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Seawater greenhouse in Oman: A sustainable technique for freshwater conservation and production

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A B S T R A C T

The recently-evolved seawater greenhouse (SWGH) technology exhibits a promising source of freshwater for irrigation in places where only saline groundwater or seawater are accessible. The SWGH recreates the "hydrologic cycle" by evaporating water from saline water source and regains it as freshwater by condensation. This technology has undergone several stages of improvements and showed a promising practical solution in places lacking freshwater for irrigation. The aim of this study was to provide a comprehensive and up-to-date review on what has been published on SWGH technique. The study also aimed at investigating the success of implementing the principle using the SWGH located in the Sultanate of Oman as a case study.

Several research studies have focused on the technical enhancement of SWGH concept, thus proposed a number of modifications to the existing design in order to augment freshwater production. However, a noticeable knowledge gap was observed in the economic aspects of SWGH due to the absence of research interest in this area. The first trial of an insight at the SWGH economics was done in this study. Main finding from this analysis is to reduce the capital costs of the dehumidification unit. On technical aspect, the SWGH is a water conservational tool as it reduces the crop water requirement by almost 67% when compared to open-field cultivation. Freshwater production from the Oman SWGH was ranging between 300 and 600 L/day, having virtually zero-salinity (<0.020 dS/m). Although this amount is half of the irrigation water demand, it was possible to increase freshwater volume by blending with raw seawater or brackish groundwater. Because the current freshwater production of SWGH in Oman is still below expectations and research studies affirm the opportunity for improvement, further R&D efforts are essential. These efforts, on technical aspects, have to be alongside with efforts on the economic aspects.

Contents

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1. Introduction

1.1. Greenhouses in arid conditions

Agricultural development and sustainability in arid countries of the world face two major constraints; high temperatures and water scarcity. In Oman, the most important agricultural area is Al-Batinah coastal plains that occupy almost half of the cultivated lands [1,2]. In this plain, summer temperatures can reach more than 45 °C, annual precipitation is between 81 and 200 mm and annual evapotranspiration is 2100 mm [3–5]. The use of evaporatively-cooled greenhouses is becoming popular as they helped to overcome the high temperature constraint and significantly reduced irrigation water demand compared to open-field agriculture [6]. This is because elevated humidity inside the greenhouse causes a reduction in crop evapotranspiration by almost 60 to 80%, i.e. large water saving [7,8]. However, the amount of water required for evaporative cooling in greenhouses is much more than water needed for irrigation. It was reported that the cooling water demand represents nearly 67% of the greenhouse gross water demand [9]. From total water consumption viewpoint, greenhouses in arid climates are water intensive and hence, fan-and-pad evaporatively-cooled greenhouses do not resolve the water scarcity constraint due to their high cooling-water demand.

Insufficient recharge of groundwater aquifers together with aggressive pumping of groundwater increased the annual depletion from 1.8 Mm^3 in the 1990s to almost 347 Mm^3 in the recent years [10,11]. This continuously-increasing depletion had led to the intrusion of seawater into the fresh groundwater reservoir. Although groundwater is available in abundant quantities in seawater-intruded areas, it is not in a usable form due to increased salinity levels. Finding a solution for utilizing this deteriorated groundwater would certainly contribute to augmenting, or at least maintaining the current, agricultural production of Al-Batinah.

1.2. Seawater greenhouse concept: A review

This section provides the latest comprehensive review on the seawater greenhouse (SWGH) technology. In this review, although the SWGH principle falls within the general themes of the “humidification–dehumidification techniques in solar desalination” and the “integrated solar still-greenhouse systems”, both topics are not considered here as they were the focus of other investigators [12–17]. This review will solely focus on the SWGH technology.

1.2.1. Concept

The SWGH concept is based on the principles of solar distillation units, so-called solar stills. These units efficiently recreate the hydrologic cycle by evaporating saline water and subsequently condensing water vapor at relatively low temperatures [18]. Similar to greenhouses, the solar stills are air-tight structures [19], covered with transparent glass or plastic covers [20,21]. More technical details about the solar stills can be obtained from previous studies [22–27]. This method of water distillation has several advantages including; low capital costs (for small-scale units) [15], low operational costs [28], low maintenance costs [29], long mean lifetime and require non-skilled labors [15].

Although solar stills have many advantages, they still suffer a few drawbacks such as; high construction costs (for large-scale plants) [12], require large area of implementation [30] and have low water production and efficiencies [15,31]. Therefore, integrating the principles of solar stills in another structure would eliminate the costs associated with construction and land and could increase the efficiency. Chaibi [12] provided a thorough review on the possibility of combining solar stills in the cavity of double-glazed-roof greenhouses to provide freshwater for irrigation. Salty water is evaporated in the bottom side of the roof cavity and then water vapor condenses on the underside of the top layer of the cavity [32]. Although these combined systems were found to be very economic [33], some of them failed to simultaneously maintain the best conditions required for crop cultivation and water distillation [34]. Therefore, several arrangements and modifications were investigated to overcome this limitation and increase water production [35–37]. One of these modifications was the seawater greenhouse (SWGH) which is reviewed henceforward.

In agricultural practices, the main purpose of constructing greenhouses is to overcome harsh ambient conditions and hence provide a microclimate with controlled environment suitable for cultivating certain crops. In hot climates, greenhouses mainly provide cool environment for plant cultivation by means of pad-and-fan evaporative cooling systems. Seawater greenhouses (SWGH) are similar to ordinary pad-and-fan greenhouses but with two extra components; an additional evaporator and a condenser. The idea of integrating a condensation unit in greenhouses is not very common [38,39] though, it has been studied by several researchers as one method of solar desalination techniques [12,40,42]. Seawater greenhouses represent a new technology which basically implements the “hydrologic cycle” principles such that humidification of dry air from saline water source followed by dehumidification of water vapor are carried out inside a greenhouse structure [30,43–45].

The working protocol of the SWGH is illustrated in Fig. 1. When ambient warm dry air passes through the first seawater-wetted evaporator, air and water release part of their sensible heat for evaporation to take place which causes a reduction in air and water temperatures and an increase in humidity. Evaporatively-cooled seawater in the first evaporator is collected and pumped to the condenser as a coolant. Finally, the coolant flows back to the first evaporator to complete the cold water circuit. Air passing through the cropping area acquires more temperature due to solar heat input and more moisture due to evapotranspiration. Owing to the fact that air moisture-holding-capacity increases with temperature, a second evaporator is placed at the end of the cropping area. The role of this evaporator is to further enrich the air with more moisture before reaching the condenser. To boost up evaporation in the second evaporator, water temperature is increased by a solar heater. The warm water circuit is then completed by pumping the water collected from the second evaporator to the solar heater again.

