Solar Desalination Greenhouse: A Comprehensive Study of Prototype Design and Performance Analysis

Igor Luketina*[1]; Everaldo Attard[2]; Helmut Schabschneider[1]; Tiziana Centofanti[1,3]

[1]alchemia-nova GmbH research institute; igor.luketina@alchemia-nova.net; helmut.schabschneider@alchemia-nova.net

[2] University of Malta, Institute of Earth Systems, Division of Rural Sciences and Food Systems; everaldo.attard@um.edu.mt

[3]Central European University; centofantit@ceu.edu; tiziana.centofanti@alchemia-nova.net;

* Correspondence: igor.luketina@alchemia-nova.net; Tel.: +43 681 1060 9008

Abstract Due to the ever-increasing impacts of climate change on food production, and increase in world population, food security is at stake. Resilient food production systems and sustainable water management practices are crucial in arid areas. The fields of saline agriculture and desalination are effective approaches to these challenges.

This book chapter offers a comprehensive review of the literature and a detailed description of a SDGH prototype design. It includes an in-depth analysis of sensor data and provides valuable insights into the growth of halophytes. The performance of Salicornia *(Salicornia europaea* L.), Purslane (Portulaca oleracea L.) and Sea Fennel (*Crithmum maritimum* L.) were compared under high dew point conditions in a 1,8 x 1,8 m greenhouse where temperature and humidity were monitored allowing insights in the humidification-dehumidification process. For a continuous period of 66 days, measurements were taken of the evapotranspiration rates and the salinity levels in the irrigation water for each species. Salicornia experienced a significant increase in the salinity of the irrigation water from 30,0 to 84,1 mS/cm within 42 days but still thrived and showed great evapotranspiration rates of up to 3,17 L/day compared to Purslane with 1,04 L/day and Sea Fennel with 1,39 L/day. High humidity was favorable for the condensation processes, but the elevated humidity levels are potentially more stressful for the plants with temperatures of more than 50°C and dew points up to 40°C. Over one growth period, 9,5 kg f.w. of halophytes was harvested, with Salicornia showing the highest yield with 5,3 kg f.w. and the highest evapotranspiration rate in this experiment. Purslane and Sea Fennel biomass at harvest was 3,2 kg f.w. and 0,9 kg f.w. respectively. A total of 191 L was condensed with a recovery rate of 54% which is well in the range of reverse osmosis (Indika, 2021).

Despite its potential, the SDGH technology is still in its early stages of development and there is a need for further research to understand its benefits and limitations fully. The results and insights presented in this book chapter will be useful for advancing the field of water desalination and resilient agriculture in arid regions.

Keywords – Humidification-Dehumidification (HDH); Solar Desalination; Greenhouse Technology; Evapotranspiration; Halophytes; Vertical Farming.

1 Introduction

Salinisation of both groundwater and irrigation water is recognized as a primary contributor to soil degradation and a decrease in crop yield. The problem stems from the infiltration of saltwater in aquifers, a phenomenon driven by both natural processes and human activities (Essink, 2001). The situation is further exacerbated by the escalating effects of climate change and desertification (Casarano et al., 2019). The majority of the conventional crops grown globally are glycophytes, which can tolerate salt concentrations not exceeding 2.8 mS/cm (~28 mM) (Shahbaz et al., 2012). Given the escalating scarcity of freshwater for the irrigation of glycophytes, and the salinization of soil and groundwater, the cultivation of alternative, salt-tolerant crops could potentially address some of the challenges associated with salinization.

Halophytes are plants that tolerate high salt concentrations in the surrounding medium, which may exceed 20 mS/cm (~200 mM) (Flowers and Colmer, 2008). In traditional agriculture, these plants have been grown in various settings, such as fields, greenhouses, saline hydroponic systems, and constructed wetlands (Ventura and Sagi, 2013). The harvested halophytic crops have found applications in medicine, cooking, energy production, and as components of animal feed, among other uses (Kong et al., 2014; Hulkko et al., 2022). Over the past three decades, halophytes have been increasingly recognized as potential solutions to issues such as food security, freshwater shortage, soil salinisation, and the need for more diverse and healthier diets (Centofanti and Bañuelos, 2015). Despite the environmental benefits of saline agriculture and the use of halophytes for food and fodder, it is crucial to develop effective farming techniques for sustainably growing crops irrigated with saline water. To meet the food requirements of a growing population, food production must increase by as much as 70% by 2050 (Falkenmark et al., 2009; De Wrachien et al., 2021). This increase presents a challenge due to the primary issues we face today:

scarcity of land and water. Therefore, solutions that allow for the use of lower quality water (such as saline water) in the production of a variety of nutritious crops, while using less land, are highly desirable. In this paper, we explore the potential of the Solar Desalination Greenhouse (SDGH), an innovative system that integrates the use of both halophytic and glycophytic crops. This integrated system aims to optimize crop yield through saline water regeneration. The SDGH, a cutting-edge technology, merges the principles of greenhouse design with the humidification-dehumidification process to desalinate saltwater and grow halophytes in vertical farming systems. The evaporation of saline water, enhanced by the microclimate within the greenhouse, enables the SDGH to produce fresh water. In this setup, halophytes play a crucial role by desalinating incoming brackish water. They absorb the saline water, accumulate salts within their tissues, and release water back into the environment through evapotranspiration. The evapotranspired water is then condensed via active and passive condensation systems, rendering fresh water, which is available and suitable for growing glycophytic crops. Traditional desalination methods are costly and energy-intensive. The SDGH, a renewable energy-based solution, has emerged as a sustainable alternative in recent research (Goosen at al., 2003; Chaibi and Jilar, 2005; Shekarchi et al., 2019). SDGH technology, which relies on solar energy and uses drought and salinity-tolerant crops, offers a sustainable, low-cost, and energy-efficient solution for regenerative agriculture (Bourouni et al., 2010). It is an alternative to conventional agriculture in resource-scarce regions, and its scalability allows integration into existing greenhouses.

This study aims to examine the effectiveness of halophytes in evapotranspiration leading to humidification, and the performance of both active and passive condensation systems in the dehumidification process. It seeks to underscore the advantages of employing halophytes in the SDGH and the potential applicability of this technology in regions grappling with water scarcity. Furthermore, this chapter intends to elucidate the challenges encountered in SDGH implementation and the prospects for future research. This chapter is a valuable resource for scientists and researchers exploring sustainable solutions for water desalination and agriculture in arid regions (Glenn et al., 1999).

