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Evaluating the Performance of a Solar Distillation Technology in the Desalination of Brackish Waters

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Abstract: Desalination is set to become a major source of drinking water in several Middle Eastern countries over the coming decades. Solar distillation is a simple power-independent method of water desalination, which can be carried out in active or passive modes. This study is among the first attempts to investigate the possibility of desalinating brackish groundwater resources under the threat of saltwater intrusion in the southern areas of Razavi Khorasan province in Iran. For this purpose, a pilot solar distillation unit was constructed to analyze the effects of the unit orientation, depth of the water pool, atmospheric conditions, input salinity, and flow continuity on the solar distillation performance. The results showed that the unit exhibited the highest efficiency when it had a 3 cm deep water pool. It was oriented facing southward while operating a continuous flow for at least 3 days under sunny weather conditions. It was found that among the studied parameters, the unit orientation and pool depth had the greatest impact on the water production performance for this type of water desalination system. Conversely, the water production efficiency was not very sensitive to the input salinity level. Overall, the solar distillation technology was able to reduce the salinity by 99.7% and the hardness by 94.7%.

Keywords: desalination; solar technology; solar distillation; brackish water; optimization

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1. Introduction

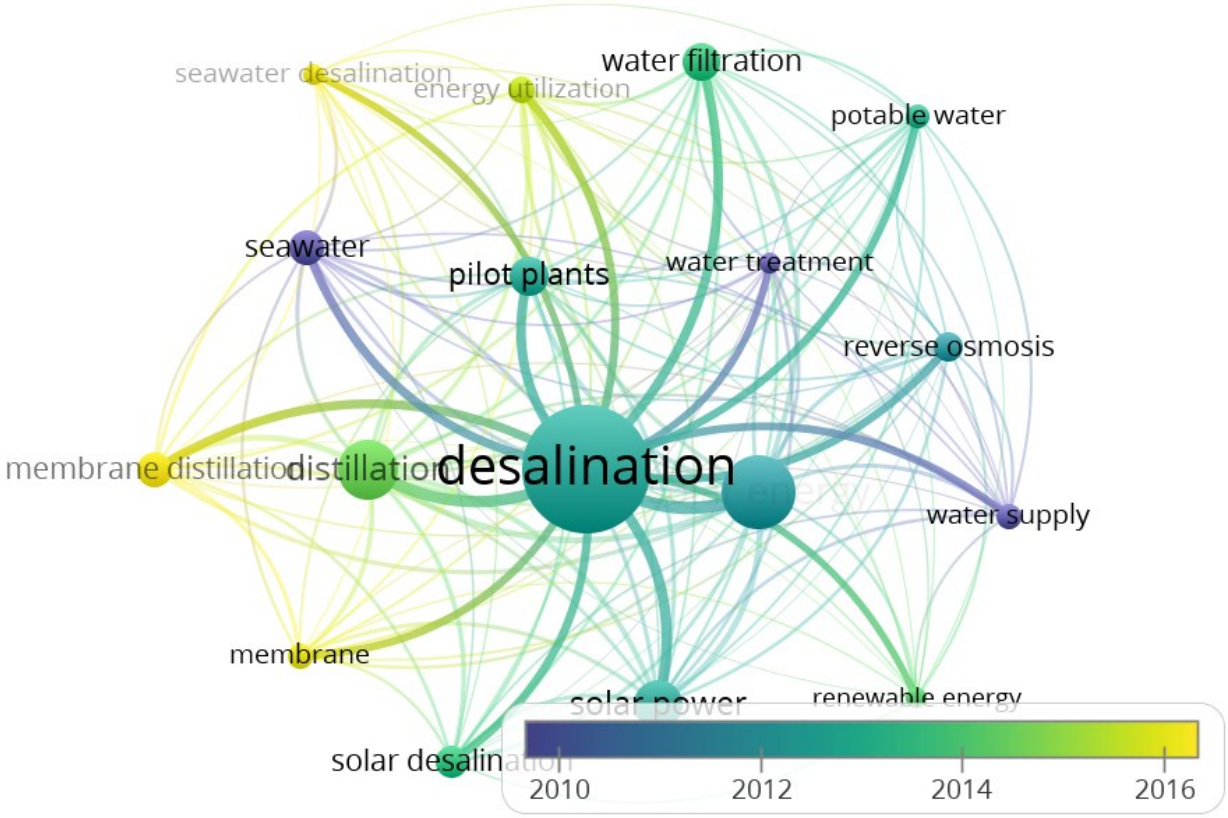
The last decade has seen a quick increase in the overexploitation and quality degradation of water resources, especially groundwater resources, in dry regions such as Iran, Saudi Arabia, and other Middle Eastern countries [1–6]. This fact highlights the need for innovative models and solutions to improve the sustainability, life, and health of the residents of such regions [5–10]. In many dry parts of the world, especially in Middle Eastern countries, the groundwater resources have undergone a great decline, not only in volume but also in quality [11–15]. Usually, the temporal and spatial distribution of the available water resources differ from what humans need for continued development and expansion [6,7]. To keep their citizens content, governments have to spend massive amounts of financial and human resources while establishing and maintaining water facilities. However, there are many difficulties and unforeseen consequences in such projects [7,8]. For example, one of the emerging water and environmental problems is the gradual transformation of groundwater resources into brackish water [8–10]. Brackish water can be desalinated using several methods, including distillation, reverse osmosis, electrodialysis, ion exchange, and freezing desalination [4]. Many arid and semi-arid regions also experience extensive sunlight exposure, which makes it economically justifiable to use solar systems and technologies for water desalination [10–15].

To justify the aforementioned contributions, some relevant studies from the last decade are reviewed here. As an example, Lashkaripour et al. [6] studied the saline and brackish groundwater resources of the city of Zahedan in Iran, while considering the possibility of the desalination of these waters [6]. In an economic analysis conducted by Banat et al. [7] on the use of small-scale solar-powered membrane distillation units, they proposed an approach that is the most sustainable and cost-effective method for water desalination for sparsely populated areas [7]. To highlight the importance of membrane processes and renewable energies and technologies for water desalination, Charcosset et al. [8] reviewed this topic, including the growing concern about the shortage of drinking water and the energy needs of these units [8].

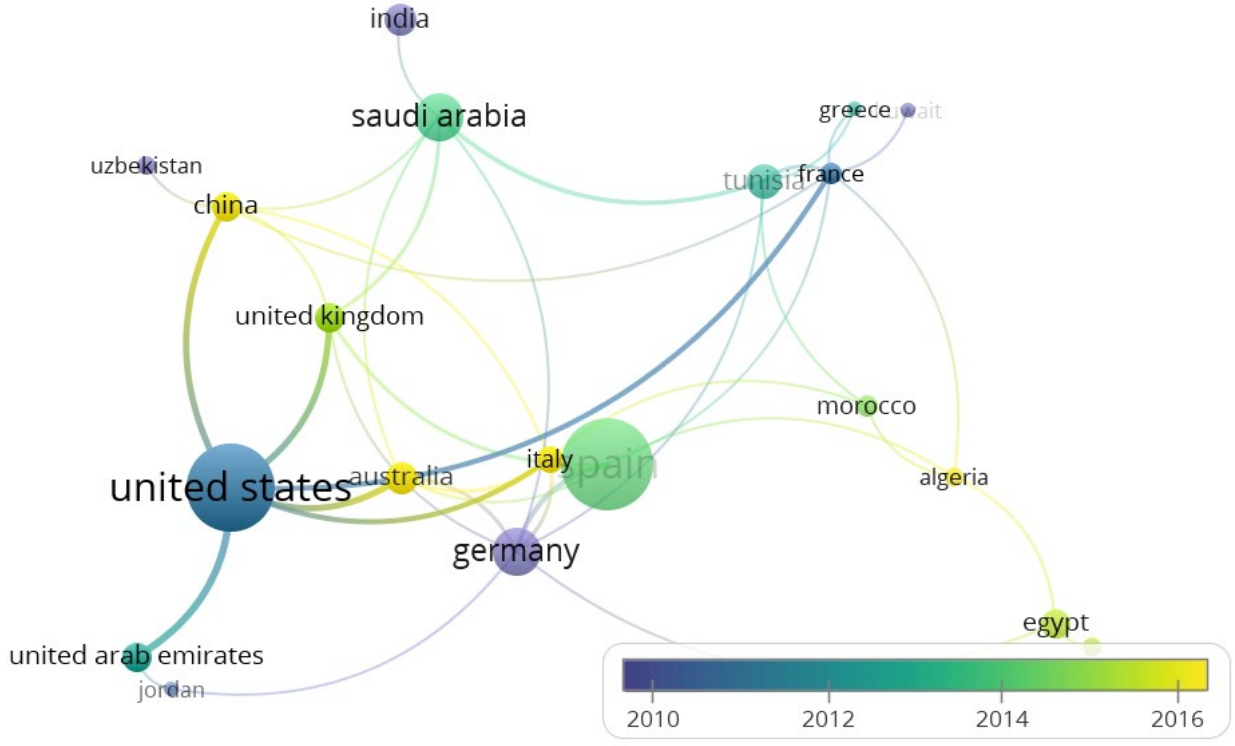
Based on the mentioned challenge, advanced technologies and processes have been developed recently [16–30]. Kabeel et al. [9] proposed a small-scale hybrid air humidification–dehumidification single-stage flashing evaporation (HDH-SSF) unit, where a comprehensive economic analysis was performed to evaluate two processes of humidification–dehumidification and water flashing evaporation [9]. Later, Li et al. [10] introduced and tested a small-scale solar-powered humidification–dehumidification (HDH) desalination unit with a new solar air heater [10]. In 2014, Amin et al. [11] analyzed the potential for solar desalination with a heat pump technology. Their main contribution was the development of a pilot solar water desalination system consisting of a direct-expansion solar-assisted heat pump (DX-SAHP) coupled to a single-effect evaporator unit [11]. In a study performed by Mofreh et al. [12] in 2015, the performance of a humidifier–dehumidifier (HD) water desalination system was investigated theoretically and experimentally through many statistical tests [12]. Taghvaei et al. [13] examined the effect of the water depth on the performance of solar desalination systems [13]. Gorjian et al. [14] studied the shortage of groundwater resources in Iran, where solar-powered water desalination technologies could be a sustainable solution to this crisis [14].