1.2.2. Historical development

To date, construction of four SWGHs has been reported at different places. The first SWGH was constructed in 1994 in Tenerife, Spain for crop cultivation and cheap seawater desalination. This greenhouse covered an area of 360 m^2 where temperate crops

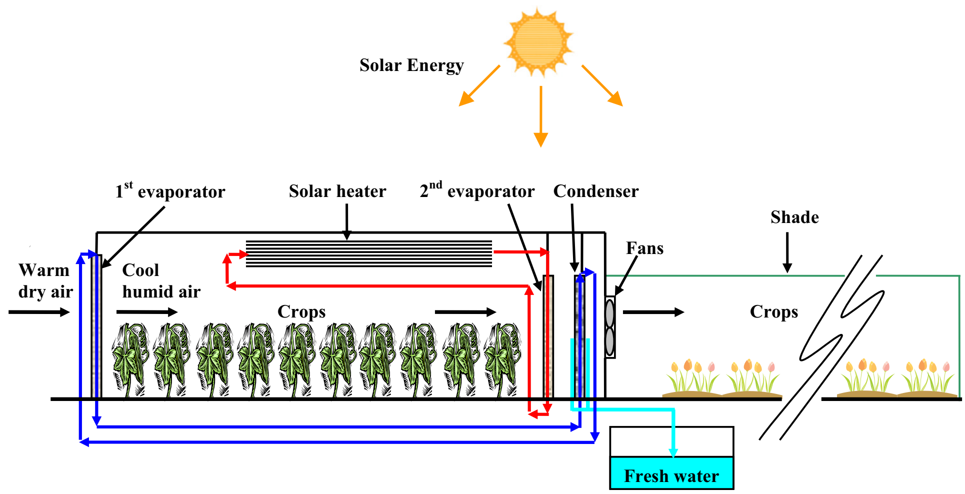

Fig. 1. Schematic of the SWGH in Oman.

such as tomatoes, spinach, dwarf pea, pepper, artichokes, French beans and lettuces were successfully cultivated [15,46]. The amount of freshwater produced by this greenhouse was nearly 1.5 m^3/day which exceeded the irrigation water requirement. The peak amount was reported to be as high as twenty times the crop water requirement of a single greenhouse [42,47].

The second SWGH was built in Al-Aryam Island, Abu Dhabi, United Arab Emirates in 2000. It was the first SWGH constructed in the Middle East because this concept was found to be more appropriate for arid places close to sea, inland places where only saline groundwater is accessible or where oil-well production water is available [48,49]. In arid conditions, the evaporation effectiveness of the greenhouse cooler is highly enhanced, resulting in higher humidification and thus, lower air and water temperatures. The total area of this greenhouse was 864 m^2 where tomato crop was grown. After several modifications, the daily water production from this greenhouse approached 1 m^3 with excellent water quality and this amount had nearly met the irrigation demand of crops [47,50].

In 2004, the third SWGH was constructed in Oman, covering an area of 720 m^2. The construction of this greenhouse was advanced by a preliminary study in an ordinary tunnel-type greenhouse (prototype) to investigate the practicality of this technique to produce irrigation water under Oman's arid climate. The findings from this study were valuable which motivated the construction of the large-scale SWGH [51–54]. However, the latter was not able to meet the water demand of the cultivated cucumber crop as the amount of freshwater production was only between 0.3 and 0.6 m^3/day [52,55].

The last SWGH was built in Port Augusta, South Australia in 2010. This greenhouse covered an area of 2500 m^2 and produced tomato and capsicums in commercial quantities. However, there is no information available, to date, neither on the quantity of freshwater produced nor on the design details of the condenser. The available knowledge about this greenhouse was only obtained from the information disseminated through media sources [56,57].

1.2.3. Research-and-development process

The SWGH concept has undergone several stages of research-and-development (R&D) which was mostly aiming at the enhancement of freshwater production. This R&D process had two distinct formats; empirical and simulation modeling. Both formats are discussed hereafter.

1.2.3.1. Empirical-based R&D. Several empirical-based modifications were performed throughout the development of the SWGH concept. These modifications focused on several aspects of the SWGH concept such as greenhouse structure and covering, enhancement of evaporation rate, modifying cropping microclimate, condenser's design, material, height and cooling technique, and electricity generation. Regarding the greenhouse structure, four different designs were tried, namely; rectangular cross-section in Tenerife, triple-hump cross-section in Abu Dhabi, double-span Quonset type in Muscat and multi-span Quonset type in Port Augusta [47,56–59]. For the covering material, the Tenerife SWGH was covered with a two-layer fiberglass covering material and seawater was sprayed into the cavity between these layers to reduce the heating effect of solar radiation. The other SWGHs were covered with a single-layer of polyethylene (PE) films because double-layer covering was causing some technical problems such as water leakage [47,60].

As mentioned in Section 1.2.1, water flowing from the second evaporator was pre-heated with a “solar heater”, made from an array of black PE tubes, in order to increase the evaporation rate and saturate the air flowing to the condenser. As a side advantage, these PE tubes provided a certain level of shading and absorbed the extra-heating of solar radiation which consequently modified the temperature of the cropping area. Therefore, the PE solar tubes were employed in the Oman SWGH to replace the commercial PE film used over the growing area of the UAE SWGH [47].

The design and material of the condenser was changed from a cupronickel-and-aluminum tube-and-fin heat exchanger, used in the first two SWGHs, to a cross-flow plastic-tube condenser in order to increase water production and decrease the cost [47,50,61,62]. Prior to the implementation of the plastic-tube condenser, an experimental work was conducted to study its performance and economics. Cost-wise, the component parts of the new design cost only a fraction of the manufacturing costs of the tube-and-fin condenser. Performance-wise, the plastic condenser outperformed the tube-and-fin condenser at various inlet air and coolant temperatures. Due to these promising results, the plastic condenser was then employed in the Oman SWGH [49]. Through experimental observations, the height of condenser tubes used in this SWGH was reduced from 2.8 to 1.8 m in order to avoid the frequent fall-down of tubes.

Alkhalidi et al. [63,64] developed and tested two simple condenser designs that could be employed in the SWGH; a plate-channel condenser and a vibrating-surface condenser. Experimental results showed that condensation rate increased with increasing air dry-bulb temperature and humidity but the influence of temperature was more dominant. It was also found that condensation rate increased with increasing air and coolant flowrates (a similar result was previously reported by [65]). Compared to the plastic-tube condenser, the plate-channel condenser produced 16.5% more freshwater.

For the cooling of the condenser, the original idea was to use deep seawater to cool the condenser of the Tenerife SWGH but because of the high expenses of pipe layout and pumping, heat pumps were alternatively used to imitate deep-sea's temperature [66–68]. However, due to the technical and economic constraints associated with the use of deep seawater and/or heat pumps, evaporatively-cooled seawater was used to cool the condenser of SWGHs in UAE and Oman. Since heat pumps provided a coolant with lower temperature than evaporatively-cooled seawater, it was noticed that the latter produced less freshwater owing to the fact that condensation is greatly driven by temperature differences [47].