2 Methodology

The SDGH prototype was installed outdoors in Vienna, Austria, between May 12 and July 19, 2022. The prototype focuses on the halophytic part of the SDGH and the condensation cycle, thus glycophytic plants were not included (Figure 1). It was constructed using lightweight aluminum profiles, forming a cube measuring 176x176x176 cm with a total floor area of 3 square meters. A two-sided roof with a 30° tilt angle covered the structure, and UV stabilized polyethylene foil was used as shell. To simulate climate conditions typical of arid and water scarce regions where the implementation of SDGHs is most promising, such as Sub Saharan Africa, the greenhouse was equipped with artificial lighting, increasing irradiation during dawn and dusk and extending daylight to 14 hours. Five temperature and relative humidity sensors were strategically placed as seen in Figure 2 within the SDGH and connected to a programmable logic controller (PLC). These sensors recorded data every 15 minutes, providing insights into microclimate conditions within the prototype. A household fan was installed within the SDGH and was responsible for promoting air circulation throughout the greenhouse. Adequate air circulation was vital for maintaining uniform environmental conditions and distributing moisture within the space.

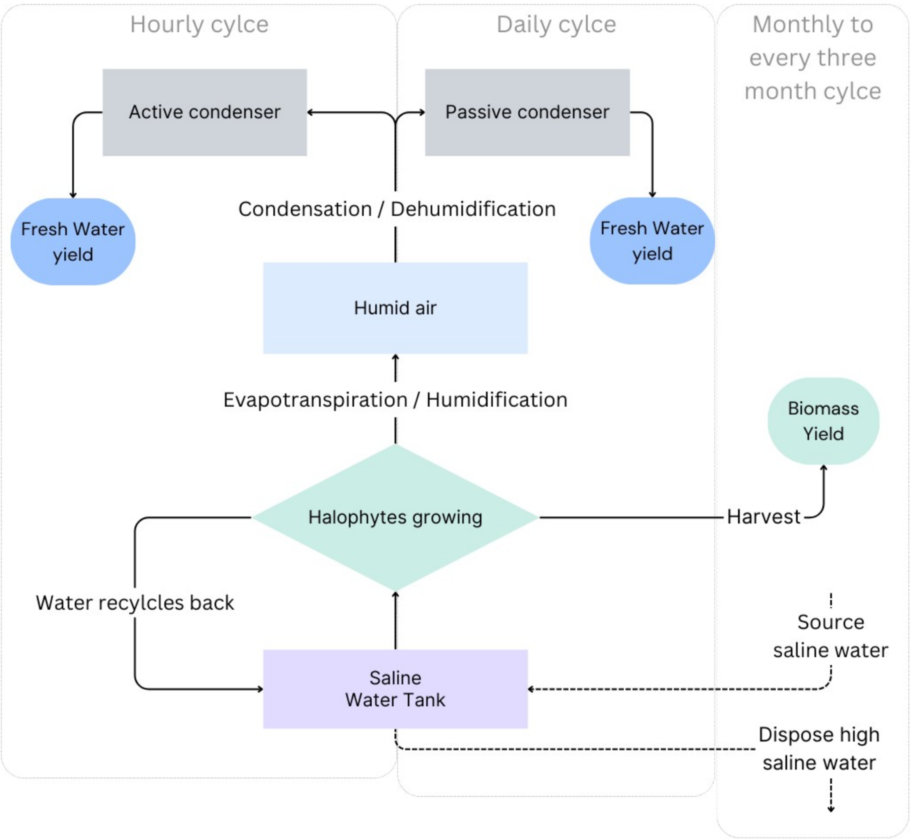


Figure 1. SDGH Humidification-Dehumidification processes and flows

Vertical Structure and Halophytes

Halophytes were grown inside the SDGH on vertical tube systems made of 160mm PVC pipes, featuring rectangular openings for plant growth on top (Fig. 2). These tubes were horizontal but arranged in a vertical farming configuration, slightly angled so almost vertical (80° to ground) to allow space for plant growth and better light exposure. A closed-loop irrigation system was implemented, where an electrical submerged pump circulated saline water from a container to the uppermost tube. The saline water then flowed through each tube, maintaining a consistent water level of approximately one-third of each tube's diameter. The tubes were filled with a mixture of expanded clay and zeolite to provide an optimal growing environment for plant root systems. Three halophyte species were cultivated in a rack of three tubes per species: *Salicornia europaea* L., *Portulaca oleracea* L., and *Crithmum maritimum* L. with 8 seedlings per tube. The seedlings of *C. maritimum* and *P. oleracea* were purchased from Alsagarden (France), while seeds also from Alsagarden (France) of *S. europaea* were cultivated in a greenhouse for 60 days and watered with tap water before being transplanted to the tubes. Upon reaching approximately 8 cm in size, the seedlings began to be irrigated with salt water. The irrigation cycle was set at 15/45 minutes on/off, with pumps running at half of their rated voltage. The irrigation saline water had a salt content of 15 mS/cm. The saline water was prepared manually by adding table salt (NaCl) and measured with a EC meter.

