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Water production for irrigation and drinking needs in remote arid communities using closed-system greenhouse: A review

A.E. Kabeel [a], *, Emad M.S. El-Said [b]

[a] *Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt*
[b] *Industrial Engineering Department, Faculty of Engineering, Fayoum University, Fayoum, Egypt*

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ABSTRACT

Water needs for agriculture, food production and drinking are considered one of the most critical challenges facing the world in the present days. This is due mainly to the scarcity and lack of fresh water resources, and the increasing ground water salinity. Most of these countries have a high solar energy potential. This potential can be best developed by solar desalination concepts and methods specifically suited for rural water supply, irrigation. In this paper, a humidification–dehumidification (HD) water desalination system with several technologies for irrigation and drinking needs in remote arid areas is introduced from technical and economic point of views. This study has investigated (1) detailed discussion of technical developments, economical and sustainable aspects; (2) benefits of the new design over traditional applications, desalination and other irrigation methods; (3) specific requirements and implementation challenges in remote and cold regions; (4) performance and reliability improvement possible techniques. Recommended researches and projects leading to high efficiency, economical and sustainable applications of some desalination devices driven by solar energy are highlighted.

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1. Introduction

About 20 percent of the world's people live in regions that don't have enough water for their needs (according to the World Health Organization), With the global population increasing by 80 million each year, a third of the planet will likely face water shortages by 2025. This looming water crisis is inextricably linked to food production because agriculture accounts for 70 percent of all fresh water used, and obtaining irrigation water in arid regions by classical methods has serious environmental impacts. Drilling wells can deplete ground water, and desalination is energy-intensive and leaves behind concentrated brine. The goal of sustainable agriculture in arid and semi arid regions is challenged as farm management needs to address the needs of crops under often difficult conditions. Plants growing in the more arid areas confront a number of stresses causing factors including drought, high temperatures, high winds, low humidity, high radiation, dust and salinity. These factors become realistic both as direct physiological stresses in the plants and indirectly, via alterations to the physical environment. To overcome these difficulties, the use of greenhouses can provide a proper environment to plant growth. There are more than 50 countries now in the world where cultivation of crops is undertaken on a commercial scale under cover. In hot climates, however, the greenhouse inside temperature can reach so high value that prevents its utilization or, otherwise, a costly mechanical air conditioning system should be used [1].

The agriculture inside greenhouses assisted by a humidification dehumidification desalination system produces crops year-round in hot, dry areas using salt water and sunlight. cucumbers, tomatoes, peppers, lettuce, strawberries, herbs-anything that can be grown in traditional greenhouses-can be grown in GHHD. The award-winning technology was inspired by the natural water cycle where salt water heated by the sun evaporates, cools to form clouds, and returns to earth as precipitation. The system involves pumping salt water (or allowing it to gravitate if below sea level) to an arid location and then subjecting it to two processes: first, it is used to humidify and cool the air, and second, it is evaporated by solar heating and distilled to produce fresh water. Finally, the remaining humidified air is expelled from the greenhouse and used

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* Corresponding author. Tel.: +20 1001543587; fax: +20 403453860.
E-mail address: kabeel6@hotmail.com (A.E. Kabeel).
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to improve growing conditions for outdoor plants. This enables the year round cultivation of high value crops that would otherwise be difficult or impossible to grow in hot, arid regions. Fig. 1 shows the basic GHHD model cycle within a controlled environment [2].

Inside the greenhouse The plants do not expose to salt. So whilst it is interesting to understand how salt hampers the growth of plants in a GHHD. The water used in the greenhouse is distilled from salt water by processes in the greenhouse and the result is that the plants get distilled water, no salt at all [3].

A few literature have been published in GHHD such as [4–6]. The technical and economical review of the GHHD system with different methods for irrigation and drinking needs in remote arid areas from technical and economic point of views studied. A several technology's applicability of solar desalination systems is also reviewed. The main objective of this work is to analysis the influence of humidification–dehumidification technology related parameters on fresh water production and the growth of crops in a greenhouse system.