For electricity generation, Davies [69] proposed to employ a solar cooling system in place of the ordinary evaporative cooling system. The solar system is basically a system that combines liquid desiccation with solar regeneration. Compared to the conventional evaporative cooler, the new system will further reduce summer maximum temperatures by 5 °C which is expected to extend the growing season for lettuce from 3 to 6 months and for tomato and cucumber from 7 to 12 months. In another study, Davies and Knowles [70] found that magnesium chloride, i.e. most abundant salt in seawater bitterns, is a very suitable desiccant solution to be used in the proposed greenhouse cooling system. The use of this solution will cause a reduction in air temperature in the range of 5–7 °C lower than that of conventional evaporative coolers. Another clean energy improvement is the one suggested by Davies [71] to use a sea-wave-powering technique to provide the electrical power requirement of the SWGH. This modification is expected to eliminate, or at least to reduce, the greenhouse reliance on fossil-fuel-powered energy.

To increase the energy reliability of the SWGH and to make it a stand-alone unit that can be employed in remote places, Mahmoudi et al. [55] studied the feasibility of using renewable energy to power the SWGH in Oman. Taking into consideration local weather data of Oman, it was found that the energy required by the SWGH can be provided by a hybrid system combining wind machines and photovoltaic solar cells. In a similar study, considering weather data of Algeria, Mahmoudi et al. [72] concluded that wind power alone can be sufficient to power the SWGH at five cities in southern Algeria. The surplus wind-generated power can then be used for other purposes such as chilling the condenser coolant and food storage rooms. To overcome fluctuations associated with solar and wind energies, Mahmoudi et al. [59] investigated the possibility of using geothermal brackish groundwater energy in the SWGH. This source of energy is considered to have less intermittence problems as compared to other renewable energy sources. This technique is expected to produce more freshwater than required for irrigation and the additional water can be used in the development of environmental projects. Recently, a huge parabolic solar collector was used in the fourth SWGH to generate most of the greenhouse's energy requirement. At times when the produced power was insufficient, diesel-fueled electricity generators were used [56,57].

1.2.3.2. Simulation-based R&D. The other R&D format, i.e. modeling and simulation, was found to be much more efficient in terms of cost and time-saving. Several investigators [15,42,44,55,73–77] have made a strong emphasis on the importance of thermodynamic simulation models to enhance the performance of solar desalination techniques. Therefore, many researchers have employed different simulation methods in order to optimize the performance of the SWGH and to augment freshwater production. These methods included three procedures; the use of simulation software (e.g. CFD), analytical heat and mass transfer models and statistical procedures.

In the conceptualization, planning, design and operation of the SWGH technology, Light Works [46] used Matlab/Simulink™ software to understand, simplify and optimize the complex physical processes of SWGH through thermodynamic simulations. These processes included evaporative air cooling, humidification, ventilation, solar heat input and condensation. After numerous number of simulation trials and verifications, the design and operating parameters of the SWGH in Tenerife were finalized. The computer-simulated performance was in a good agreement with the actual performance of the built SWGH (see also reference [62]).

For improving SWGH performance, Davies et al. [47] employed a CFD model to study airflow patterns over the Tenerife SWGH and tried to find the optimal attack angle of air. This simulation was very crucial for the Tenerife SWGH as it was ventilated using wind pressure alone without the use of mechanical fans and hence orienting the greenhouse to face the prevailing wind direction was very important. Another CFD model was also used to investigate the influence of three proposed airflow patterns (Fig. 2) on the average canopy temperature and the rate of freshwater production [61]. The simulation was based on the UAE SWGH design. Validation of simulated results against measured values showed a good agreement. As compared to the two other options, the third option (Fig. 2c) offered the maximum reduction in canopy temperature (7.5 °C lower than UAE design) and a maximum increase in freshwater production (63% more than UAE design). This option, where an array of black PE pipes was used to shade the greenhouse canopy and to pre-heat the water flowing to the second evaporative cooler, was then implemented in the SWGH in Oman.

Zurigat et al. [78] used a simple CFD model to demonstrate the potential of using an integrated steady-state simulation model to understand the heat and mass transfer processes of SWGHs. This study aimed at conducting a detailed survey on the CFD works concerning the microclimate of agricultural buildings and to identify the mathematical relations governing the physical processes of SWGHs. Therefore, it did not incorporate much of information on the influence of heat and mass transfer processes on freshwater production of SWGHs. Further work was highly recommended.

Using the second simulation procedure, i.e. analytical heat and mass transfer equations, Raoueche [66] simulated the first SWGH in Tenerife (see also references [48,79]). Five greenhouse components/sections were simulated, namely; evaporative coolers, greenhouse microclimate (air temperature and humidity, plant temperature and transpiration, soil temperature, CO_2 concentration), roof cavity and the condenser. Findings from these simulation studies were employed to optimize the design (i.e., dimensions, evaporator and condenser areas, water flow rates, and temperatures) of the subsequent SWGHs [40]. Raoueche et al. [79] predicted a drop in water production if evaporatively-cooled seawater is used as a coolant instead of deep seawater. This became evident in the UAE and Oman SWGHs because evaporatively-cooled seawater has a temperature relatively higher than the temperature of deep seawater.

Davies and Paton [68] developed a simplified heat and mass transfer approach for understanding the SWGH processes at different loci within the greenhouse. Results showed that the maximum effectiveness of the condenser is attained when air leaving the condenser is cooled to the ambient wet-bulb temperature, i.e. coolant temperature. This study also derived the following equation that estimates the minimum effectiveness of the condenser (ε) required to make the greenhouse self-sufficient in irrigation water.

$$\varepsilon \geq 1/(1+(1/F)-2\alpha) \tag{1}$$

Where, F is the fraction of solar radiation transmitted to growing area and α is the fraction of air bypassing the condenser. Eq. (1) implies that as more solar radiation is allowed to reach the crops, a more effective condenser will be required to meet irrigation water demand.

Prior to the construction of the SWGH in Oman, a comprehensive technical and economic feasibility study was conducted using an integrated thermodynamic heat and mass transfer model that was developed through the experience gained from the SWGH in Tenerife [39,44,73–77,80]. Using local weather data of Oman, simulations showed that the wide shallow SWGH (200 m widex50 m deep) produced 125 m^3/day of freshwater while the narrow long greenhouse (50 m widex200 m deep) only produced 58 m^3/day. In terms of power consumption, the former greenhouse consumed less power (1.16 kWh/day) than the latter (5.02 kWh/day). It was also found that the oasis-type microclimate scenario produced the highest amount of water (23,529 m^3/ha.year) with the highest power consumption (2.3 kWh/m^3) as compared to the other two scenarios; temperate (20,370 m^3/ha.year and 1.9 kWh/m^3) and tropical (11,574 m^3/ha.year and 1.6 kWh/m^3). It was concluded that the dimensions of the greenhouse have the greatest overall influence on freshwater output.