In the present research, “desalination”, “solar”, and “pilot” are considered as the main keywords [31–44]. Choi et al. [45] evaluated the performance of a solar-based desalination system in different scenarios related to the aeration intensity and energy consumption. In the investigation, the economic aspects of a solar membrane distillation pilot system are appraised with classical computation methods. Likewise, Andrés-Mañas et al. [46] developed a pilot for air gap membrane distillation modules coupled to solar systems. In the mentioned research, aspects of the module performance, including the specific thermal energy consumption and permeate flux, were appraised. In a subsequent study, Subiela-Ortín et al. [47] presented a valid guideline for the integration of renewable energy resources with reverse osmosis technology, which can be applied for desalination processes. In their study, the index of the energy recovery system was considered as a tool for the assessment of the system performance. In another novel study, Koutroulis et al. [48] presented an attractive method for the site selection of solar-based desalination facilities with the application of an online geographical information system and a focus on solar radiation.

In the next step, with the application of the VOS viewer software and Scopus databank, the “desalination”, “solar”, and “pilot” keyword are evaluated as per their keyword occurrence and country distribution, as demonstrated in Figure 1. As per the mentioned scheme (Figure 1), it can be found that the optimization of the physical specifications of the solar-based desalination system is not reflected; however, this gap will be filled by the present study. Additionally, the issue is more popular in the USA and Spain than in other countries, and Iran is considered an important region in this field.



(**a**)



(**b**)

Figure 1. Results of the bibliography analysis based on (**a**) keywords and (**b**) country contributions.

The present study aims to: (1) present a pilot-scale solar-based desalination setup for experimental applications; (2) study the use of solar technologies for the desalination of brackish waters in sparsely populated rural areas; (3) investigate the impacts of the unit orientation, water pool depth, atmospheric conditions, input salinity, and water flow continuity on the performance of the solar energy technologies; and (4) present sustainable managerial insights for the implementation of green water supply systems.

The rest of this paper is organized as follows. Section 2 presents the research methodology, where the case study, pilot units and tests, and desalination mechanism are studied. Section 3 presents comprehensive analyses and computational results from different statistical tests. Finally, Section 4 presents a discussion of the findings, while concluding this research with possible future remarks.

2. Methodology

2.1. Case Study

The Bajestan Plain is one of the driest regions in Razavi Khorasan province, located in the northeast of Iran, a country in the Middle East. This plain is located near a desert, which investigations have shown to be the source of saline waters infiltrating into the plain and making its groundwater resources brackish. As a result of this process, significant increases have been observed in the total dissolved solids (TDS) and electrical conductivity (EC) of the northern wells of this area (which, despite the brackishness, are still being used in agriculture). Considering the described trend of the salinization of the groundwater resources of the Bajestan Plain, this study was carried out based on the geography and qualitative requirements in the area of Razavi Khorasan province in Iran. The location of the case study is shown in Figure 2.

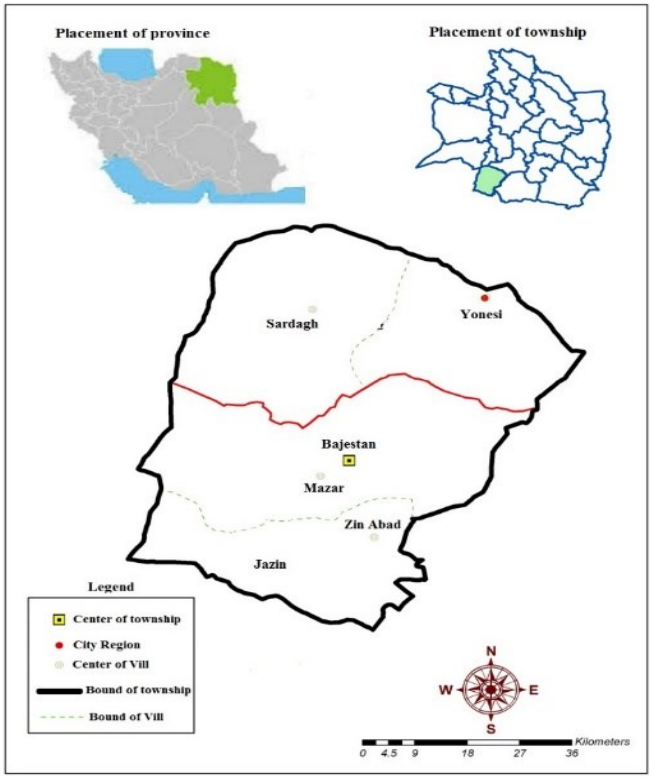


Figure 2. Geographical location of the Bajestan Plain in Razavi Khorasan province, Iran.

2.2. Pilot Units and Tests

As shown in Figure 3, the pilot scale unit includes an aluminum body, Styrofoam protector casings, a transparent glass, reflective surfaces, a droplet collector pipe, an opaque (i.e., darkened) pool floor, and a water inlet.

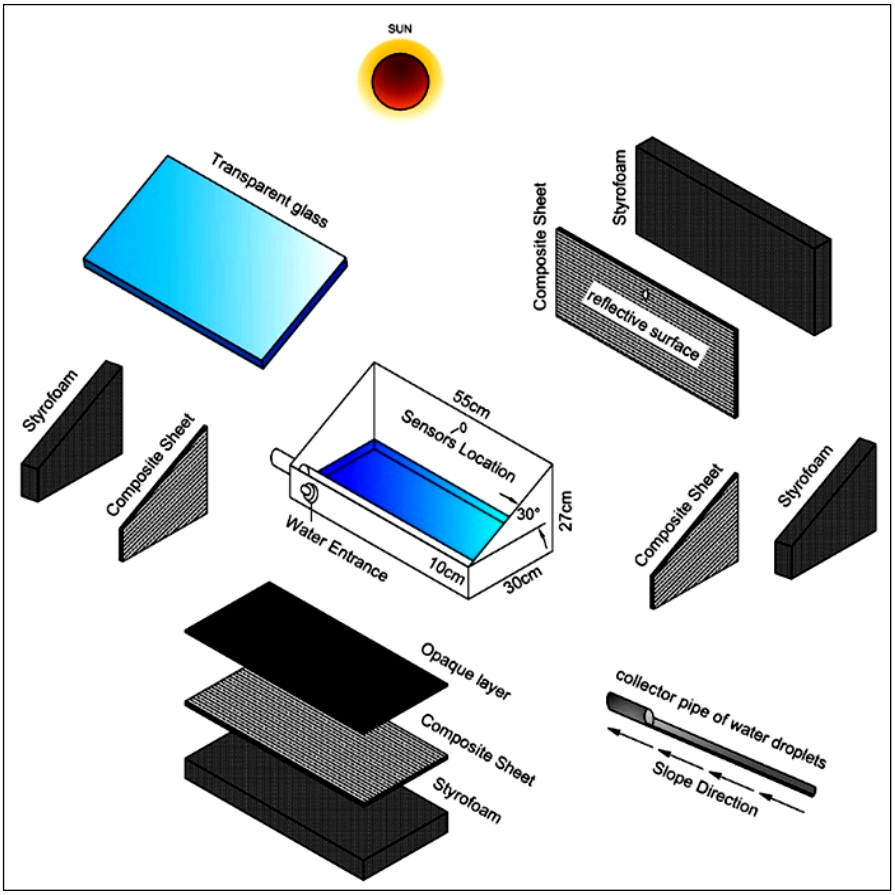


Figure 3. General schematic diagram of the solar desalination unit used in the study.