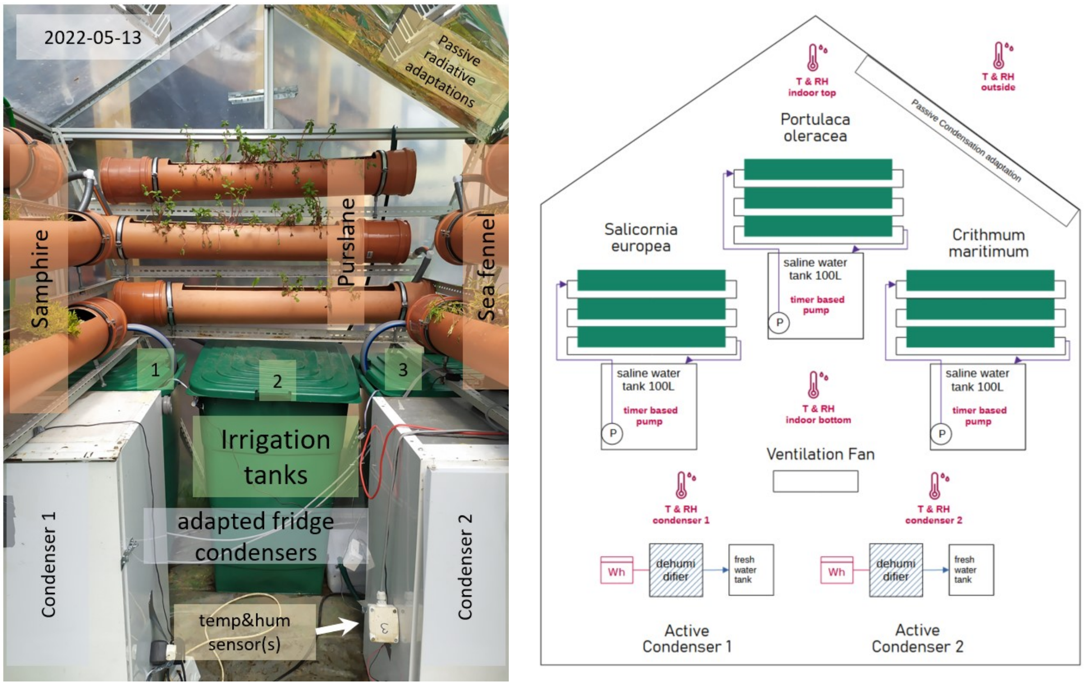


Figure 2. SDGH Setup with interior equipment and adaptations

Active condensation

Active condensation techniques like the ground heat exchanger (Aydin et al., 2015) have been investigated. However, they have not been implemented to circumvent high costs and harmful soil practices associated with the necessary vertical boreholes. The SDGH, instead, features two active condensers, each equipped with a thermostat set just above freezing to optimize the condensation process. These units, essentially repurposed refrigerators, were designed for cost-effectiveness and efficient condensation. Air is drawn into these units by PC fans and initially cooled via aluminum pipes. The air then moves to the cooler end of the heat pump, where it condenses into droplets that are expelled through a pipe. The refrigerators, equipped with cooling pipes on the rear, enhance the vapor-compression cycle. They are primarily designed for high condensation with low input, making them crucial to the SDGH's functionality, especially in remote areas with limited access to specialized equipment. Temperature control ensures efficient operation of the cooling elements within the refrigerator, allowing for rapid air moisture condensation. The units also feature 24-volt PC fans, strategically placed to promote airflow. This airflow maintained consistent temperatures conducive for condensation and ensured effective formation of condensate droplets on the cooling surfaces.

Passive condensation

The prototype developed in this study employed various passive condensation collection techniques. These include passive radiative cooling with an infrared (IR) coating, passive condensation without any coating, passive condensation with a transparent OPUR coating, and a combination of OPUR and IR coatings.

To facilitate a comprehensive comparative analysis of the efficiency and feasibility of the condensation methods used in this study, an area of the east roof of the SDGH was strategically divided into four separate sections, with each section serving as a dedicated testing area. The contemporaneous application of four condensation methods on the same SDGH allowed a comparison of the effectiveness of each passive condensation technique in real-world conditions, providing valuable insights into their potential for enhancing water recovery within the SDGH.

The four condensation methods are described below:

No Coating (1st section): This section of the east roof served as a control group with no special coating applied. This provided a baseline for assessing passive condensation under standard conditions.

Subsequent sections will discuss the application of passive radiative cooling techniques, which involve the use of specialized materials and IR coatings on the surface of the greenhouse's roof. These materials are designed to reflect thermal radiation at specific wavelengths, allowing radiation of heat away from the surface and into the adjacent cold air (Maestre-Valero et al., 2012). As a result, the SDGH roof surface cools down, creating temperature differentials that encourage condensation to form on the cooled surface.

Transparent OPUR Coating (2nd section): This section was coated with a transparent OPUR coating which is a mixture of 16% mass parts of OPUR pigments manufactured by and acquired from the International Organization For Dew Utilization (France) and the other part being OBI radiator paint acquired from OBI (Austria). This coating aimed to enhance condensation by promoting efficient heat exchange and condensate formation on the greenhouse surfaces. OPUR coatings are known for their ability to enhance radiative cooling by selectively emitting heat, which can enhance condensation rates (Silva, 2021).

Rescue blanket (3rd section): This section of the roof featured only the application of an IR reflecting foil in the form of a thermal rescue blanket acquired from OBI (Austria). This foil was attached to the inside part of the roof with adhesive tape to assess the impact of infrared radiation reflection on passive condensation without the influence of additional coatings.

OPUR Coating with rescue blanket (4th section): In this section, the transparent OPUR coating was applied in combination with the same infrared (IR) reflecting foil. This combination was designed to maximize heat retention and enhance condensation rates by reflecting infrared radiation back into the greenhouse. When OPUR is combined with IR, high condensation potential can be obtained. The scope of this study was to compare the condensation efficiency of the active and passive systems. Efficiency of desalination systems is characterized by the ratio of desalinized water to saline water use. The following equation takes into account the cumulative active and passive condensation and transpired water by the three halophytic species:

$$\% \, efficiency = \frac{active \; + passive \, condensation}{evapotranspiration} \, x \; 100\%$$

Thermodynamic data analysis

Manually measured water amounts and tank height were combined with logged data from the monitoring setup, and visual observations were incorporated to gain insights into the thermodynamic behavior and processes within the SDGH. The data, consistent with a temperature sensor threshold of 50°C, primarily included humidity and temperature readings from sensors within the greenhouse. Measurements of evapotranspiration and condensation processes were also considered evaluating the assumptions made by the data logging. The software used was Python-based, predominantly operated via prompts with ChatGPT4 Data Analysis tool, and later adapted in a Python notebook. The data was processed and organized to allow for a unified interpretation of manual measurements and constant data logging intervals.

3 Results

Microclimate

Figure 3 depicts the fluctuation in temperature within the regulated SDGH setup compared to the external environment. The mean temperature within condenser 1 (20.5 ℃) was lower than that of condenser 2 (23.6 ℃). There was a slight variation for indoor temperatures between the bottom and top areas of the SDGH, with the mean top temperature being higher than the mean bottom temperature (means = 26.9 ℃ and 24.8 ℃, respectively). The mean outside temperature (22.4 ℃) was lower than the mean inside temperature, as expected. There is no statistical difference between temperatures, except for condenser 1 and the top indoor temperature. The location of condenser 1 may not be ideal for an efficient condensation of water, given that air at higher temperatures is generally located at the top of the SDGH.