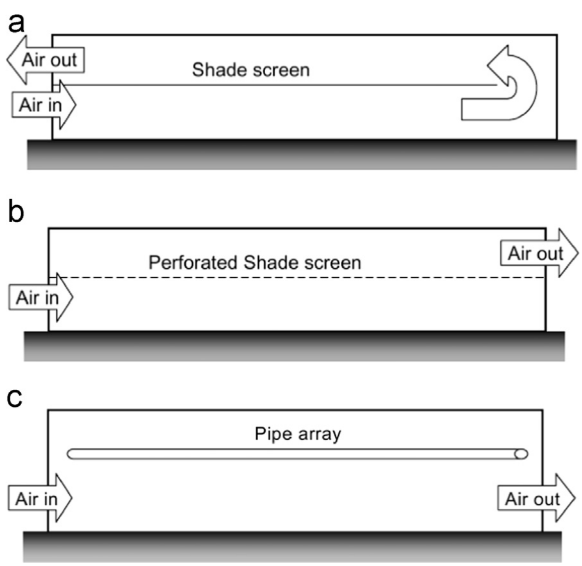

Fig. 2. Schematic of proposed airflow patterns; (a) elbow-shape air path, (b) air path through a perforated shade screen and (c) air path underneath a tube-array [61].

Because temperature and design of the condensation unit are two factors considerably affect the amount of freshwater production of SWGHs, Zurigat et al. [78] and Dawoud et al. [81] investigated on eleven possible techniques to lower the condenser's temperature and suggested a new design arrangement in the condensation unit. Simulation models were used to evaluate the most applicable cooling techniques and the following conclusions were drawn. The use of evaporatively-cooled surface seawater as a condenser coolant was found to be more applicable technique in dry areas than in humid ones as evaporative cooling is impaired with high humidity. This technique would stay valid even under humid conditions provided that (a) moisture of ambient air is reduced via a desiccating machine, (b) ambient air temperature is increased by regaining the latent heat of condensation or (c) the temperature of moist air entering the condenser is increased. Option (c) is currently operated in the Oman SWGH due to the economic and technical constraints associated with the other two options. Dawoud et al. [81] recommended improving the design of the SWGH condensation unit by dividing the process into two cooling loops according to what is depicted in Fig. 3. This improvement is expected to increase water production.

Zurigat et al. [78] provided a comprehensive steady-state simulation model for the SWGH in Oman. This model integrated all major components of the greenhouse, namely; first evaporator, greenhouse growing area, second evaporator and the condenser. For a precise simulation, the growing area was subdivided into seven layers; far-sky, ambient air, cover, inner air, crop canopy, soil surface and sub-soil layers. Although the model seems to be very detailed which most probably would lead to good predictions, it was not tested because this simulation was not within the scope of the study. Therefore, it was highly recommended to explore the accuracy of this integrated model and envisage potential ways to utilize it in the optimization of the SWGH processes.

Tahri et al. [82–84] simulated water production from the condensation unit of the SWGH in Oman using a mathematical model that was based on heat balance of all heat sources and sinks within the condenser. This model predicted the mass condensation rate of the condenser taking into account the key operating and weather

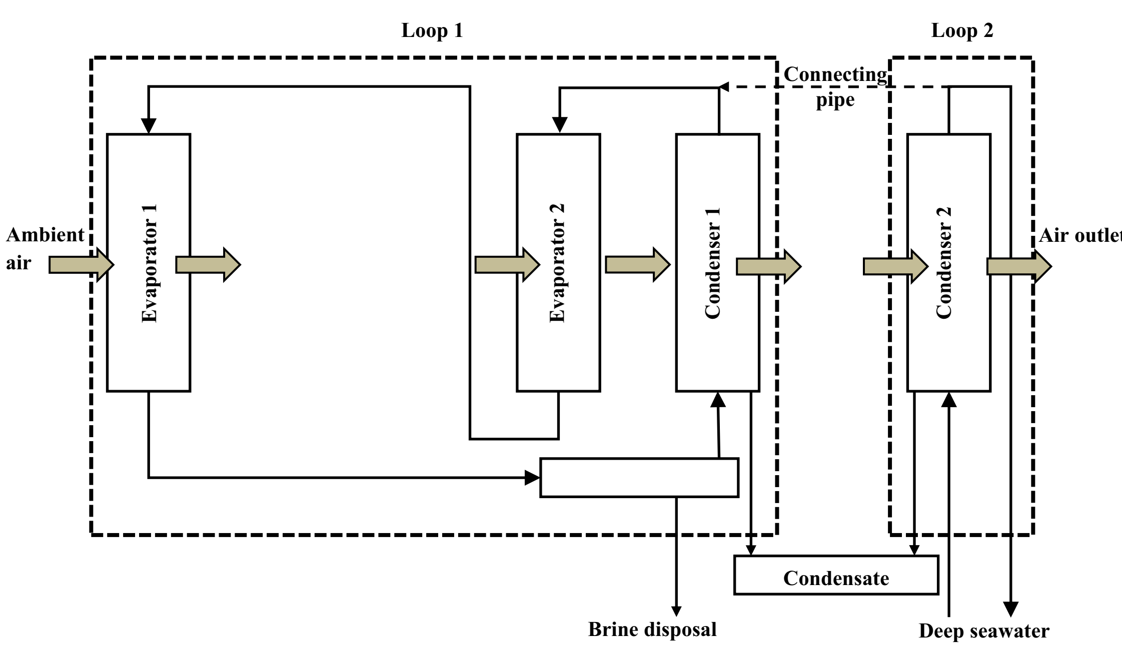

Fig. 3. Schematic of the suggested improvement on the design of SWGH in Oman [81].

parameters such as; inlet air dry-bulb temperature, relative humidity and solar radiation. Results of the validation experiments showed that the accuracy of the model to predict mass condensation rate was in the range of 8 to 15%. The results also showed that condensation rate was directly proportional to solar radiation intensity and dry-bulb temperature of moist air (see also, references [58,85]). However, solar radiation is considered to be the most important weather parameter influencing the performance of the SWGH (a similar finding was also stressed by [47,49,86]).

Due to the realization that the concept of SWGH primarily depends on the performance of condensation unit [50,63,78,81,87], Mahmoudi et al. [88] looked carefully at the existing condenser and found that it's performance was below expectations and recommended certain improvements. This condenser had low freshwater production rate, suffered frequent seawater leaks which deteriorated the quality of the produced freshwater and required pumps to be operated. Therefore, two passive condensers were proposed to overcome these limitations. The new designs were passive containment cooling systems in which one design was for an immersed-in-water condenser and the other was for an external passive condenser (Fig. 4). Simulation results showed that water production increases with increasing tube length and decreasing cooling water temperature. The new designs were predicted to increase daily water production from 0.298 m^3 (existing condenser) to 40.25 m^3. In addition to this outstanding increase in water production, the dependency on pumps, valves and accessories for water circulation is eliminated.