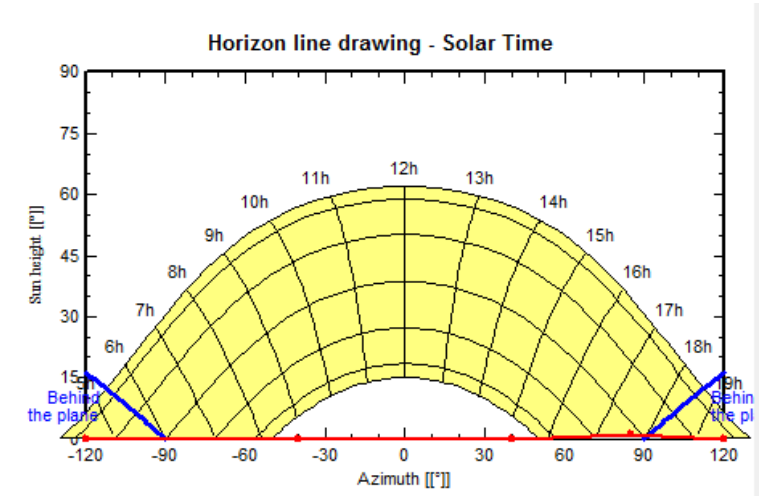
Considering the latitude, longitude, and climatic conditions of the study area, transparent glass was mounted on top of the unit at a 30-degree angle [15].

This feature was set based on the outputs of the literature review [15] for the design and execution of the pilot study. In the mentioned research, for each climate and geographical condition, there are different optimum situations against solar radiation harvesting. Therefore, based on the geographic specifications of the case study, a 30-degree angle was allocated.

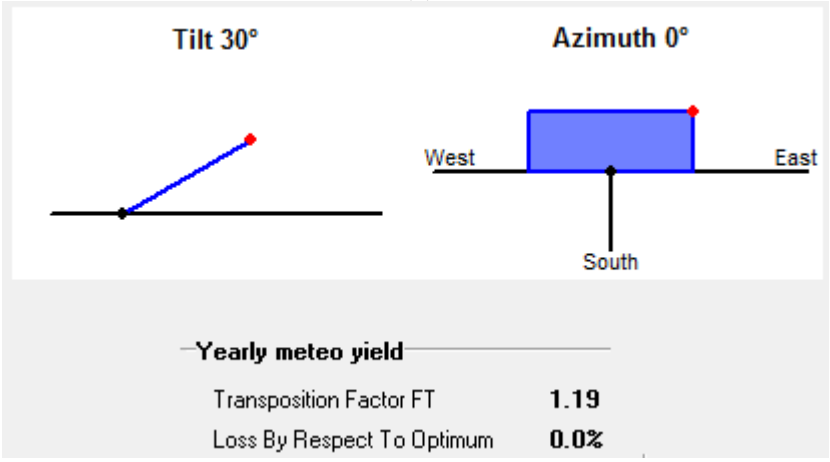
Modeling in PVSyst software has been used to determine the exact mechanism of the solar-energy-receiving potential. According to the calculations, the studied area has solar potential, as shown in Figure 4a. Meanwhile, according to Figure 4b, it can be seen that at 30 degrees, the amount of energy loss and the transposition factor index are in the most optimal possible state. This simulation result is confirmed by the case study results and the research background [15].

The pool was designed with a width of 30 cm and a length of 55 cm (1.5–2 times the width) [16], and with a maximum water depth of 10 cm [17]. While assembling the unit, thermal sensors were installed on the glass, the internal wall, and the floor of the evaporation pool, as well as the unit exterior.

To assess the water quality in the study area, groundwater resources from the Bajestan Plain were sampled and tested for their levels of salinity (NaCl), chloride, bicarbonate, nitrate, sulfate, hardness, and alkalinity, based on the standard methods used for the examination of water and wastewater [18]. Measurements of sodium, calcium, magnesium, and potassium metal ions were performed using an AA-7000 flame atomic absorption spectrophotometer (Shimadzu) located in Mashahd, Iran. After designing and assembling the solar distillation unit, the effects of the unit orientation, pool depth, atmospheric conditions, water salinity, and water flow continuity were investigated.



(**a**)



(**b**)

Figure 4. Simulation of harvested solar radiation with a 30-degree glass angle based on the PVSyst simulation: (**a**) solar radiation potential; (**b**) title of system efficiency.

2.3. Desalination Mechanism

All distillation methods were based on the simple idea that heat evaporates the water and dissolved gases in saline water, thereby separating them from the dissolved solids, such as salt. In a typical solar technology, salt water enters a shallow container that is completely insulated from outside air. This container is covered on the top by a transparent surface (glass or plastic) that lets in sunbeams of different wavelengths but prevents the reflection rays from leaving. This surface also limits the heat transfer through convection. This setup traps the thermal energy of the sunlight within the container and gradually heats and evaporates the salt water held within. Leaving its dissolved salt in the bottom of the pool, the evaporated water gathers on the transparent surface and condenses into fresh water, and then moves towards the collector mounted at the end of this surface. Thus, the device exploits the solar energy to desalinize the water through distillation. The performance of such a solar technology can be measured by its efficiency (η), which depends on the amount of distilled water and the solar radiation in the area. For the solar desalination unit used in this study, the efficiency can be obtained from Equation (1):

$$\eta = \frac{m_t h_{fg}}{AI} \tag{1}$$

where m_t is the daily freshwater production (kg), h_{fg} is the latent vaporization heat of water (J/kg), A is the area of transparent cover (m^2), and I is the total solar radiation. It should be

noted that the investigations in this study were carried out within a limited time frame, during which the values of h_{fg} and I were roughly constant. Thus, the efficiency of the unit was mostly a factor of the daily freshwater production (m_t).

3. Results and Discussion

3.1. Water Quality

The salinity and contents of the groundwater of the studied area are shown in Table 1. The salinity rate of 11,000 mg/L, chloride concentration of 6674 mg/L, and sodium concentration of 7393 mg/L are clear signs of a concerning salinization problem that limits the drinkability of the groundwater and even its use in agriculture.

Table 1. Groundwater quality parameters.

Parameter	Value	Parameter	Value
Electrical conductivity	1700	Potassium	17.2
Salinity (NaCl)	11,000	Bicarbonate	305
Sodium	7393	Nitrate	38
Chloride	6674	Sulfate	1000
Calcium	256	Hardness (based on $CaCO_3$)	1100
Magnesium	111	Alkalinity	350

All concentrations are in mg/L. Electrical conductivity is in mS/cm.

3.2. Effect of Unit Orientation

At the beginning of the tests, the researchers investigated the performance of the solar distillation unit when placed facing the northward and westward directions, but given the observed dismal efficiency, further investigations were restricted to the southward and eastward directions. The average hourly flux of water produced over a 7-day period per square meter of transparent glass by the units placed facing the east and south directions are presented in Figure 5. Note that in these tests, the weather was sunny, the pool depth was 5 cm, and the input salinity level was 11,000 mg/L.