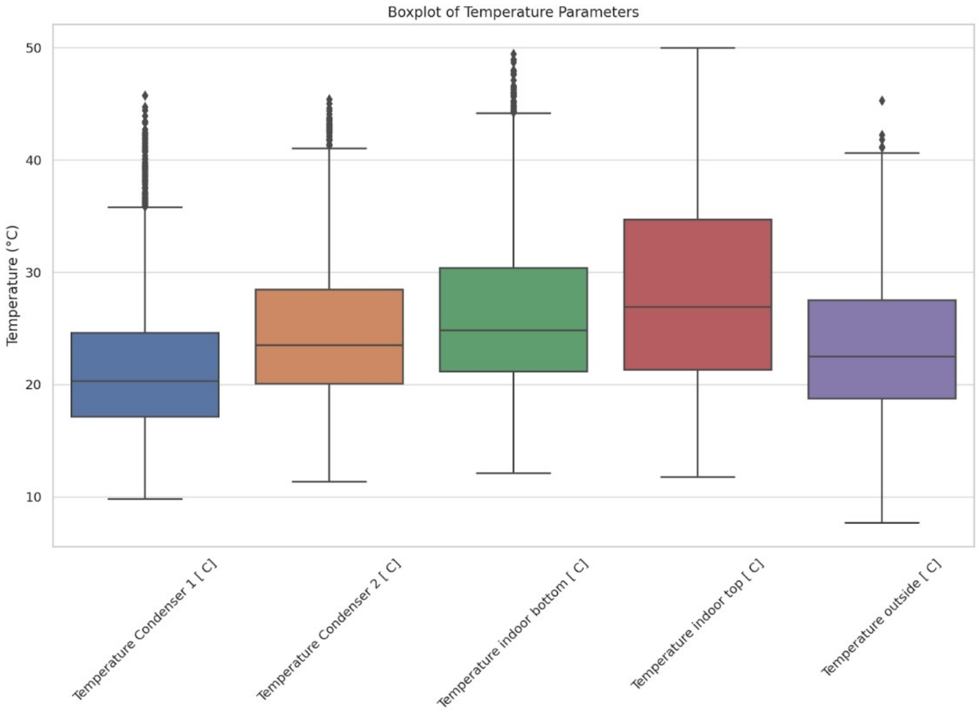
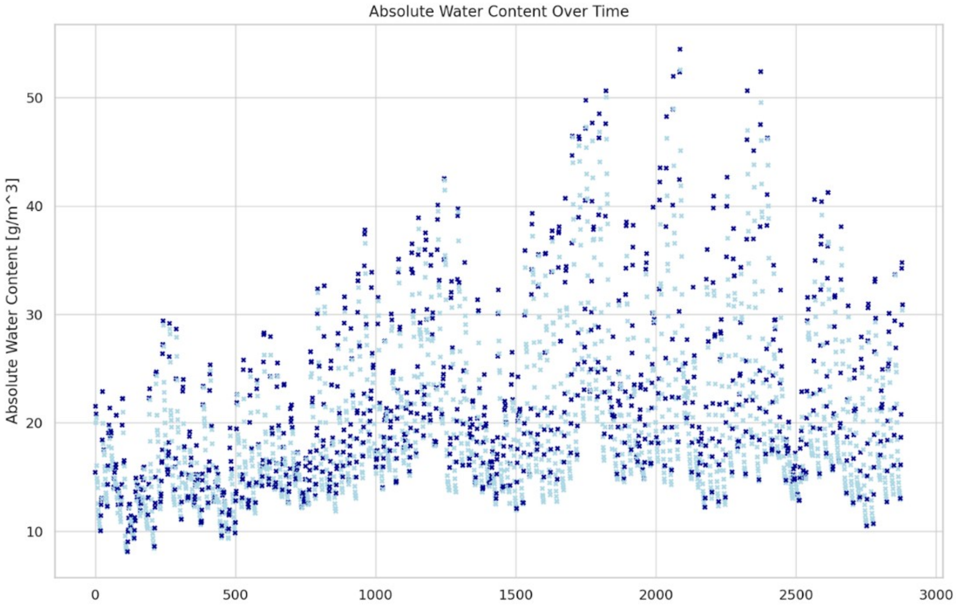


Figure 3. Box plot representing all temperature sensors both inside and outside the SDGH, clearly showing the distribution of temperature stratification.

The absolute water content, within the SDGH, is expressed as the density of water in g per m3. The highest density was recorded on day 89 (55.25 g/m3), followed by days 101 and 78 (52.88 and 50.99, respectively).



1Figure 4. The absolute water content within the SDGH microclimate is represented, with darker dots indicating dominance of evaporative processes and lighter dots indicating dominance of condensation processes. (x-axis represents time (hours)).

Humidification

Figure 5 presents the evapotranspiration rates and cumulative evapotranspiration for the three halophytic species being studied. The three halophytes exhibited a similar trend from day 0 to day 123, with peaks occurring mainly at days 28, 56, 81 and 103 (Fig. 5). The highest rate of evapotranspiration was performed by *Salicornia europaea* (3,15 L/day), followed by *Crithmum maritimum* (1,17 L/day) both at day 81 and finally *Portulaca oleracea* (1,02 L/day) at day 56. These peaks coincide with the peaks for absolute water content within the SDGH (Figure 4). However, differences were distinctively observed for the cumulative evapotranspiration of the three species. Over the 123-day period, *Salicornia europaea* accumulated the highest amount of water (174,4 L), followed by *Crithmum maritimum* (88,67 L) and finally *Portulaca oleracea* (67,98 L).

Salicornia showed a biphasic water evapotranspiration with a rate of 0,55 L/day for the first 39 days followed by a rate of 2,02 L/day till day 123. *Portulaca* and *Crithmum*, both experienced a constant evapotranspiration rate of 0,58 and 0,79 L/day, respectively over the 123-day period.