Salehi et al. [89] and Hajiamiri and Salehi [90] provided a detailed simulation model of the SWGH in Oman. Weather conditions of Bandar Abbas City, Iran were used in the simulation runs. Results showed that water production can be increased by decreasing air flowrate and/or increasing seawater flowrate through the first evaporator. Douani et al. [91] developed a heat transfer model to simulate the SWGH condenser, which was based on the previous model by Tahri et al. [82,83] with some modifications. New calculation techniques for estimating air-saturation temperature, coolant temperature and condenser-tube temperature were adopted. Results showed that the new model was more accurate in predicting the mass condensate rate than the previous model. However, some discrepancy between predicted and measured condensate rates still existed. Tahri et al. [85,92] tried to overcome this discrepancy through a mass transfer model. This model took into account all mass flows within the condenser of SWGH and predicted the mass condensate rate. It was found that the mass-transfer model developed in this study gave better estimates of mass condensate rate than the heat model developed earlier by Tahri et al. [82,83]. It was also found that the mass condensate rate is directly proportional to air velocity through the condenser such that the condenser produced the highest amount at the maximum air velocity of 7 m/s (a similar finding was also reported by [93]).

Following the recommendations to use direct-contact condensers as they are expected to have much higher condensation rates and are simpler in design [78], Zamen et al. [94] suggested and simulated two major changes on the existing design of the SWGH in Oman. The first modification is to replace the condenser with a direct contact dehumidifier (DCD) and the second is to use a more efficient and economical seawater heater (SWH). In the new design (Fig. 5), seawater in the hot water storage tank is pre-heated by the SWH until it reaches a threshold temperature and only at this temperature the humidification-dehumidification (HD) unit starts operating. The freshwater circulated in the dehumidifier is cooled down by heat-exchanging with surface seawater which is relatively cooler than the humid air leaving the humidifier. Both the humidifier and dehumidifier are made up from a polypropylene packing which is a long-lasting, corrosion-free and heat-resistant material with a specific surface area reaching 320 m^2/m^3. Simulations showed that the height of HD units plays a vital role in water production and a height of 60 cm is optimal. It was also found that water production increased to a peak point with increasing airflow velocity and then started decreasing at various seawater temperatures in the storage tank (see also reference [65]). Maximum water production was obtained at air velocity of 0.16 m/s and seawater temperature of 60 °C. In the case of SWH with 80 tubes, it was concluded that a SWGH with an area of 200 m^2 could produce 0.6 to 2.25 L/m^2.day at different months of the year. This amount is more than the amount reported for the existing condenser, i.e. 1 to 2 L/m^2.day [62].

On the third simulation procedure, Yetilmezsoy et al. [95] employed a statistical approach to derive an empirical power-law relation (Eq. 2) using the simulation results generated by earlier studies [44,73,74,76]. This relation estimates the condensation rate (R_c) of SWGHs from the width-to-length ratio (W/L):

$$R_c = 81.861\ (W/L)^{0.1571} \quad R^2 = 0.9972 \tag{2}$$

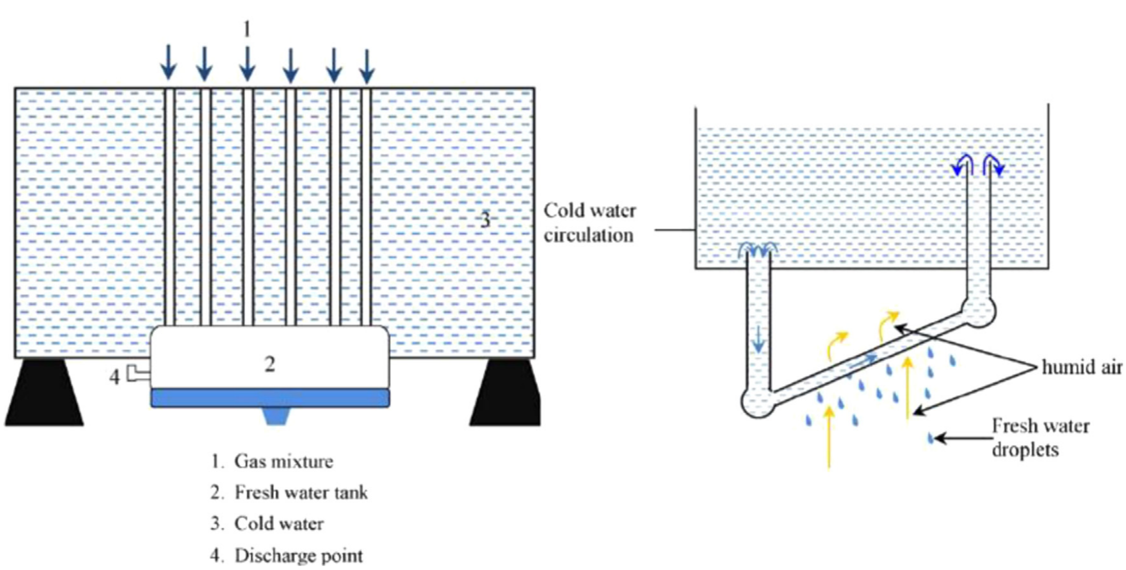

Fig. 4. Passive containment cooling systems; immersed-in-water condesner (left) and external passive condenser (right) [88].