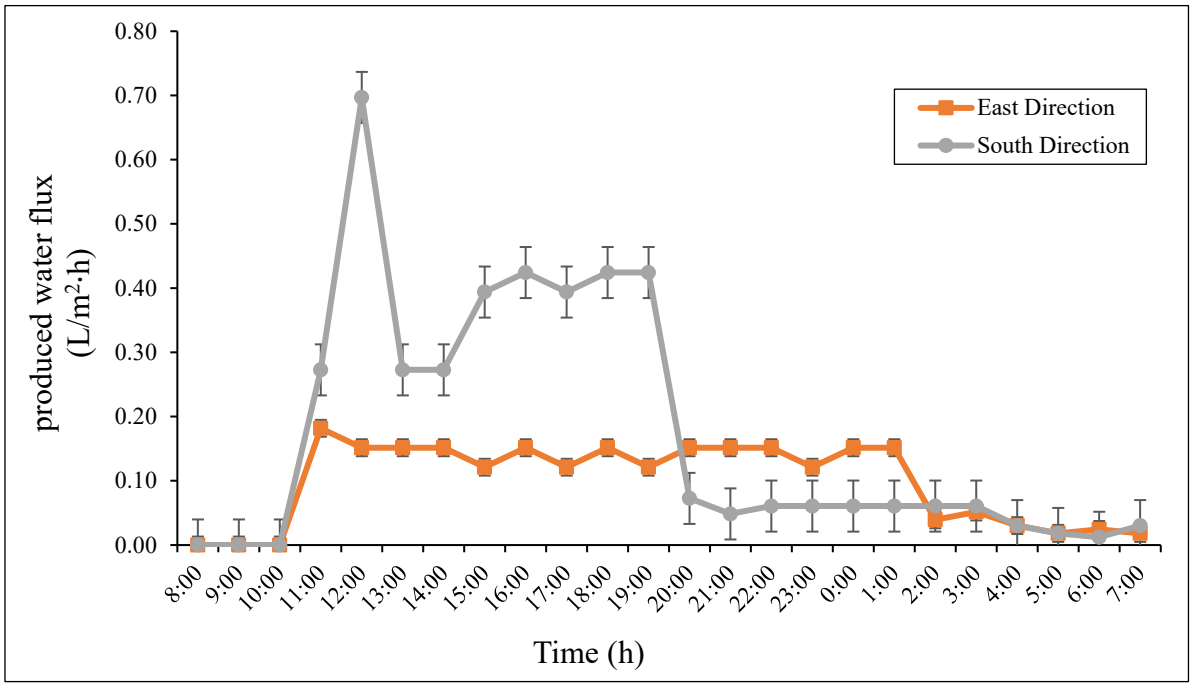


Figure 5. Effect of the unit orientation on the water production rate.

In the following, due to exact determination of the solar-based desalination system, the PVSyst simulation tool was employed. As per Figure 6, it can be understood that when the system was located at a 30-degree tilt and facing the southward direction, the solar radiation loss was equal to 0, and in the eastward direction (90-degree differential) the parameter was computed equal to be –20%. Therefore, with this simulation approach, the validity of the experimental outputs was verified.

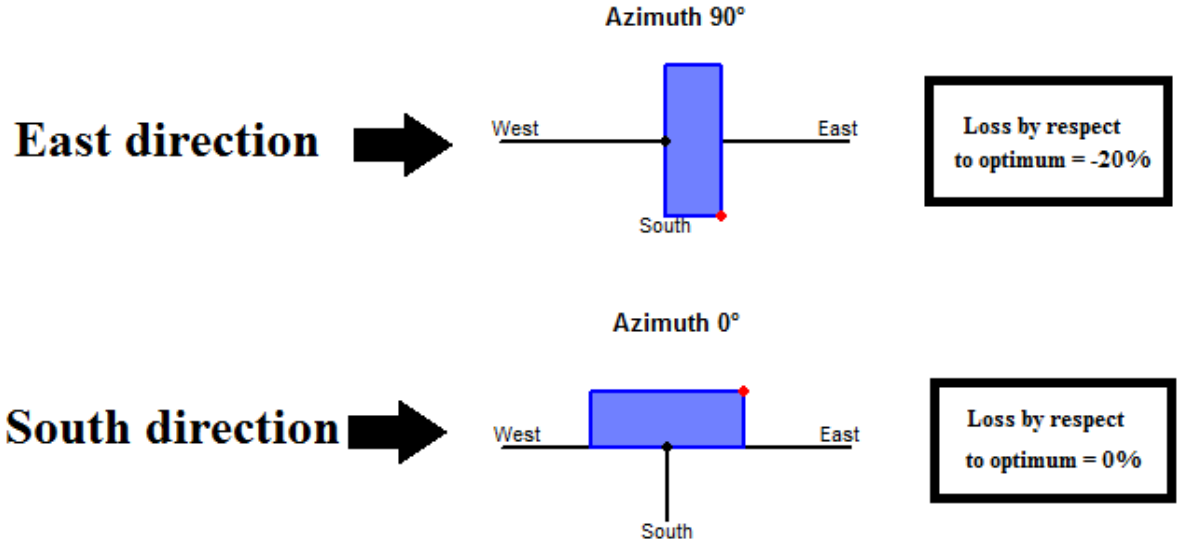


Figure 6. Simulation of the solar radiation loss with respect to the optimum in different directions.

These results show that the overall water production rate when the unit was placed facing east was 2.36 L/m^2·day, but when the unit was placed southward, this value was 4.15 L/m^2·day. Between noon and evening (11:00–19:00), the southward orientation resulted in up to 2.7 times higher water production than the eastward orientation. When the unit was placed facing east, the production started to decline from 1:00, but in the southward orientation this decline started at 19:00. The results also show that the maximum hourly water fluxes in the eastward and southward orientations, which both occurred within the 11:00–12:00 period, were 0.18 and 0.7 L/m^2·h, respectively (74% difference between the two orientations). In general, the southward placement of the unit resulted in a higher water production efficiency than the eastward placement. This was because the orientation of the solar distillation unit had a direct correlation with the intensity of the solar radiation. In a study by Velmurugan et al. [19], they used solar technology reservoir systems with fins in the basin plate to desalinate the effluent of wastewater treatment plants. It was reported that the highest efficiency was observed in fin-type steel with sand sponge, for which the daily efficiency (η) rates reached 68.3 and 69.1% in low and high solar radiation conditions, respectively [19].

Again, due to evaluation of the system performances at different times of day, a PVSyst simulation was performed, as illustrated in Figure 7. According to the mentioned Figure 7, it is clear that after 13:00, the received solar irradiance was reduced, meaning the performance of the system was abridged. However, in the experiments, there were some uncontrollable features such as noise. Meanwhile, the simulation outputs can confirm the experimental results and can help with increasing the certainty of the empirical outputs.

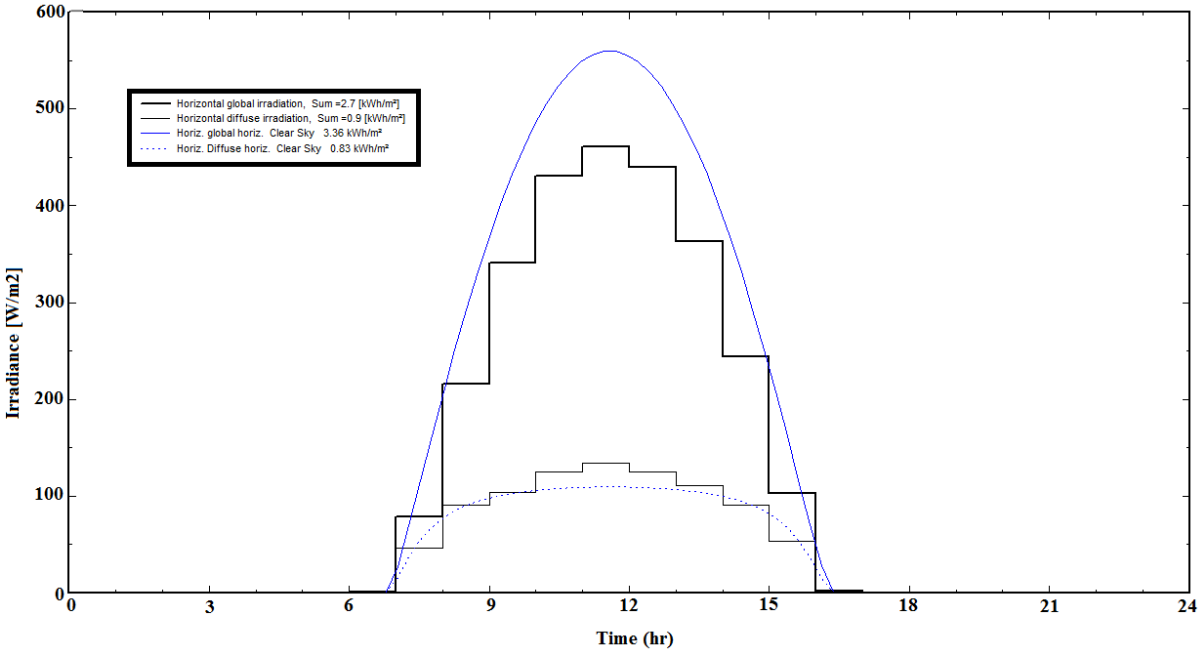


Figure 7. Solar irradiance simulations at different times of day through the PVSyst platform.

