight increase was observed in the final water conductivity at July 2023 experiments (Table 2). Additionally, summer experiments also corresponded to the higher temperatures, as showed in Error! Reference source not found. This suggests that higher ambient temperatures might influence the system's performance. On the one hand high temperatures can boost evaporation process, beyond what solar radiation can achieve, enhancing productivity, especially on the summer when both solar radiation and temperature are at their peak (Fig. 10a and b). On the other hand, the increased thermal stress, due to higher temperatures, on summer may slightly reduce the productivity, as observed for the experiment of 7th July (Fig. 10b), as also decrease the desalination process efficiency (Table 2), as also observed by other authors [25].

Applying Eq. (1) to temperature and productivity results, a moderately strong positive correlation of 0.78 was obtained, indicating that system performance increase with temperature, yet not as greatly as with solar radiation. This finding suggests that, despite the temperature relevance, solar radiation is the dominant factor influencing the desalination system productivity. Previous works had already identified solar radiation as a key driver variable in the performance of solar desalination [35,36].

An additional advantage of the pilot-scale unit is that it allows scalability, since more units can be added as water demand increases, which directly enhances the system's applicability for communities like Culatra Island, where water demand fluctuates seasonally due to tourism. Furthermore, modularity facilitates easier maintenance since individual units can be serviced or replaced without interrupting the entire system's operation, ensuring continuous water production.

4.3. System performance analysis

Based on Isah et al. [37] work, the ability of the pilot-scale unit to convert feedwater into desalinated water was also determined. Thermal efficiency assesses the energy efficiency of the solar still by measuring the heat gained by the water in relation to the incident solar radiation. Heat losses are considered and is typically expressed as a percentage. Conversion efficiency represents the overall efficiency of converting solar energy into desalinated water, considering both thermal efficiency and the efficiency of the desalination process [37]. In this work, the conversion efficiency was determined using the provided Eqs. (2) and (3), allowing for the calculation of the system efficiency based on the experimental parameters.

$$Q = m \times H_{fg} \tag{2}$$

$$\eta = \frac{Q}{IA} \times 100 \tag{3}$$

Eq. (2) states that the energy used by the fluid (Q) is equal to the product of the evaporated water mass (m), measured in kg, and the seawater heat of evaporation (Hfg), given in kJ/kg and adapted to experimental water and salinity. Eq. (3) defines the system efficiency (η) as the ratio of the total useful heat gained by the fluid (Q) to the product of the hourly average solar irradiation intensity (I), given in W/m^2, the area of the glass cover (A), measured in m^2, and multiplied by 100 to be expressed as a percentage.

Using these set of equations, it was obtained a system efficiency of 29.05 % for the Pilot-scale unit, which compared with conventional solar desalination system, varying from 7 to 15 % [37], showed a remarkable increase in efficiency, led by the improvements made to the system and highlighted in the Methodology section.

5. Conclusions

This work highlights the robust performance of both Prototype 1 and Pilot-scale unit as effective desalination systems, efficiently removing salinity from hypersaline effluent and seawater. The experimental

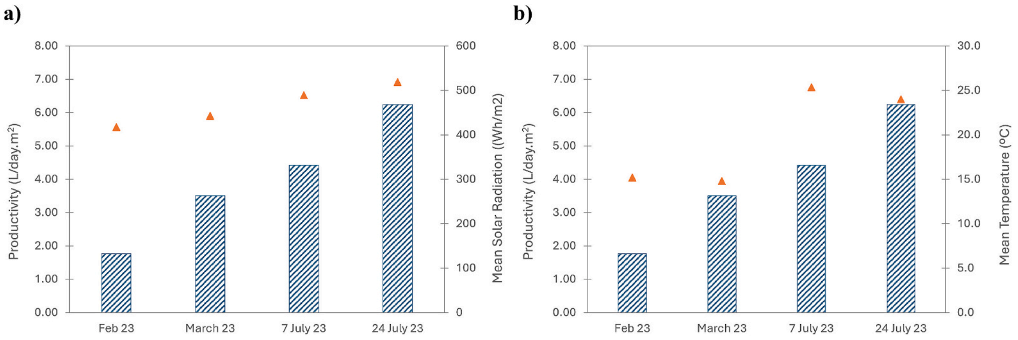

Fig. 10. Pilot-scale unit productivity in relation with solar radiation and temperature.