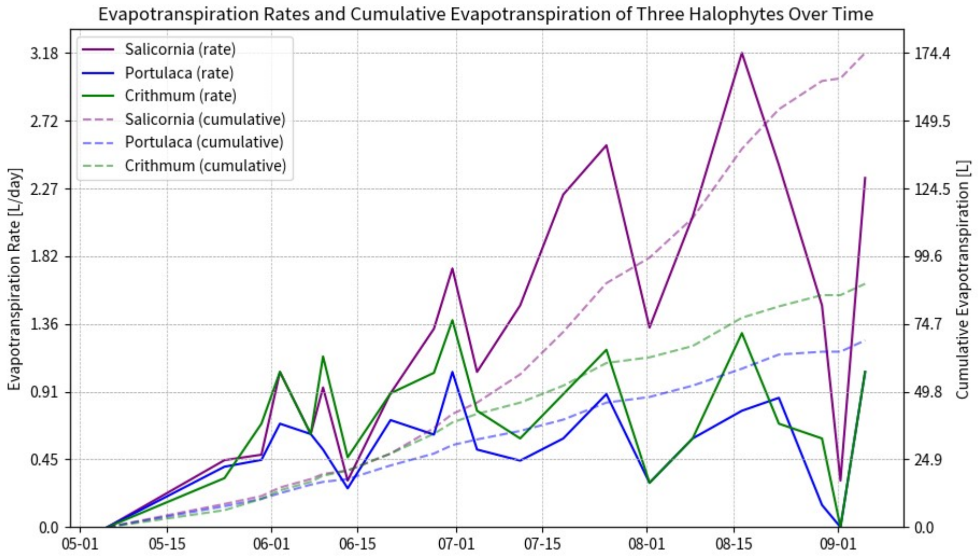


Figure 5. Evapotranspiration rates and cumulative evapotranspiration for the three halophytic species over time.

Dehumidification

Active condensation

Figure 6 illustrates the calculated daily condensation rate and cumulative condensation yield over the 123-day period. It was observed that the cumulative condensation yield also followed a biphasic accumulation, as was observed for the cumulative evapotranspiration for *Salicornia europaea.* Till day 39, the condensation rate of 1,25 L/day increased to 1,67 L/day from day 40 to day 123. Considering the summative evapotranspiration of the three species, the biphasic evapotranspiration exhibited a rate of 1,55 L/day till day 39, and a rate of 3,41 L/day from day 40 to day 123. The discrepancy in cumulative volume between evapotranspiration (331,06 L) and active condensation (191,34 L) is in part attributed to the passive condensation and residual humidity within the SDGH, which was not effectively captured by the condensers.

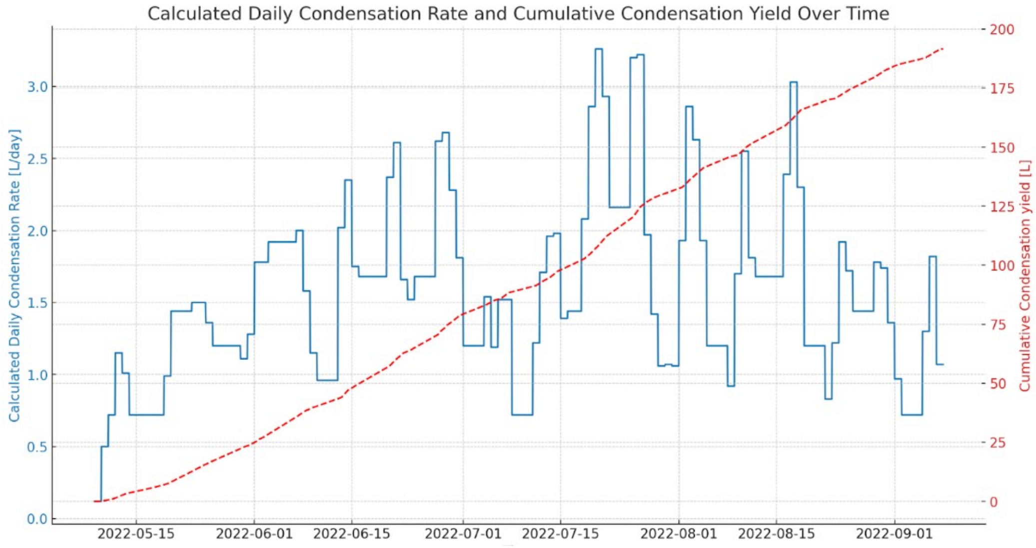


Figure 6. Calculated daily condensation rate and cumulative condensation yield over time of both condenser 1 and 2.

Overall, condenser 2 exhibited a better performance compared to condenser 1 particularly during the months of June, July and August, which represent the peak period for evapotranspiration of the three halophytic species (Fig. 7). The highest water accumulation for condenser 1 was observed in June (26,66 L) and that for condenser 2 was in August (29,21 L). Owing to the greater water accumulation in the first month (May), condenser 1 amassed a total of 96,81 L of water, which was more than the 94,33 L accumulated by condenser 2 (Fig. 7). The combined water accumulation by both condensers amounted to 191,14 L.

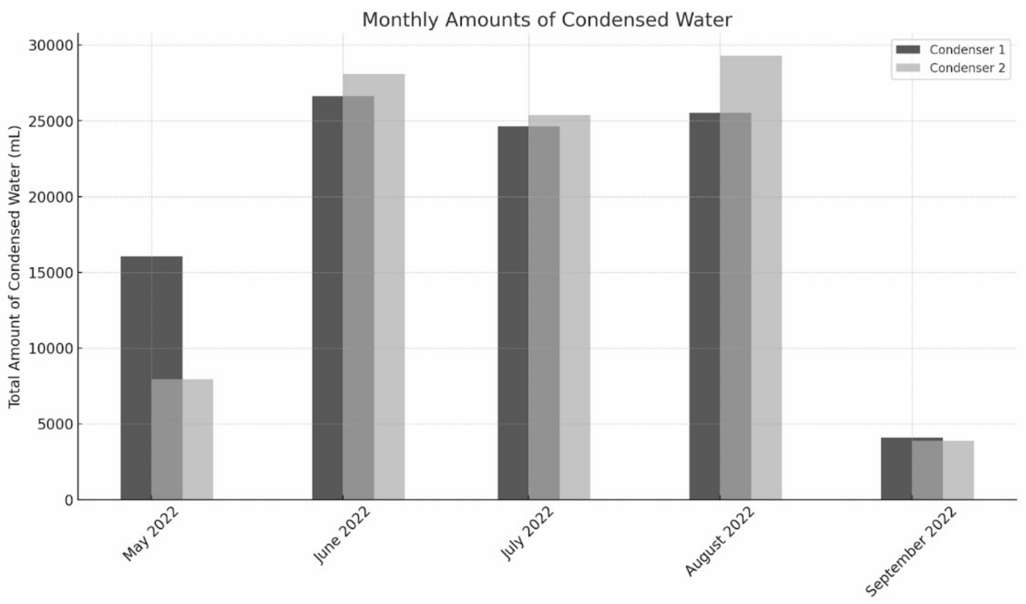


Figure 7. Monthly amounts of condensed water showing some difference between condenser 1 and 2.