3.3. Effect of Pool Depth

The depth of water inside the evaporation pool plays a key role in how well a solar technology operates. This pool should be deep enough to hold enough water for evaporation, but not so deep that it would undermine the heating process. Given that the pool depth in the initial tests was 5 cm, the unit performance in the southward orientation was remeasured with the pool depths set to 2, 3, 4, 5, and 6 cm. Figure 8 shows the trends of freshwater production for different pool depths. For all pool depths, water production was almost zero in the first hours and reached a maximum between 12:00 and 16:00. The results also showed that the highest freshwater production rate, 5.48 L/m^2·day, was achieved with a pool depth of 3 cm. The next highest freshwater production rates were 3.24, 3.10, 3.06, and 2.94 L/m^2·day, which were achieved with the pool depths of 4, 5, 2, and 6 cm, respectively. In these tests, the highest hourly freshwater production rate was 0.73 L/m^2·h, which was achieved with a pool depth of 3 cm at 14:00.

The existing reports on the effect of the pool depth in solar technologies vary in terms of the geographic conditions of the studies. Kumar et al. [20], Kumar and Tiwari [21], Singh and Tiwari [22], Badran and Al-Tahaineh [23], and Dimri et al. [24] have reported that there is an inverse relationship between the pool depth and the efficiency of water desalination, although the reported degrees of correlation are vastly different. On the other hand, another study conducted by Tiwari et al. [25] in a different geographic condition reported a direct relationship between the pool depth and the freshwater production efficiency. According to Taghvaei et al. [13], the pool depth is a key determinant of the desalination performance that reveals its effect within the first 24 h of operation, if not the first few hours. This study reported that the depth of the water pool can also affect the inside temperature from the first day onwards. In the end, it was concluded that lower pool depths result in higher efficiency during the first two days, but from the second day onwards, using a slightly higher depth is more efficient, although making the pool too deep still reduces the efficiency [13].

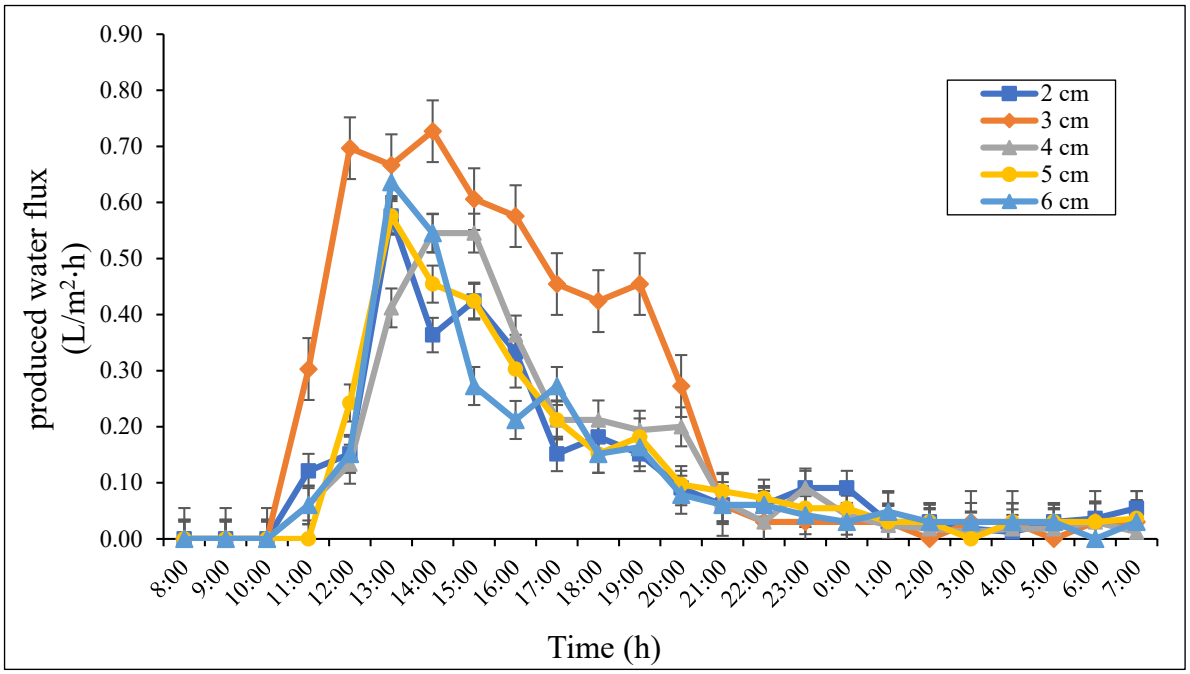


Figure 8. Effect of the pool depth on the water production rate.

3.4. Effect of Atmospheric Conditions

In this section, the performance of the southward-orientated unit with a pool depth of 3 cm in sunny and cloudy weather conditions is investigated. To increase the reliability of the gathered data, the unit was left to operate for 3 days under sunny conditions and for 3 days under cloudy conditions. The average results are illustrated in Figure 9.

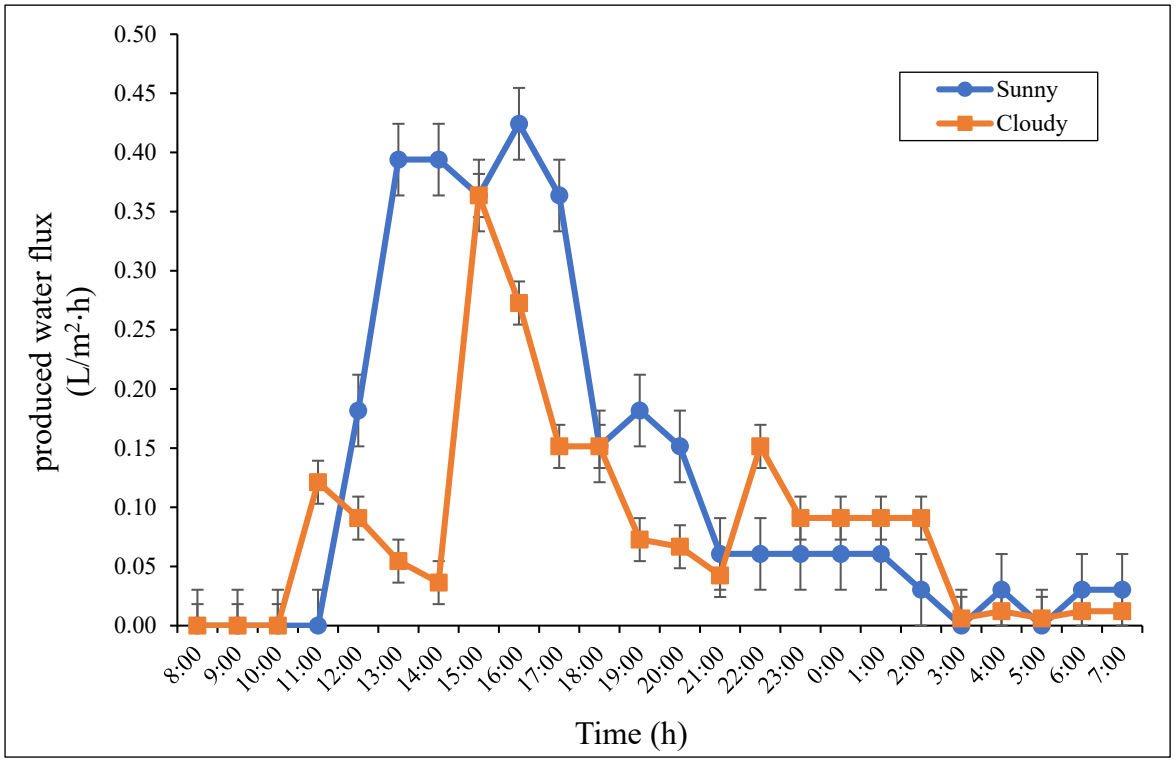


Figure 9. Effects of atmospheric conditions on the water production rate.