2. GHHD benefits over traditional greenhouse and other irrigation methods

The GHHD systems are designed to create an environment that is cool, humid and bright, a reverse of the warming effect of typical cold climate greenhouses. It is for use in desert climates adjacent to saline water. None of the methods currently used to supply irrigation water in arid regions, including over-abstraction from ground reserves, diverting water from other regions and energy-intensive desalination, are sustainable in the long term. Traditional greenhouses and other irrigation methods the GHHD as a whole sounds great, and has a several benefits as follows:

1. **Dry air treatment**; facing the prevailing the entire dry air from humidifier catch salt water and evaporates it. It increasing of the humidity inside the GHHD reduces water use and creates a cold and humid environment in the planting area.
2. **Airborne contaminants**; the saline water humidifiers are effective at removing or reducing airborne contaminants, including salt spray, dust, pests, pollen and insects [7].
3. **Fresh water production**; the fresh water produced is pure and distilled from salt water, without chemical additives or treatment.
4. **Renewable energy utilization**; the GHHD considered by developing small stand-alone desalination plants that can utilize renewable.

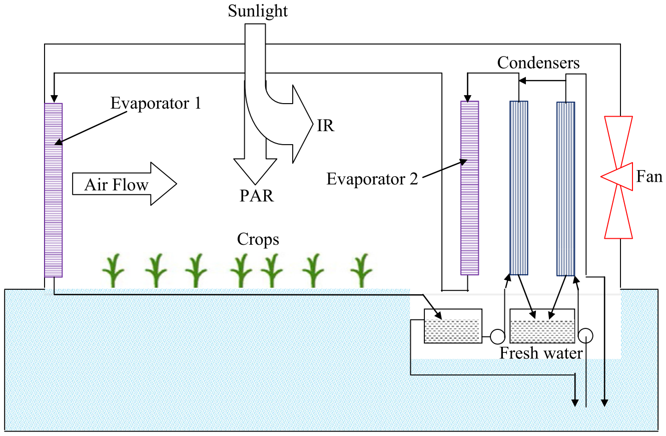

Fig. 1. Section through GHHD (figure is used with permission from [2]).

5. **Fossil-fuel requirements**; unlike traditional greenhouses, which often rely on gas or other fossil fuels for temperature control and CO_2 enrichment, GHHD use saline water and sunlight to control the growing environments, with low grade electrical power to feed pumps and fans.
6. **Water saving**; water collection and reduces water shortage in dry periods.
7. **Pesticide need**; the salt water humidifiers have a biocidal and a scrubbing effect on the ventilation airflow. This greatly reduces or eliminates the need for pesticides [8].
8. **Economics effectiveness**; commercial grade crop yields are coupled with significantly lower capital and operating costs result in enhanced operator economics [7].

Currently there are some 200,000 ha of conventional greenhouses in the Mediterranean region. Most of these, if not all, face water quality and availability issues and indeed many contribute to the depletion of ground water. By using greenhouses to create fresh water from salt water, the problem is reversed [7].

3. Specific requirements and implementation challenges of GHHD in remote regions

A GHHD produces crops in hot, dry areas using mainly salt water and sunlight. So, the main specific requirements are energy and water. The next section will discuss briefly these requirements in remote regions.

3.1. Energy requirements

In GHHD the thermal solar energy converts salt water to water vapor. The electrical requirements for fans are modest and, in the absence of grid power, can be provided by photovoltaic panels without the need for batteries, inverter or standby generator. Table 1 shows the performance of GHHD in terms of fresh water production and the power consumption of the fans and pumps per cubic meter of fresh water.

3.2. Water requirements

The GHHD system requires only a supply of salt water (seawater or brackish water) and discharges salt water into the sea or other reservoir. It is therefore intended for use near the coast or ground water wells. Table 2 shows the general water and environmental requirements for some crops.

3.3. Implementation challenges

That the provision of the necessary requirements for the GHHD is not enough to run it in the arid remote regions, but must also overcome some of the implementation challenges such as:

1. The process operation is not stable. The ventilation fans must change as the weather shifts and the wind blows in from different directions. These fans also always be powered. The

Table 1
Performance of GHHD for three climate conditions [9].