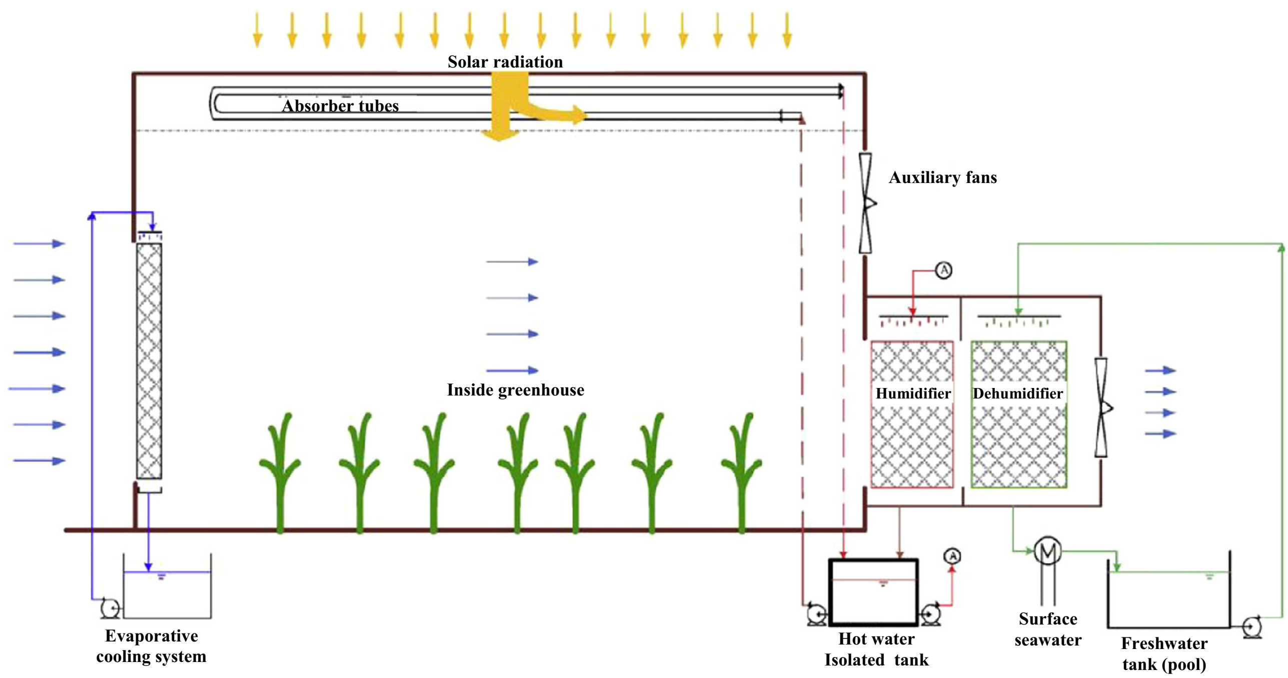

Fig. 5. Proposed changes of the SWGH in Oman [94].

When the real dimensions of the Oman SWGH (W=16 m and L=45 m) are substituted in Eq. (2), the freshwater production was estimated to be 69.59 m^3/day. However, this is a great overestimation when compared to the measured maximum water production of less than 1 m^3/day of this SWGH [52]. Therefore, the accuracy of this empirical relation needs to be further verified.

To overcome the complexity and time-consuming nature associated with analytical heat and mass transfer modeling, a multiple-regression model predicting the condensation rate (R_c) of the Oman SWGH was developed [95], Eq. (3). Comparison between the predictions and measured data, the model accurately predicted the condensate rate. Additionally, this model was found to be more accurate than the analytical heat transfer model of Tahri et al. [82,83] and less accurate than the mass transfer model of Tahri et al. [92].

$$R_c = \frac{(0.001883)(RH_{in})^{3.382}(T_{dbin})^{2.915}(m_a)^{0.222}}{(T_{swin})^{0.147}(m_{sw})^{0.073}} \quad R^2 = 0.9919 \tag{3}$$

Where R_c is the mass condensation rate (kg/hr), RH_{in} is the inlet relative humidity (fraction), m_a is the air mass flowrate (kg/s), T_{dbin} is the inlet air dry-bulb temperature (°C), T_{swin} is the inlet seawater temperature (°C) and m_{sw} is the seawater mass flowrate (kg/s).

1.2.4. Concluding remarks on review

Although the SWGH technology is relatively new (circa 20 years old), several empirical and theoretical studies have focused on improving the technical performance of this technology; mainly the condensation unit. It was clearly noticed that many promising theoretical improvements were not practically implemented yet. Therefore, future work should focus on analyzing those suggested improvements and implementing the most efficient ones with respect to two criteria; technical performance and cost-effectiveness. As reported by a number of researchers [49,78,94,96,97] that the direct-contact dehumidifiers (DCD) meet both criteria. Therefore, it is highly recommended to further investigate the potential of using this type of dehumidification technique.

2. Experimental findings from SWGH in Oman

2.1. Experimental set-up

This section presents some important experimental findings from the experimental setup of the Oman SWGHs (Fig. 6). This greenhouse is a double-span tunnel-type greenhouse, located 50 m from the seashore. It consists of two water circuits; cold and warm (Fig. 1). The cold circuit links the first evaporator with the condenser and the warm circuit links the solar heater with the second evaporator. The solar heater is integrated inside the greenhouse just under the covering plastic sheet in order to provide the necessary shading and to avoid the extra-heating effect of solar radiation. The condenser is a cross-flow heat exchanger consisting of 4832 plastic tubes in which evaporatively-cooled seawater flows [82].

Delta-T dual temperature/relative humidity sensors were used to measure air temperature and humidity variations across the greenhouse. Inlet and outlet temperatures of the coolant and heater's water were monitored using two Delta-T sealed temperature probes. A Delta-T tipping bucket gauge was used to measure the dehumidification rate. Solar insolation was monitored using a Delta-T photodiode. Data from all sensors were retrieved and recorded at ten-minute intervals using a Delta-T datalogger.

2.2. Results and discussion

2.2.1. Air temperature and humidity changes

Air temperature and humidity variations due to cooling and humidification across the first evaporative cooler (1^{st} evaporator) are illustrated in Fig. 7. The maximum air temperature drop was 9.8 °C when the ambient air temperature and relative humidity were 38.5 °C and 25.4%, respectively. Under drier conditions, the temperature drop can even reach 12 °C [98,99]. On the other hand, the maximum increase in relative humidity was 37.7%.

As air streams through the cropping area of the greenhouse, its temperature increased due to the solar heat input. Fig. 8 illustrates this temperature gradient at three positions in the cropping area; front, middle and back. However, this gradient is not very obvious

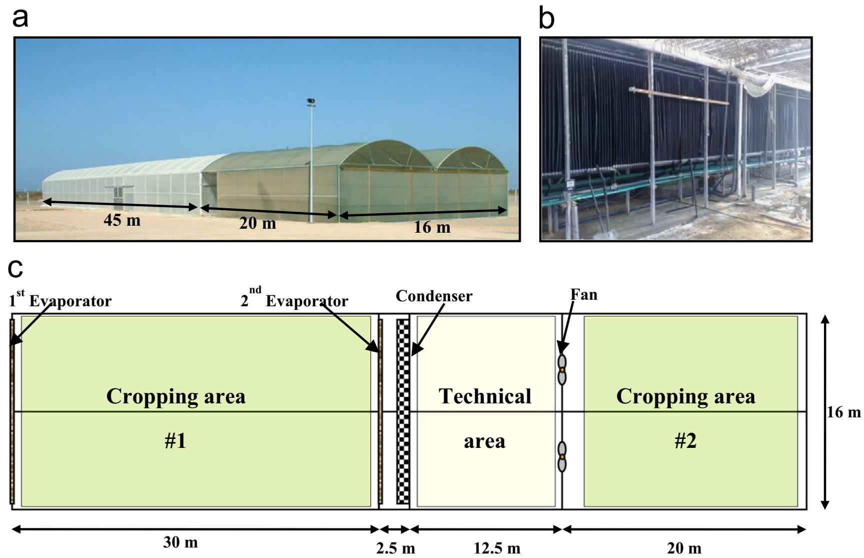

Fig. 6. Illustration of SWGH in Oman; (a) Side-view, (b) condenser and (c) plan view.