As the results show, the water fluxes in cloudy and sunny conditions were respectively 1.99 and 3.03 L/m^2·day. The highest hourly freshwater production rates under cloudy and sunny conditions were 0.36 and 0.42 L/m^2·h, respectively. Naturally, when a cloudy sky lasts for several hours or for the entire day, its water vapors disrupt the direct and continuous exposure of the unit and its water to solar radiation, which in turn reduces the desalination performance. By comparing the results obtained in cloudy and sunny weather conditions (Figure 9), it can be concluded that a cloudy sky, even with dispersed clouds, can significantly affect the continuity of the unit function, and over time minimizes the freshwater production rate of the unit.

3.5. Effect of Salinity

In this section, we discuss how the unit desalinates brackish water (with a salinity of 11,000 mg/L) and relatively freshwater (with a salinity of 1000 mg/L). In these tests, the unit was placed facing southward, the pool depth was 3 cm, and the weather condition was sunny. The mean freshwater production fluxes achieved with high and low salinity levels were respectively 3.27 and 3.24 L/m^2·day, which indicated that the system's performance does not significantly depend on this variable. The highest hourly freshwater production rate achieved with both high and low input salinity levels was 0.55 L/m^2·h, which was observed at 14:00–15:00 and 13:00, respectively, as shown in Figure 10.

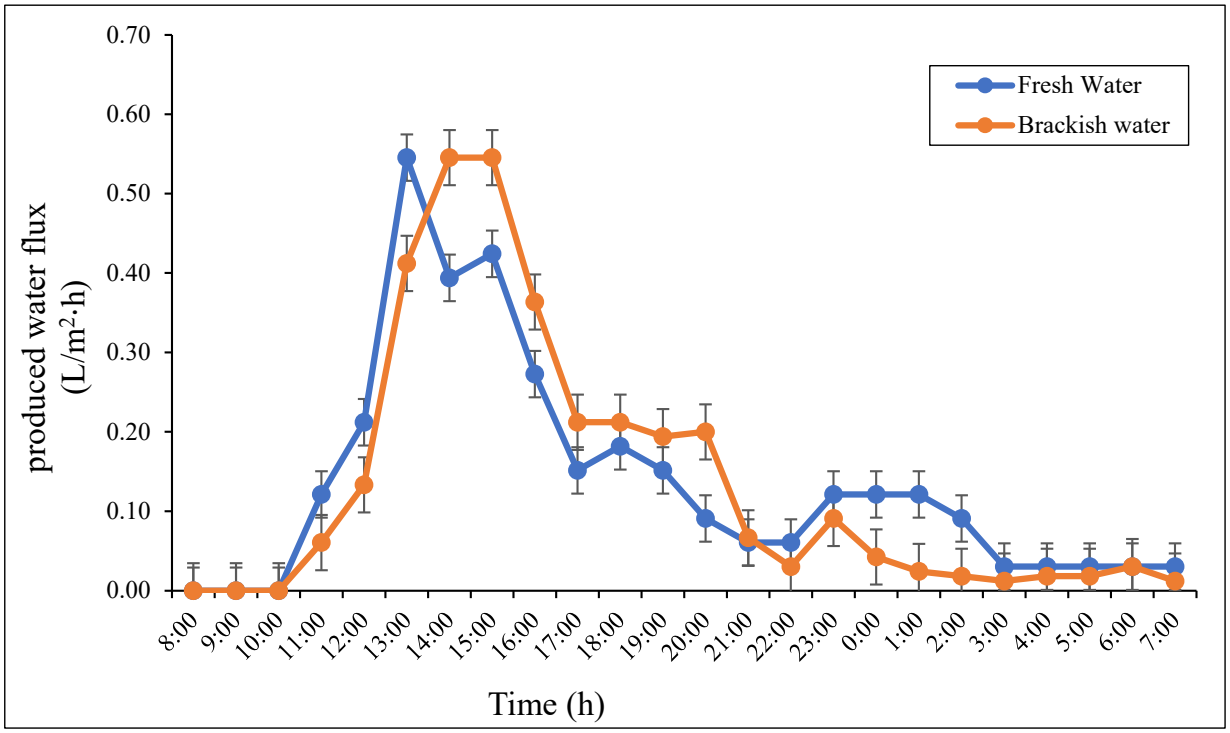


Figure 10. Effect of the salinity of the input water on the water production rate.

The results also indicate that during the midday hours, when solar radiation generates more heat in the still, the unit works slightly better with high-salinity water than with low-salinity water. In contrast, at night, the unit works slightly better with low-salinity water. This may be related to the specific heat capacity of the water, which varies with the salinity level.

3.6. Effect of Water Flow Continuity

One of the most important parameters of desalination with solar stills is whether water is introduced into the unit continuously or in batches. To investigate the effect of this variable, a test was performed to determine what happens if the unit is left to

function continuously for 5 days. This test showed a discontinuity in the hourly freshwater production rates during the first day of operation, which may have been due to temperature differences in different parts of the unit (Figure 11). Over time, however, it can be observed that an increase in the water production flux occurred, as well as an increase in continuity of the hourly production. The production fluxes recorded on the first to fifth days were respectively 3.82, 4.27, 4.36, 4.33, and 4.36 L/m^2·day. The findings show that from the third day onwards, the freshwater production reached a steady state.