results clear underlined the significant improvements achieved by scaling up the system. Prototype 1 presented productivity values of 0.45 L/day.m^2 with hypersaline water and 0.50 L/day.m^2 with seawater. In contrast, the Pilot-scale unit showed a remarkable increase in productivity, with values of 1.77 L/day.m^2 in February 2023 until 6.24 L/day·m^2 by late July 2023. While the Prototype 1 presented as a valuable "proof of concept", the Pilot-scale unit represented a considerable step forward, considering the significantly higher productivity and efficiency in conductivity removal. Pilot-scale unit achieved a conductivity removal of 99.8 % from seawater in February and March 2023, presenting a final conductivity of approximately 80 μS/cm, indicating a strong ability to produce high-quality desalinated water even during winter. This reflects the effectiveness of Pilot-scale unit to treat larger water volumes while maintaining high efficiency, demonstrating its scaling up potential.

The high correlation achieved for solar radiation and productivity (0.92), suggests that solar energy capture maximization is fundamental for enhancing system output. On the other hand, the correlation found for temperature and productivity (0.78) indicates that despite temperature plays an important role in enhancing water evaporation, solar radiation stays as the primary driver of productivity.

In summary, the Pilot-scale unit displayed high and consistent performance throughout different seasons, demonstrating its robustness for continuous operation under diverse conditions, positioning as a promising solution, effective and non-intrusive to produce water for non-potable use, especially in regions with abundant solar resources, such as Southwest Europe. However, the slight decrease in productivity under higher temperatures, highlights the need to optimize the system performance in extreme heat and solar conditions. Future study will relate the difference of temperature of inner glass and water temperature to further increase freshwater productivity.

The results support the ongoing research and advance of solar still technologies, with a focus on improving efficiency by design and operational parameters optimisation. Future research could focus on explore advanced materials to improve solar energy absorption and integration of adaptative control systems that reply dynamically to environmental changes, such as temperature and humidity.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2024.118421.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] WWF, in: R.E.A. Almond, M. Grooten, D. Juffe Bignoli, T. Petersen (Eds.), Living Planet Report 2022 – Building a Nature Positive Society, WWF, Gland, Switzerland, 2022 (60p).

[2] UN Water, The United Nations World Water Development Report 2021: Valuing Water, Grance, Paris, 2021, ISBN 9789231004346 (187p.).

[3] UN Habitat, World Cities Report 2022: Envisaging the Future of Cities, 2022, ISBN 978-92-1-132894-3 (Nairobi, Kenya, 422p.).

[4] H.N. Panchal, S. Patel, An extensive review on different design and climatic parameters to increase distillate output of solar still, Renew. Sust. Energ. Rev. 69 (2017) 750–758, https://doi.org/10.1016/j.rser.2016.09.001.

[5] E. Jones, M. Qadir, M.T.H. Vliet, V. Smakhtin, Seong-mu Kang, The state of desalination and brine production: a global outlook, Sci. Total Environ. 657 (2019) 1343–1356, https://doi.org/10.1016/j.scitotenv.2018.12.076.

[6] K. Elsaid, M. Kamil, E.T. Sayed, M.A. Abdelkareem, T. Wilberforce, A. Olabi, Environmental impact of desalination technologies: a review, Sci. Total Environ. 748 (2020) 141528, https://doi.org/10.1016/j.scitotenv.2020.141528.

[7] S. Bhojwani, K. Topolski, R. Mukherjee, D. Sengupta, M.M. El-Halwagi, Technology review and data analysis for cost assessment of water treatment systems, Sci. Total Environ. 651 (2) (2019) 2749–2761, https://doi.org/10.1016/j.scitotenv.2018.09.363.

[8] M. Goosen, H. Mahmoudi, Y. Alyousef, N. Ghaffour, Solar desalination: a review of recent developments in environmental, regulatory and economic issues, Solar Compass 5 (2023) 100034, https://doi.org/10.1016/j.solcom.2023.100034.