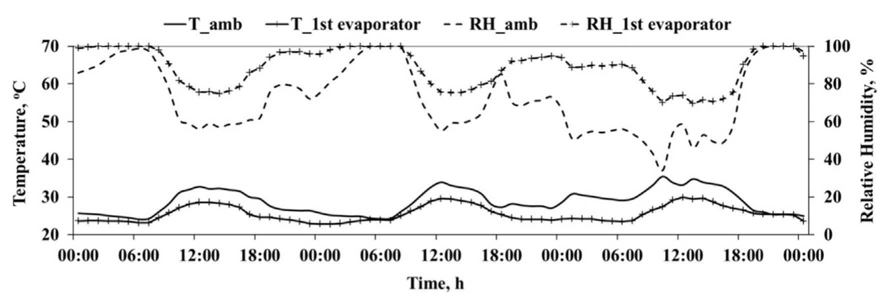

Fig. 7. Temperature and relative humidity changes across the first evaporator.

when the greenhouse was cultivated due to the cooling effect caused by the evapotranspiration process and due to the shading effect exerted by the solar water-heating tubes placed over the canopy. In cases when solar tubes were not employed, the portion of solar radiation in excess to what plants need for photosynthesis is turned into hot growing conditions and hence, increased the irrigation requirement [55,74,81]. Fig. 9 clearly shows the temperature gradient at occasions of dry bare soil (non-cultivated greenhouse) when solar tubes were not used. This increase in air temperature caused a simultaneous decrease in relative humidity which, in turn, caused an increase in the air moisture-holding capacity. Therefore, this justifies adding a second evaporator before the condenser in order to further load the air with moisture. Fig. 10 illustrates that the second evaporator was successful in achieving a near-saturation level (90–100% relative humidity) at most of the times as compared to the lower humidity levels of ambient air and after the first evaporator.

2.2.2. Water temperature and condensation potential

Condensation of water vapor is strongly influenced by the temperature of the condenser [48] that should be maintained below the dew-point temperature of moist air streaming through the condenser tubes in order for condensation to take place. As a result of evaporative cooling, the seawater used to moisturize the 1st evaporator experienced a decrease in temperature from top to bottom. The maximum drop in temperature reached 2 °C. Al-Ismaili [51] and Perret et al. [53,54] found that the temperature of water flowing down the first evaporator was always below the dew-point of moist air passing through the condenser of their prototype SWGH (see also reference [100]). This was very evident in the Oman SWGH during the daytime when the outlet seawater from the first evaporator was used as a coolant in the condenser (Fig. 11). This is because the moist air entering the condenser was pre-heated and humidified in the second evaporator using hot seawater coming from the solar heater [50,62,68]. Hence, this heating effect only takes place during the daytime but at night (no solar heating) the coolant temperature becomes greater than the dew-point temperature of the moist air, i.e. no condensation.

2.2.3. Freshwater conservation and production

The SWGH in Oman works as a conservational means of freshwater resources by saving almost 2/3 of freshwater demand in ordinary greenhouses [8]. This is because in SWGHs, seawater or saline groundwater is used to moisten greenhouse evaporators that normally consume almost 2/3 of the total water demand in greenhouses. The overall aim of SWGHs is to produce the remaining 1/3 of freshwater for irrigation. Fig. 12 shows that condensation rate for typical summer days coincides with the ambient solar insolation. It also coincides with occasions when the dew-point temperature is higher than coolant temperature (see Fig. 11). It was also observed that almost 98% of freshwater production occurred between 9:00 and 18:00 h [55,83,88,91,92].

Average cumulative water production of the Oman SWGH ranged from 300 to 600 L/day [52,55]. However, this amount represents almost half of the irrigation water demand (nearly 1000 L/day) of a fully-developed cucumber crop which grows best at salinity ≤ 2.5 dS/m (cucumber is selected because 90–95% of greenhouses in Oman are cultivated with this crop, see references [6,101–103]. Since

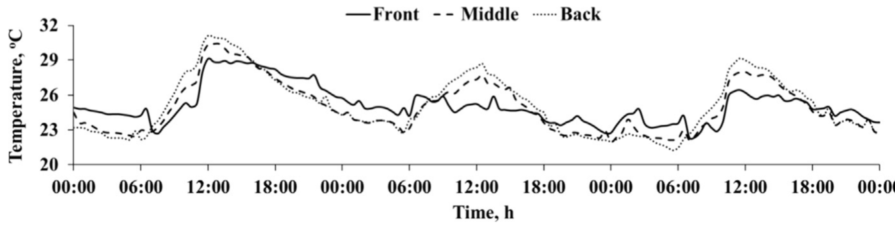

Fig. 8. Temperature gradient of air flowing through cultivated area of greenhouse.

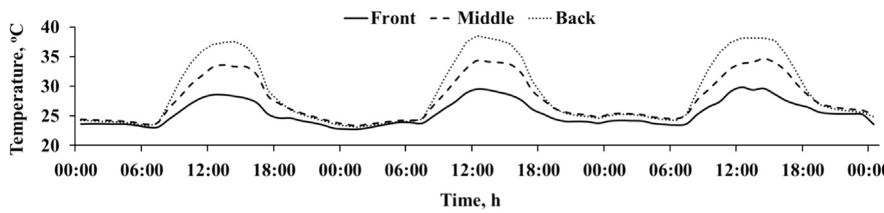

Fig. 9. Temperature gradient of air flowing through non-cultivated area of greenhouse.

the produced water has a distilled-water quality with an EC value of less than 0.020 dS/m (virtually zero salinity, [47,49,55,62,78,81,87]) then there is a great potential to increase water volume by blending it with saline groundwater (EC=4 dS/m). Doing so would increase the volume by nearly 100% depending on the salinity of the groundwater and the desired salinity of the mixed water. A similar mixing was practiced by other researchers in order to bulk out the amount of water used for irrigation [17,104,105].

2.3. Concluding remarks on experimental findings

Although the produced irrigation water, so far, is less than required, there is still a room for improvement as seen in Section 1.2.3. Therefore, further research-and-development work is highly recommended. Future work should focus in the optimization of three major areas which are thought to be very significant in increasing freshwater production. The first one is to optimize the design and efficiency of the condenser to harvest water vapor from the moist air. The second is to increase the temperature of the moist air entering the condenser. The last one is to lower the temperature of the condenser's coolant.

3. SWGH economics

It is well comprehended that economic evaluation of SWGH is a prerequisite to the commercialization of this technology. Nevertheless, it was found that the available cost information for solar desalination, in general, and for humidification–dehumidification desalination (HDD) processes, in particular, is very limited [16,106]. Chaibi [12] stated that this information deficiency is also true for integrated greenhouse solar stills. For the SWGH, the situation is even worse owing to the fact that not a single study found in literature was devoted for the economic aspects of SWGH. Most of these studies concentrated on the technical part and did not touch the economic part. A given desalination system could be technically-efficient yet it could be uneconomic because the cost of water production is too high. Therefore, the technical and economic criteria of SWGH ought to be simultaneously considered when optimizing the SWGH technique for a commercially-viable freshwater production [15,55,59,74]. Failing to conduct a thorough economic analysis could end-up with decommissioning of the whole desalination project once the water production process is judged to be uneconomic [58,61].