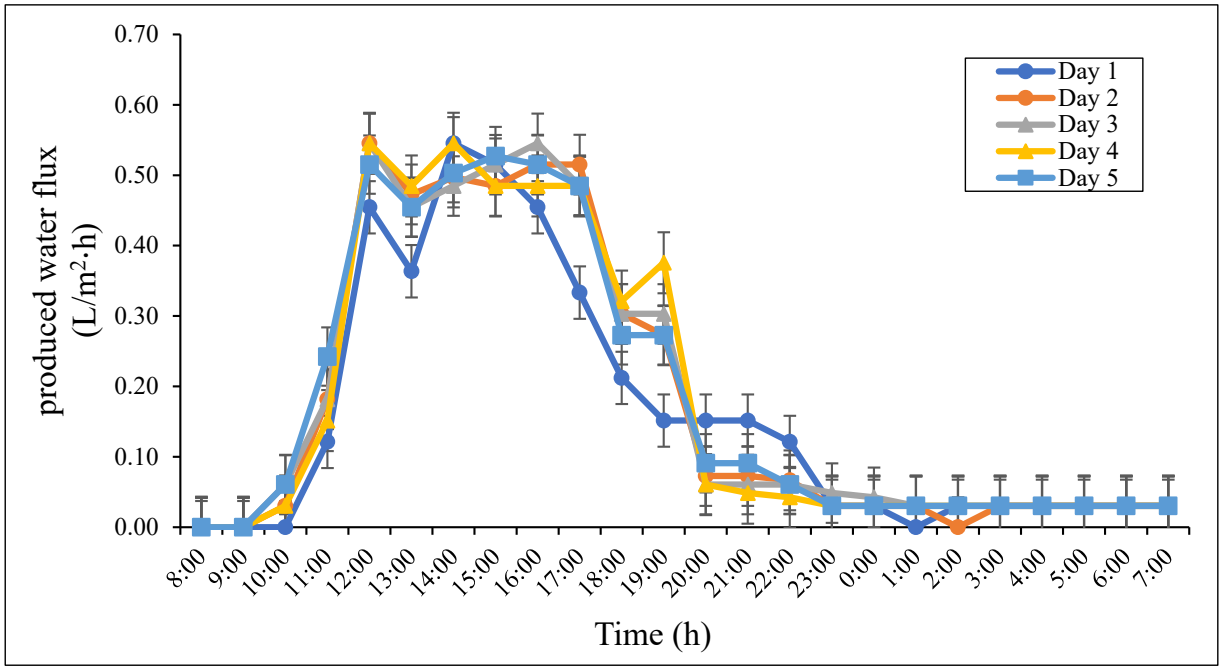


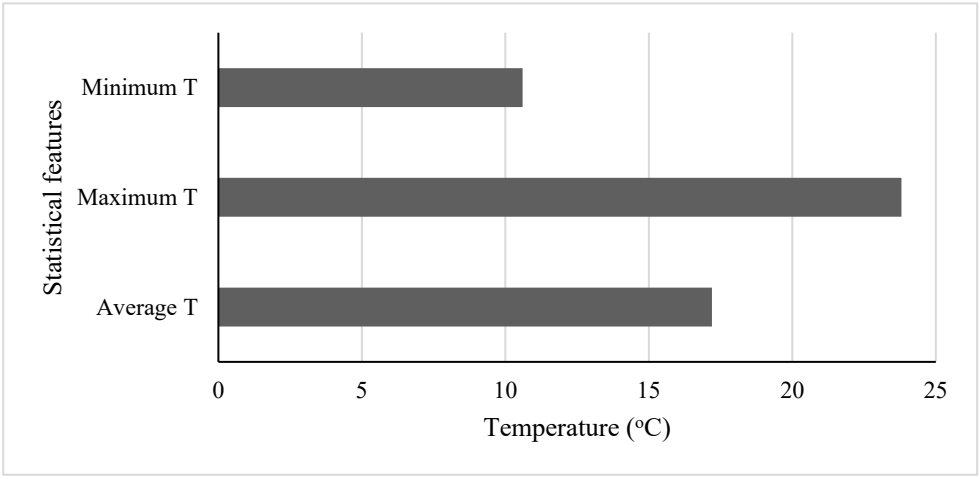
Figure 11. Effect of the flow continuity on the water production rate.

The results also indicate that when operating with continuous flow, the unit exhibited the highest water production rate during the hours of 12:00–17:00. In a study by Taghvaei et al. [13], where they examined the behavior of solar stills over periods of 1 to 10 days, it was found that with a continuous flow, the efficiency peaked on the second day and remained steady until the seventh day, but began to decline from the eighth day [13].

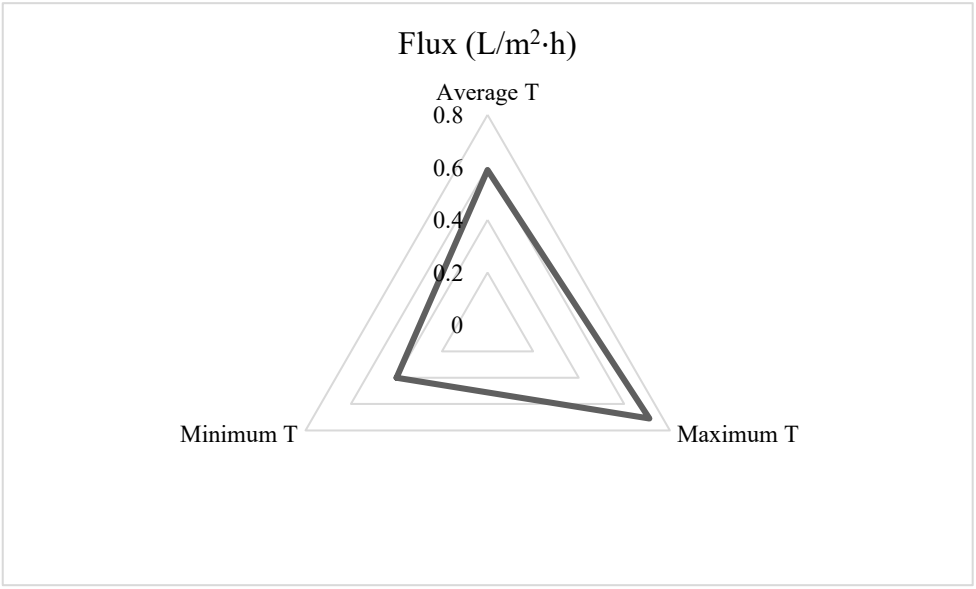
In the following phase, the pilot study was set to optimum conditions (unit orientation, water pool depth, atmospheric conditions, and water flow continuity) and the effects of the different temperatures (maximum, minimum and average temperatures) were appraised. The different assessed temperatures and output fluxes under optimum conditions are demonstrated in Figure 12a,b.

According to the outputs (Figure 12), it is clear that in the hottest seasons, the flux was 43% greater than in the coldest season. Therefore, the climate features influence the performance of the solar-based desalination process. However, this factor cannot be controlled by operators and it should be predicted for water resource management.

As per the data achieved through the optimization process, it was found that the maximum water produced in the high performance conditions was equal to 0.71–0.75 L/m^2·h and the demonstrated tolerance was related to the uncertainty of the experimental outputs and errors. The optimum conditions were experimented with and three produced water rates of 0.71, 0.74, and 0.75 L/m^2·h were recorded.



(**a**)



(**b**)

Figure 12. Effect of (**a**) the atmospheric temperature on the (**b**) water production rate.

3.7. Statistical Analysis and Water Quality Assessment

The analysis of variance (ANOVA) was used to analyze the impacts of the evaluated parameters on the unit performance. The results of this analysis are presented in Table 2. It should be noted that the ANOVA for each parameter was performed with the mean water production flux of the corresponding test used as the target function.

Table 2. ANOVA of the parameters influencing the water production efficiency.

Parameter	Mean Square	F Value	*p*-Value
Pool depth	10,554.710	743.928	<0.0001
Flow continuity	283.805	20.003	0.0004
Unit orientation	73.296	5.166	0.0382
Weather condition	21.186	1.493	0.2406
Input salinity	15.397	0.956	0.6317

As is clear from the ANOVA analysis, all factors have their own special role, and these indicators definitely have significant effects on each other; however, in terms of

nature, they are completely independent of each other. On the other hand, these parameters can have a significant impact on the produced water flux with a small change (Figures 8–11). As a result, they are completely independent of each other and are known as non-dependent components.

The results of the statistical analysis show that the pool depth (p-value < 0.0001) has the strongest impact and the input salinity (p-value = 0.6317) has the weakest impact on the target function; that is, the amount of water produced due to desalination. After the pool depth, the parameters with the next greatest effect on the target function are the flow continuity and unit orientation. Next, the quality of the water obtained from the unit with optimal configurations and under optimal conditions (southward orientation, pool depth of 3 cm, sunny weather, salinity of 11,000 mg/L, continuous flow) was measured. The results of this measurement are presented in Table 3.

Table 3. Quality parameters of the water produced by the solar distillation unit.

Parameter	Freshwater (Output)	Parameter	Freshwater (Output)
Electrical conductivity	270	Magnesium	5.5
Salinity (NaCl)	250	Potassium	2.3
Sodium	67.1	Sulfate	52.8
Chloride	42.95	Nitrate	7.1
Calcium	14	Hardness (based on $CaCO_3$)	57.5

All concentrations are in mg/L. Electrical conductivity is in mS/cm.

A comparison of the quality of the produced freshwater with the raw water shows that the unit had 99.3%, 81.3%, and 94.7% efficiency in removing chloride, nitrate, and sulfate anions, respectively; and 94.5%, 95%, and 99% efficiency in removing calcium, magnesium, and sodium cations, respectively. The results indicate that the unit managed to make a 99.7% reduction in salinity and 94.7% reduction in hardness. It should be noted that unlike other methods of water desalination such as ultrafiltration and nano-filtration, which require consuming massive amounts of energy during the desalination process, solar stills are power-independent systems that could be a sustainable solution for producing freshwater for remote, rural, and sparsely populated areas. In a study by Jacobson et al. [26] in 2011, where they used microbial desalination cells (MDCs) to remove salt contaminants from water, it was found that MDC systems are able to remove NaCl compounds with HRT for 4 days, with an efficacy rate of more than 99%, and that in addition to removing salt contaminants, this method can generate electricity through the electrochemical reactions [26]. It should, however, be noted that since this desalination process results from the microbial activity, it is much more complex than solar distillation. Additionally, we note that the present study used flat solar collectors to increase the efficiency of the distillation process, a method that was also approved by Voropoulos et al. [27] in 2004.