[9] H. Sharon, K.S. Reddy, A review of solar energy driven desalination technologies, Renew. Sust. Energ. Rev. 41 (C) (2015) 1080–1118, https://doi.org/10.1016/j.rser.2014.09.002.

[10] S. Bianchelli, M. Lo Martire, L. Pola, C. Gambi, E. Fanelli, R. Danovaro, C. Corinaldesi, Impact of hypersaline brines on benthic meio- and macrofaunal assemblages: a comparison from two desalination plants of the Mediterranean Sea, Desalination 532 (2022) 115756, https://doi.org/10.1016/j.desal.2022.115756.

[11] I. Ihsanullah, J. Mustafa, A.M. Zafar, M. Obaid, M.A. Atieh, N. Ghaffour, Waste to wealth: a critical analysis of resource recovery from desalination brine, Desalination 543 (2022) 116093, https://doi.org/10.1016/j.desal.2022.116093.

[12] G. Hasanin, A.M. Mosquera, A. Emwas, T. Altmann, R. Das, P.J. Buijs, J. S. Vrouwenvelder, G. Gonzalez-Gil, The microbial growth potential of antiscalants used in seawater desalination, Water Res. 233 (2023) 119802, https://doi.org/10.1016/j.watres.2023.119802.

[13] P. Yu, X. Chen, Z. Yi, Y. Tang, H. Yang, Z. Zhou, T. Duan, S. Cheng, J. Zhang, Y. Yi, A numerical research of wideband solar absorber based on refractory metal from visible to near infrared, Opt. Mater. 97 (2019) 109400, https://doi.org/10.1016/j.optmat.2019.109400.

[14] A.E. Kabeel, T. Arunkumar, D.C. Denkenberger, R. Sathyamurthy, Performance enhancement of solar still through efficient heat exchange mechanism – a review, Appl. Therm. Eng. 114 (2017) 815–836, https://doi.org/10.1016/j.applthermaleng.2016.12.044.

[15] S. Kalogirou, Seawater desalination using renewable energy sources, Prog. Energy Combust. Sci. 31 (2005) 242–281, https://doi.org/10.1016/j.pecs.2005.03.001.

[16] A.S. Abdullah, W.H. Alawee, S.A. Mohammed, A. Majdi, Z.M. Omara, F.A. Essa, Increasing the productivity of modified cords pyramid solar still using electric heater and various wick materials, Process. Saf. Environ. Prot. 169 (2023) 169–176, https://doi.org/10.1016/j.psep.2022.11.016.

[17] A.F. Lauvandy, F.A. Raihananda, M.J. Estefan, W.S. Damanik, G.F. Mu'min, F. B. Juangsa, P. Sambegoro, Application of a low-cost floating solar still in Indonesia, Energy Sustain. Dev. 79 (2024) 101410, https://doi.org/10.1016/j.esd.2024.101410.

[18] A.E. Kabeel, S.A. El-Agouz, Review of research and developments on solar stills, Desalination 276 (1/3) (2011) 1–12, https://doi.org/10.1016/j.desal.2011.03.042.

[19] H. Panchal, K.K. Sadasivuni, M. Israr, N. Thakar, Various techniques to enhance distillate output of tubular solar still: a review, Groundw. Sustain. Dev. 9 (2019) 100268, https://doi.org/10.1016/j.gsd.2019.100268.

[20] T. Abderachid, K. Abdenacer, Effect of orientation on the performance of a symmetric solar still with a double effect solar still (comparison study), Desalination 329 (2013) 68–77, https://doi.org/10.1016/j.desal.2013.09.011.

[21] R.S. Hansen, C.S. Narayanan, K.K. Murugavel, Performance analysis on inclined solar still with different new wick materials and wire mesh, Desalination 358 (2015) 1–8, https://doi.org/10.1016/j.desal.2014.12.006.

[22] A. Negi, L. Ranakoti, P. Bhandari, R. Khargotra, T. Singh, Thermo-physical characteristics and storage material compatibility in nano-enhanced phase change materials for solar distillation applications: a critical assessment, Sol. Energy Mater. Sol. Cells 271 (2024) 112870, https://doi.org/10.1016/j.solmat.2024.112870.