The total cost of freshwater production from HDD systems is affected by the partial costs of several important factors, namely; material availability and cost, fabrication, plant size, land price, labor, maintenance, replacements, pumping of feed water, interest/amortization rates and magnitude and price of produced freshwater [15,29,107,108]. Luckily in the SWGH, some of the costs required for HDD systems are already considered in the construction costs of the greenhouse. For instance, the large collection area necessary for solar desalination, which is considered as a major disadvantage [29,109], is the same area of the greenhouse. Similarly, the structure for the desalination unit and the greenhouse is the same. Likewise, the cooling process required for cultivation and the evaporation process required for desalination take place in the same evaporative cooler. Definitely, the SWGH freshwater production can be more economic when the costs of land space, structure and humidifier is excluded from the cost of freshwater production and when the profits gained from cultivating high-value crops and utilizing the surplus water is included [49,58].

The SWGH is considered to be an energy efficient technology. Comparing to the reverse osmosis desalination technique which has the lowest energy cost among other techniques (<4 kWh/m^3), the SWGH is even more energy efficient with an energy consumption of less than 3 kWh/m^3 [49]. Furthermore, simulation studies conducted by several researchers showed that the energy consumption of the SWGH can be as low as 1.9 kWh/m^3 [39,44,73–77,80].

Table 1 presents the first trial to have an insight at the capital and operational costs of the SWGH technology using the SWGH design in Oman and local costs of material, utilities and labor. This analysis is conducted for a 20-year lifetime which is a common practice in solar desalination systems [74,107,110]. As clearly seen from the table, the SWGH as a solar desalination technology is a capital intensive enterprise [16,74,111] where almost 58% of the total cost is for the materials and construction. The condensation unit alone costs more than 20% of the total cost. Therefore, the commercialization of the SWGH technology necessitates the reduction of the capital costs. This can be particularly attained by replacing the existing all-plastic condenser with a direct contact dehumidification (DCD) unit. The DCD condensers were reported to have several superior characteristics such as high condensation rates, simple design, low cost, corrosion-free and fouling-free [49,78,94,96,97]. Cost estimation of produced freshwater from solar desalination is a complicated process as it requires a wide-ranging investigation which takes into account all possible

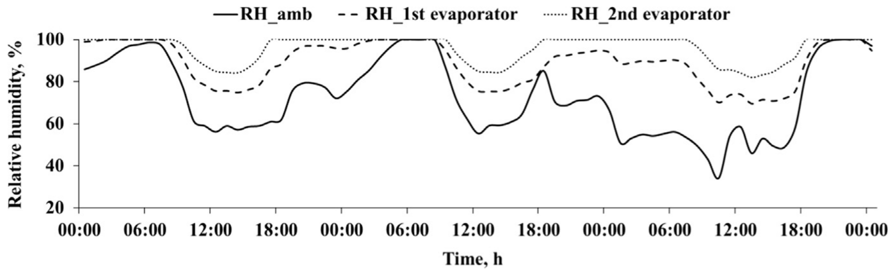

Fig. 10. Relative humidity of ambient air, after 1st evaporator and after 2nd evaporator.

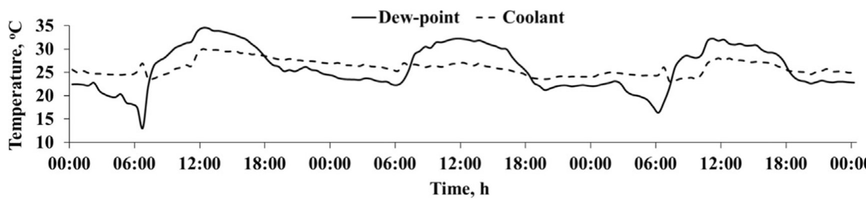

Fig. 11. Dew-point temperature of moist air and coolant temperature.

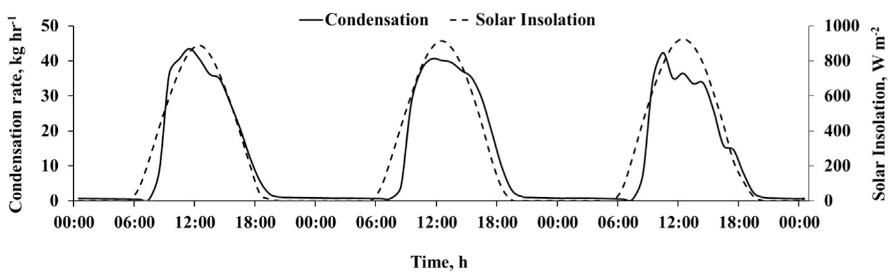

Fig. 12. Condensation rate and ambient solar insolation of the SWGH in Oman.

Table 1
Cost-benefit analysis of the SWGH in Oman (all prices in USD).

Parameters	Year(s)					Total
	1	2–5	6–10	11–15	16–20	
Capital Costs:						
Structure for basic greenhouse	52,765	3186	11,337	8151	10,062	85,501
Structure for HDD system	43,356	0	2016	3836	2016	51,224
Machinery and equipment	2165	40	1135	1765	1135	6240
Total	98,286	3226	14,488	13,752	13,213	142,965
Variable Costs	5152	20,608	25,760	25,760	25,760	103,040
Benefits from crop yield	22,500	90,000	112,500	112,500	112,500	450,000
Net Return	−80,938	66,166	72,252	72,988	73,527	203,995

tangible and hidden costs and benefits [88]. Such an economic study is highly recommended [78].

4. Final conclusions and recommendations

Based on the review and discussions presented in the above sections, the following conclusions and recommendations were made:

- This review provided the first comprehensive insight of the recently-evolved SWGH technology. It has highlighted the importance of this concept as a water conservational and augmenting tool.
- The amalgamation of water desalination and crop cultivation in the same structure is very unique and would definitely contribute to agricultural sustainability in salt affected areas of the world.
- Although the SWGH concept has undergone several stages of improvements, the freshwater production from the SWGH located in Oman is still below expectations.
- Tremendous efforts have been dedicated towards investigating possible techniques that would enhance the technical performance of SWGH, i.e. more freshwater production. These investigations included analytical and empirical modeling as well as CFD simulations. Results from these studies showed a significant possibility to increase water production and so, new approaches have been proposed.
- Literature revealed a noticeable gap in the knowledge of SWGH economy as it was found that not a single study was dedicated to study the economic aspects.
- Because technical and economic criteria of SWGH ought to be simultaneously considered for a commercially-viable freshwater production, thorough economic studies are strongly recommended.
- On the basis of various ideas posted in previous studies, further R&D work is highly encouraged.

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