Passive condensation

The accumulation of water via passive condensation exhibited a different pattern than active condensation (Figure 8). The different passive applications implemented in this study resulted in different water accumulation over time. The 1st and 2nd section combined (no coating and OPUR coating) accumulated a volume of 0,62 L. The 3rd section alone (rescue blanket) accumulated 0,89 L and the 4th section (OPUR coating and rescue blanket) accumulated 1,57 L of water. A total of 3,08 L was collected on a surface of 1,5 m² resulting in an average of 2,05 L/m² over the 123-day period. The mean values for these sections were 0,07±0,017, 0,08±0,014 and 0,1±0,021 L, respectively, with no statistical difference between means. However, passive condensation was delayed by 24 days, with a volume of 0,09 L of water accumulated and no further increase until day 33. At day 39, which coincides with the biphasic pattern for the evapotranspiration of *Salicornia europaea* and active condensation, the amount increased to 0,28 L. From day 39, there was an exponential increase in water accumulation till day 123.

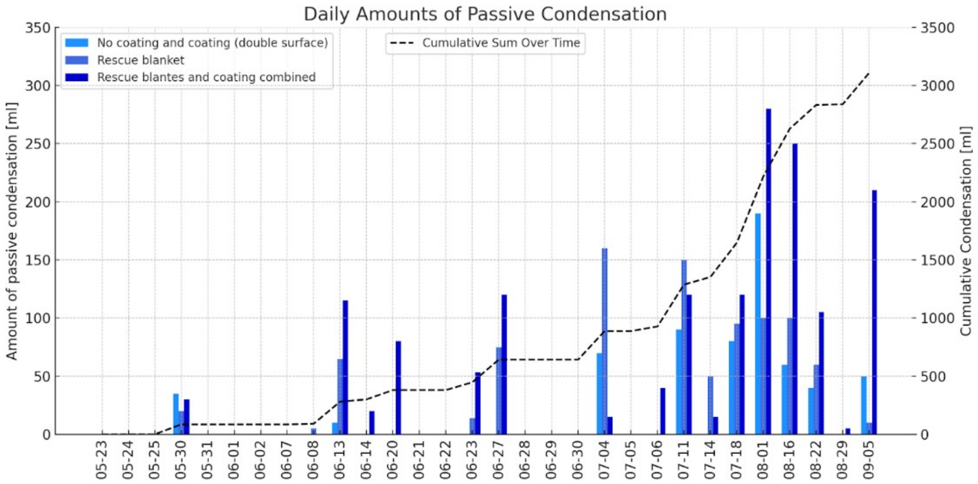


Figure 8. Daily mounts of passive condensation over time

4 Discussion

Evapotranspiration is a process that is dependent on various climatic conditions and the inherent capability of a plant. Evapotranspiration is generally calculated using the Food and Agriculture Organisation of the United Nations Penman-Monteith equation (FAO-56 PM) based on a number of meteorological conditions (Allen et al., 1998) and the simplified Turc equation (Turc, 1961) or the Hargreaves-Samani equation and its derivatives based on temperature-based models (Valipour, 2015). While the first relies on a number of conditions that need to be monitored *in situ*, the second, temperature-based model, operates well within a mean temperature range of 12-18 °C. According to the current findings, the temperature-based model would be functional if outdoor temperatures were considered (mean = 22.4 °C) but not within the SDGH (mean temperature range = 24.8-26.9 °C). Consequently, in this study, evapotranspiration was calculated directly from the consumption of water by the plant. The current experiment was conducted during the time of the year when atmospheric humidity and temperature impact significantly evapotranspiration rate (Moratiel et al., 2010). As the mean temperature rose between the months of May and August, the absolute water content within the SDGH increased progressively.

In this present study, it was ensured that the humidification of the SDGH environment was due to evapotranspiration via the plant and not due to surface evaporation from the supporting medium. Several studies have shown that the rate of evapotranspiration, in the case of *Salicornia*, is generally 1.5 to 2.5 times the evaporation of water from an evaporating basin (Grattan et al., 2008). Other studies demonstrated that tissue water content decreases with time (Turcios et al., 2023). This decrease may be associated with a more efficient loss of water, via evapotranspiration, as was demonstrated in our study. On average, the indoor and outdoor relative humidity were 73.70±0.21% and 57.31±0.31%, respectively. This underscores the role of halophytes in the humidification process within the SDGH. Over a span of 17.5 weeks, *Salicornia europaea* made a significant contribution to humidification, followed by *Crithmum maritimum,* and lastly, *Portulaca oleracea.* In the initial 5.5 weeks, Salicornia's evapotranspiration rate was similar to that of the other halophytes. However, it later exhibited the highest rate, contributing to the efficient transformation of saline water into fresh water through evapotranspiration.

In the context of the SDGH, besides its contribution to the water cycle, Salicornia serves multifaceted purposes. Salicornia can be cultivated as a nutritious food source for local markets and as fodder for livestock, providing a potential stream of income in arid and drought-prone areas. Additionally, the seeds of Salicornia are rich in oil that can be processed into biofuel, offering a sustainable energy solution. The versatility of Salicornia underscores its economic viability and aligns with global trends toward the utilization of crops that support food security and renewable energy production.

Halophytes flourish in high salinity conditions. In this study, the incoming water had a conductivity of 15 mS/cm, over five times the salinity that glycophytes can tolerate, but within the tolerance range of the three halophytic species studied. The conductivity values of the water, after passing through the tubes where the halophytes were grown, showed that Salicornia europaea had the highest conductivity (29.68±0.31 mS/cm), followed by Crithmum maritimum (23.25±0.14 mS/cm), and finally Portulaca oleracea (20.52±0.09 mS/cm). These results suggest that the water became more saline upon contact with the halophytes as they absorbed the water, leaving behind a more saline medium. Each species' salinity values align with their ability to absorb and remove water via evapotranspiration. Specifically, *S. europaea* exhibited the highest volume of transpired water and the highest salinity, while *P. oleracea* showed the lowest volume of transpired water and the lowest salinity. Typically, a crop transpires 50,000 L of water per hectare per day (FAO, 1998). As a result, about 20% of the world's irrigated farming systems use approximately 70% of the global freshwater supply (Steduto et al., 2012). Rain-fed systems also face challenges due to unpredictable rainfall patterns and droughts induced by climate change (Radulovich and Umanzor, 2021). This study extends beyond merely substituting glycophytes with halophytes, addressing the escalating strain on water quality and resources.