[23] A. Shukla, K. Kant, A. Sharma, Solar still with latent heat energy storage: a review, Innovative Food Sci. Emerg. Technol. 41 (2017) 34–46, https://doi.org/10.1016/j.ifset.2017.01.004.

[24] H.G. Hameed, H.A.N. Diabil, M.A. Al-Moussawi, A numerical investigation of the enhancement of single-slope single-basin solar still productivity, Energy Rep. 9 (2023) 484–500, https://doi.org/10.1016/j.egyr.2022.11.199.

[25] A.E. Kabeel, M. Abdelgaied, A. Eisa, Enhancing the performance of single basin solar still using high thermal conductivity sensible storage materials, J. Clean. Prod. 183 (2018) 20–25, https://doi.org/10.1016/j.jclepro.2018.02.144.

[26] A. Negi, G.S. Dhindsa, S.S. Sehgal, Experimental investigation on single basin tilted wick solar still integrated with flat plate collector, Materials Today: Proceedings 48 (5) (2022) 1439–1446, https://doi.org/10.1016/j.matpr.2021.09.210.

[27] A. Pacheco, J. Monteiro, J. Santos, C. Sequeira, J. Nunes, Energy transition process and community engagement on geographic islands: the case of Culatra Island (Ria Formosa, Portugal), Renew. Energy 184 (2022) 700–711, https://doi.org/10.1016/j.renene.2021.11.115.

[28] K.J. Khatod, V.P. Katekar, S.S. Deshmukh, An evaluation for the optimal sensible heat storage material for maximizing solar still productivity: a state-of-the-art review, Journal of Energy Storage 50 (2022) 104622, https://doi.org/10.1016/j.est.2022.104622.

[29] R.B. Baird, C. Rice, A. Eaton, Standard Methods for the Examination of Water and Wastewater, 23rd, Water Environment Federation, American Public Health Association, American Water Works Association, 2017.

[30] W. Musie, G. Gonfa, Fresh water resource, scarcity, water salinity challenges and possible remedies: a review, Heliyon 9 (8) (2023) e18685, https://doi.org/10.1016/j.heliyon.2023.e18685.

[31] A.S. Isah, H.B. Takaijudin, B.S.M. Singh, K.W. Yusof, T.O. Abimbola, A.H. Jagaba, Evaluation of distillate quality produced by using a hybrid solar desalination system, Ain Shams Eng. J. 15 (7) (2024) 102879, https://doi.org/10.1016/j.asej.2024.102879.

[32] P. Patel, A. Patel, Low cost model for desalination of water using solar energy to overcome water scarcity in India, Materials Today: Proceedings 47 (7) (2021) 1409–1415, https://doi.org/10.1016/j.matpr.2021.02.804.

[33] K.S. Reddy, H. Sharon, D. Krithika, L. Philip, Performance, water quality and enviro-economic investigations on solar distillation treatment of reverse osmosis reject and sewage water, Sol. Energy 173 (2018) 160–172, https://doi.org/10.1016/j.solener.2018.07.033.

[34] H. Sharon, K.S. Reddy, D. Krithika, L. Philip, Viability assessment of solar distillation for desalination in coastal locations of Indian sub-continent – thermodynamic, condensate quality and enviro-economic aspects, Sol. Energy 197 (2020) 84–98, https://doi.org/10.1016/j.solener.2019.12.080.

[35] F.E. Ahmed, R. Hashaikeh, N. Hilal, Solar desalination: a review of recent advances and future perspectives, Desalination 453 (2019) 54–76, https://doi.org/10.1016/j.desal.2018.12.002.

[36] G.N. Tiwari, S.K. Shukla, I.P. Singh, Computer modeling of passive/active solar stills by using inner glass temperature, Desalination 154 (2) (2016) 171–185, https://doi.org/10.1016/S0011-9164(03)80018-8.

[37] A.S. Isah, H.B. Takaijudin, B.S.M. Singh, U.A. Abubakar, S.J. Mohammad, T. O. Abimbola, Assessing the performance, sustainability, and economic viability of a photovoltaic-based solar desalination system for water scarce regions, J. Clean. Prod. 421 (2023) 138528, https://doi.org/10.1016/j.jclepro.2023.138528.