Finally, the solar distillation unit must be compared with other methods of desalination, such as solar humidification–dehumidification, solar chimney, solar reverse osmosis, and solar electrodialysis. Simple solar stills, like the one used in this study, have a very high efficiency in terms of their quality but are not efficient in quantitative terms [28]. An economic analysis showed that humidification–dehumidification systems are much more suitable for smaller quantities, but optimizing the operation for high quantities requires stacking a high number of stages, which greatly increases the cost of the unit. As such, this system needs a relatively high cross-sectional area for condensers and humidifiers, and even for desalination at lower quantities [29,30]. Solar chimneys are neither suitable nor economical for small-scale operations. In fact, the simultaneous production of power and freshwater from a single solar chimney, although attractive, can only be achieved with the availability of large unused lands or coastal areas [31]. Photovoltaic (PV)-powered reverse osmosis desalination systems are in use at both small and industrial scales. However,

the PV-powered reverse osmosis desalination process is generally more suitable for small units rather than medium or large units. Additionally, the energy consumption of such units and the price of the produced water strongly depend on the membrane arrangement, system efficiency, and salinity of the feed water. The system's energy consumption and the price of the produced water can be reduced by using high-efficiency panels, new solar tracking systems, and new long-lasting membranes. Although solar panel prices are projected to decline, the main problem in such systems is the massive size of the initial investment required [32–34]. Solar electrodialysis systems have several advantages over reverse osmosis units, but are not very suitable for highly saline waters (such as sea water) and are best used for brackish waters or waters with a moderate salt concentration [35,36]. Overall, given the economic viability of solar stills and their simplicity, which makes them easy to build, repair, and operate without expert knowledge, the solar distillation method is the best desalination method for the sparsely populated rural areas of Iran in their present condition.

As a conclusion, a comparison of different desalination methods is demonstrated in Figure 13. Based on the declared scheme, it can be seen that each method has specific advantages and disadvantages, which can be utilized in different climatic, economic, technical, and managerial conditions [26–34]. However, it can be found that the created system in the present study can be applied in low-population communities and as rural infrastructure. This is because in addition to the low investment and operational costs, the consumed energy of the system is not considerable and its efficiency is acceptable.

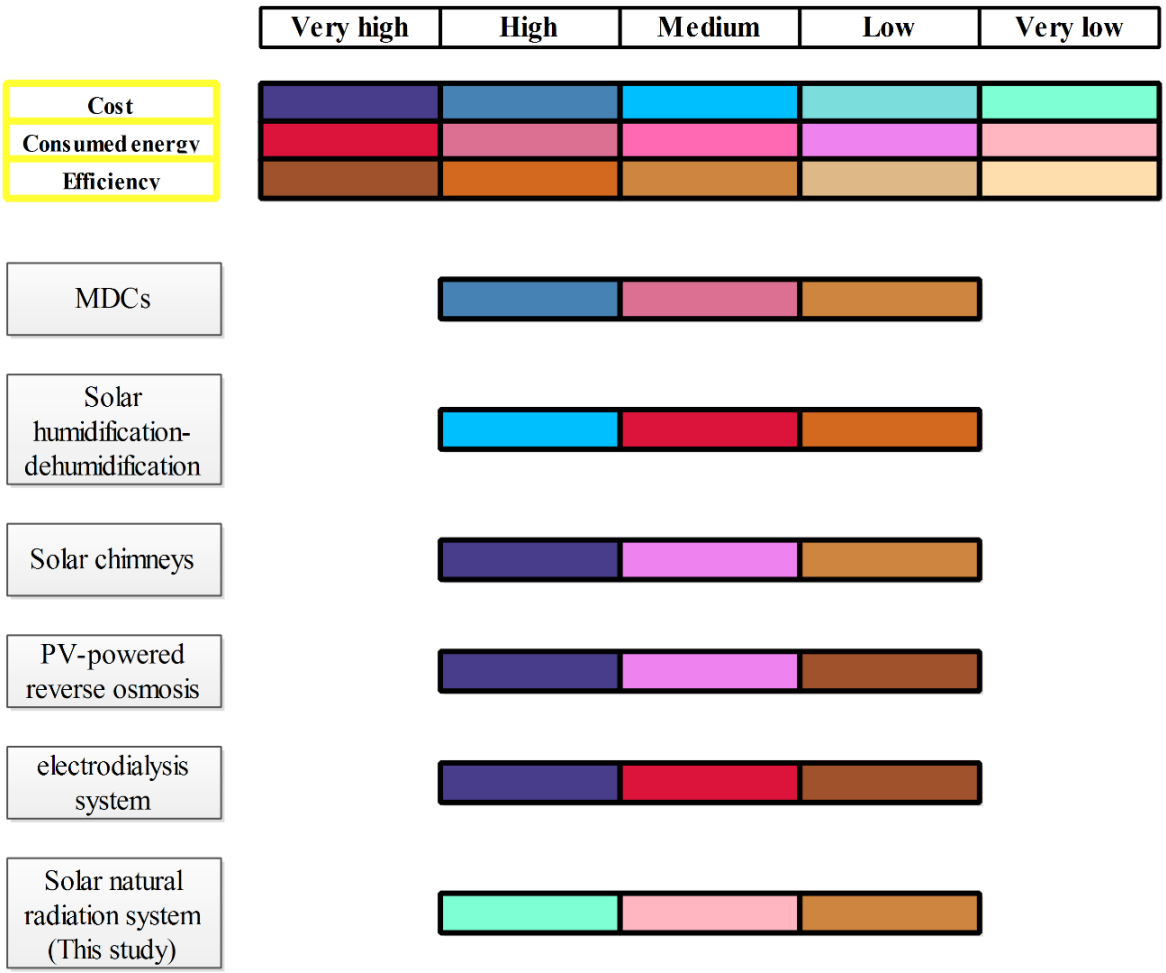


Figure 13. Schematic plan of the different desalination technologies' advantages and disadvantages [26–34].

In this part of the study, a set of management tips are presented in order to implement a stable structure, with the aim of achieving sustainable development goals [37–42]. According to the calculations, with a per capita consumption rate of 250 L per day (for example, Iran), for a family of four, about 60 square meters should be provided for the current research system. In this regard, according to the pilot costs, a cost equivalent to 12k USD can be considered as the investment cost for the mentioned family. Meanwhile, 10% of this monthly amount should be considered as the amortization and maintenance cost. However, due to the low investment and operation costs, the mentioned method can be considered as a bridge in the direction of implementing the public water supply plan [43–48] and increasing accessibility in dry areas, which could lead to the realization of sustainable development goals [49–56].

4. Conclusions and Recommendations

In recent decades, many Middle Eastern countries have wrestled with the problem of the qualitative and quantitative degradation of their water resources. In arid and semi-arid regions, the declining quantity of water resources, especially groundwater, has led to the concentration of their dissolved compounds, which is reflected in the increasing salinity of the groundwater resources. The existing technologies provide a range of simple and complex solutions for desalinating brackish waters. However, the method of desalination should be chosen based on the climatic and environmental conditions of the area of interest in the project. In Middle Eastern countries such as Iran, which have access to rarely interrupted intense sunlight, desalination through solar distillation is becoming increasingly popular.

In this study, the researchers built a pilot solar distillation unit and investigated the operation conditions in Razavi Khorasan province in Iran. In this investigation, the effects of the unit orientation, pool depth, atmospheric conditions, salinity, and flow continuity on the unit performance were evaluated and the configurations and conditions that yield the best results were determined. The results showed that the optimal operating conditions that result in the best efficiency are to place the unit facing south, maintain the pool depth at 3 cm, and let the unit operate with a continuous flow for at least 3 days under sunny weather conditions. Under such conditions, the unit managed to reduce the salinity levels from 11,000 mg/L to 250 mg/L. It was found that the water production efficiency is 76% higher when the unit is oriented southward than when it has an eastward orientation. The production efficiency achieved with the optimal pool depth, i.e., 3 cm, was 69, 76, 79, and 85% higher than the efficiency levels achieved with the depths of 4, 5, 2, and 6 cm, respectively. The results also showed that water production efficiency did not significantly vary with the input salinity level. Finally, the ANOVA results showed that the unit efficiency was most strongly influenced by the pool depth (p-value < 0.0001) and to a lesser extent by the flow continuity (p-value = 0.0004). From a qualitative perspective, the unit managed to produce water of satisfactory quality, with a 99.7% reduced salinity level.

Although in this research we performed a lot of statistical analyses for the possibility of desalination of brackish groundwater reserves under the threat of saltwater intrusion in the southern areas of Razavi Khorasan province in Iran, there are some opportunities for future studies. First of all, the geographic information system and statistical description methods can improve the efficiency of the outcomes [43]. The parameters of the model can be estimated using metaheuristics and machine learning methods [44]. Finally, many other factors to improve the water systems while removing mechanical errors can be considered in future studies [45–56].

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