Studies show that evapotranspiration is negatively related to relative humidity levels (Eslamian et al., 2011). The higher the relative humidity, the lower the evapotranspiration. In this present study, dehumidification is the driver for the removal of moisture from the atmosphere, which enhances the loss of water via evapotranspiration. This process is necessary to maintain the medium-plant-atmosphere water continuum (Norman and Anderson, 2005). Although in this study, the cumulative active condensation of water exhibited a slightly different pattern compared to the cumulative evapotranspiration by the three halophytes, the trends show similar behavior in water flow rates. However, the degree of passive condensation and uncondensed water should also be taken into account.

In this present study, the efficiency of the system was 58.73%. The design of this prototype using modified refrigeration equipment can be improved with the use of commercial dehumidifiers. However, one should also weigh commercial dehumidifiers' economic and energetic implications. The potential accumulation of moisture within the higher temperature region (top region of the SDGH), might be more efficiently condensed by the setting up of a ducting system that extracts humidified air at the top of the SDGH.

While the current system combines humidification (via halophytes) and dehumidification (through active/passive condensation) processes to measure freshwater generation, future research will adapt this system to a greenhouse setup where traditional glycophytic crops could be cultivated and irrigated using the water produced from the humidification/dehumidification system. A potential setup is illustrated in Figure 9. Crops that are grown within such an environment would not only benefit from the desalinated water but also contribute to the evapotranspiration process.

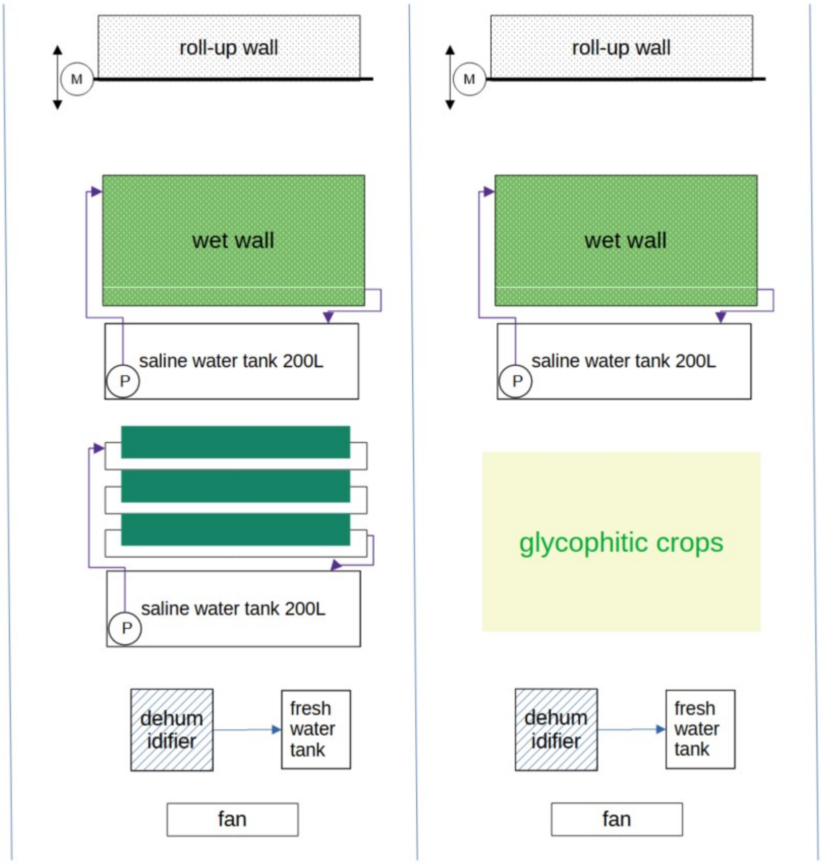


Figure 9. A scaled-up simplified SDGH features a vertical setup on the left side of the separating wall within the greenhouse, with glycophytic crops occupying the right compartment.

5 Conclusion

In conclusion, this study highlights the significant role of halophytes in evapotranspiration and their potential use in sustainable agriculture. The research demonstrates that halophytes, particularly *Salicornia europaea*, can effectively transform saline water into fresh water through evapotranspiration, contributing to the Solar Desalination Greenhouse (SDGH) humidification process.

The study also reveals that the efficiency of the current system is 58.73%, suggesting room for improvement. The design of this prototype, which uses modified refrigeration equipment, could be enhanced with the use of commercial dehumidifiers. However, the economic and energetic implications of this change should be considered. Furthermore, the study suggests that a ducting system that extracts humidified air from the top of the SDGH could more efficiently condense the potential accumulation of moisture within the higher-temperature region. Future research will adapt this system to a greenhouse setup where traditional glycophytic crops could be cultivated and irrigated using the water produced from the humidification/dehumidification system. Crops grown in such an environment would not only benefit from the desalinated water but also contribute to the evapotranspiration process. This research opens up new avenues for sustainable agricultural practices, particularly in regions grappling with water scarcity and high salinity conditions. The findings provide a strong foundation for future research aimed at optimizing the use of halophytes and SDGH technology in sustainable agriculture (Centofanti and Bañuelos, 2019).

6 Acknowledgements

The authors acknowledge the essential contributions of key individuals and institutions to this research. We appreciate Mr. Efecan Toker's work in building and maintaining the greenhouse and equipment, along with his diligent data collection. Mr. Angie Nandhagopal's thorough record-keeping and measurements were invaluable. Special thanks to Mr. Joseph Mizzi from EcoGozo for coordinating the MEDWET project and aiding the success of the MEDWET EU-funded initiative. The support from the EU project DIVAGRI, under grant agreement No 101000348, was crucial during the SDGH prototype's construction and testing phase. This research reflects the collective effort of a dedicated team, supported by projects aimed at sustainable agricultural and water management solutions. We thank all contributors for their commitment and support.

References

1. Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, 300(9), D05109.

2. Aydın, M., Sisman, A., Gultekin, A., & Dehghan, B. (2015). An Experimental Performance Comparison between Different Shallow Ground Heat Exchangers.

3. Bourouni, K., Chaibi, M. T., & Taee, A. A. (2010). Water Desalination by Humidification and Dehumidification of Air, Seawater Greenhouse Process.

4. Casarano, D., Dragone, V., & Polemio, M. (2019). Groundwater resources at salinisation risk: effects of climate and utilisation changes in the case of Apulian coastal aquifers (Southeastern Italy*). Acque Sotterranee-Italian Journal of Groundwater*, 8(1).

5. Centofanti, T., & Bañuelos, G. (2019). Practical uses of halophytic plants as sources of food and fodder. *In Halophytes and climate change: adaptive mechanisms and potential uses* (pp. 324-342). Wallingford UK: CABI.

6. Chaibi, M.T. and Jilar, T., 2005. Effects of a solar desalination module integrated in a greenhouse roof on light transmission and crop growth. *Biosystems engineering*, 90(3), pp.319-330.

7. De Wrachien, D., Schultz, B. and Goli, M.B., 2021. Impacts of population growth and climate change on food production and irrigation and drainage needs: A world-wide view. *Irrigation and Drainage*, 70(5), pp.981-995.

8. Eslamian, S., Khordadi, M. J., & Abedi-Koupai, J. (2011). Effects of variations in climatic parameters on evapotranspiration in the arid and semi-arid regions. *Global and Planetary Change,* 78(3-4), 188-194.

9. Essink, G. H. O. (2001). Improving fresh groundwater supply—problems and solutions. *Ocean & Coastal Management*, 44(5-6), 429-449.

10. FAO. (1998). Crop evapotranspiration (guidelines for computing crop water requirements) (FAO irrigation and drainage paper 56). *Rome: FAO*.

11. FAO Intergovernmental Technical Panel on Soils. Status of the World's Soil Resources. ISBN 9789251090046 (2015).

12. Falkenmark, M., Rockström, J. and Karlberg, L., 2009. Present and future water requirements for feeding humanity. *Food security*, 1, pp.59-69.

13. Flowers, T. J. & Colmer, T. D. Salinity tolerance in halophytes. New Phytol. 179, 945–963. *https:// doi. org/ 10. 1111/j. 1469- 8137. 2008. 02531.x (2008).*

14. Glenn, E. P., Brown, J. J., & Blumwald, E. (1999). Salt Tolerance and Crop Potential of Halophytes. *Critical Reviews in Plant Sciences,* 18(2), 227–255.

15. Goosen, M.F.A., Sablani, S.S., Paton, C., Perret, J., Al-Nuaimi, A., Haffar, I., Al-Hinai, H. and Shayya, W.H., 2003. Solar energy desalination for arid coastal regions: development of a humidification–dehumidification seawater greenhouse. *Solar energy,* 75(5), pp.413-419.

16. Grattan, S. R., Benes, S. E., Peters, D. W., & Diaz, F. (2008). Feasibility of irrigating pickleweed (Salicornia bigelovii Torr) with hyper-saline drainage water. *Journal of environmental quality,* 37(S5), S-149.

17. Imadi, S. R., Shah, S. W., Kazi, A. G., Azooz, M. M., & Ahmad, P. (2016). Phytoremediation of saline soils for sustainable agricultural productivity. *Plant metal interaction,* 455-468.

18. Indika, S., Wei, Y., Hu, D., Ketharani, J., Ritigala, T., Cooray, T., Hansima, M. A. C. K., Makehelwala, M., Jinadasa, K. B. S. N., Weragoda, S. K., & Weerasooriya, R. (2021). Evaluation of Performance of Existing RO Drinking Water Stations in the North Central Province, Sri Lanka. *Membranes,* 11(6), 383.

19. Kong, Y., & Zheng, Y. (2014). Potential of Producing Salicornia bigelovii Hydroponically as a Vegetable at Moderate NaCl Salinity. *HortScience,* 49(9), 1154–1157.

20. Maestre-Valero, J. F., Ragab, R., Martínez-Alvarez, V., & Baille, A. (2012). Estimation of dew yield from radiative condensers by means of an energy balance model. *Journal of Hydrology*, 460–461, 103–109.

21. Moratiel, R., Durán, J. M., & Snyder, R. L. (2010). Responses of reference evapotranspiration to changes in atmospheric humidity and air temperature in Spain. *Climate research*, 44(1), 27-40.

22. Munir, N., Hasnain, M., Roessner, U., & Abideen, Z. (2022). Strategies in improving plant salinity resistance and use of salinity resistant plants for economic sustainability. *Critical Reviews in Environmental Science and Technology*, 52(12), 2150-2196.

23. Norman, J.M., & Anderson, M.C. (2005). SOIL–PLANT–ATMOSPHERE CONTINUUM. 513-521. *(https://web.archive.org/web/20170517101404id_/http://ecosensing.org:80/wp-content/uploads/2012/03/Soil-Plant-Atmoshere-Continuum.pdf)*

24. Radulovich, R., & Umanzor, S. (2021). Halophyte use and cultivation. In Handbook of halophytes: from molecules to ecosystems towards biosaline agriculture (pp. 2517-2535). *Cham: Springer International Publishing.*

25. Shahbaz, M., Ashraf, M., Al-Qurainy, F., & Harris, P. J. (2012). Salt tolerance in selected vegetable crops. *Critical reviews in plant sciences*, 31(4), 303-320.

26. Shekarchi, N. and Shahnia, F., 2019. A comprehensive review of solar-driven desalination technologies for off-grid greenhouses. *International Journal of Energy Research*, 43(4), pp.1357-1386.

27. Silva, L. C. C. da, Filho, D. O., Imbuzeiro, H. M. A., & Monteiro, P. M. de B. (2021). Analysis of different condensing surfaces for dew harvesting. *Water Science & Technology: Water Supply*, 22(1). DOI: 10.2166/ws.2021.242.

28. Steduto, P., Hsiao, T., Fereres, E., & Raes, D. (2012). Crop yield response to water (FAO irrigation and drainage paper no. 66). *Rome: FAO*

29. Turc L (1961) Estimation of irrigation water requirements, potential evapotranspiration: A simple climatic formula evolved up to date. *Ann Agron* 12:13–49 (in French)

30. Turcios, A. E., Braem, L., Jonard, C., Lemans, T., Cybulska, I., & Papenbrock, J. (2023). Compositional Changes in Hydroponically Cultivated Salicornia europaea at Different Growth Stages. *Plants,* 12(13), 2472.

31. Valipour, M. (2015). Temperature analysis of reference evapotranspiration models. Meteorological Applications, 22(3), 385-394.

32. Ventura, Y. & Sagi, M. Halophyte crop cultivation: The case for Salicornia and Sarcocornia. Environ. Exp. Bot. 92, 144–153. *https://doi. org/ 10. 1016/j. envex pbot. 2012. 07. 010 (2013).*