Climate conditions	Fresh water produced, m^3/year-ha	Power consumed, kWh/m^3
Temperate	20,370	1.9
Tropical	11,574	1.6
Oasis	23,529	2.3

Table 2
Main crop requirements inside greenhouses (adapted from [1]).

Crop type	Required water (L/m^2)
Tomato	3
Cucumber	3
Pepper	3
Lettuce	3
Flower	8

cardboard layers must be custom designed for each location in order to optimize the size and shape of the ducts.
2. The technology requires salt water pumping from water source to greenhouse.
3. Despite the availability of the technology, such obstacles may still prevent the people from adopting this new farming method in some countries.
4. Large (outside) air volumes are required for cooling, making it impossible to supply the plants with extra CO_2 concentration which must stay between 360 and 1000 ppm to increase crop growth [10].
5. Seasonal heat storage requirements for closed GHHD, which is expensive and not possible in many regions.
6. Problems of specific produced water quality such as high salinity manganese, fluoride, heavy metals, bacterial contamination and pesticide/herbicide residues [11].

So, in the next sections we will discuss some of technical development of GHHD which may help to perform and save the requirements and face the implementation challenges in remote regions.

4. Technical developments of GHHD

A large number of researchers, institutes and industries apply serious effort to develop and improve the performance of solar thermal energy driven GHHD and make it highly desirable and applicable. Advancement's technical development of GHHD applications for different types of systems reported in the last few years are briefly described and analyzed below.

4.1. GHHD performance development

Kim et al. [12] studied the distribution of humidity in a greenhouse using three-dimensional (3-D) computational fluid dynamics (CFD). Two types of humidity distribution were considered: humidifying using a fog cooling system, and dehumidifying using refrigerative dehumidifiers to reduce the overall difference of humidity between the middle and bottom zones of a greenhouse in addition to a fog cooling system.

Also, Davies and Paton [13] modeled a GHHD combines a solar desalination system by using a CFD modeling tool and calibrate it with results from a prototype of greenhouse in the United Arab Emirates (UAE).

A key feature in improving overall efficiency is the need to gain a better understanding of the thermodynamics of the processes and how the designs can be made more efficient. Goosen et al. [14] determined the influence of greenhouse-related parameters such as dimension of the greenhouse (width and length), roof transparency, height of the front evaporator, height of planting area, height of the rear evaporator, height of the condenser, orientation of greenhouse, seawater pipe diameter, length; volumetric flow; pit depth, height, wall thickness; air change; fin spacing and depth on a desalination process that combines fresh water production with the growth of crops in a greenhouse.

Davies [15] studied a liquid desiccation with solar regeneration as a means of lowering the temperature in evaporative cooled greenhouses. Fig. 2 shows the system used. The air is dried prior to entering the evaporative cooler. The cooling is assisted by using the regenerator to partially shade the greenhouse. The heat of desiccation is transferred and rejected at the outlet of the greenhouse. The cooling system lowers the maximum summer temperatures by 5 °C compared to a greenhouse cooled by simple fan ventilation. This is improvement can be obtained with a conventional evaporative cooling system as is commonly used in greenhouses today.

Zaragoza et al. [16] developed a GHHD consists of humid air solar collector system that follows the principle of a closed two phase thermosiphon to increase the possibility of water purification. The decentralization of heat and water supply opens the possibility of residential areas where greenhouses fed with low quality water (gray water and brackish water) could be used to produce distilled water as well as heat and fruits. Fig. 3 gives cross-section diagrams of the greenhouse and its functionality during day and night [17].

Vadiee and Martin [18] presented theoretically a qualitative economical assessment of a closed greenhouse. By considering borehole thermal energy storage (BTES) system as the seasonal storage, with a phase change material or a stratified chilled water daily storage system to manage the peak load. A BTES primarily stores low temperature heat such that a heat pump would be needed to supply the heat at a suitable temperature. The major investment could be paid within 7–8 years with the savings in auxiliary fossil fuel considering the seasonal TES systems. However, the payback time may be reduced to 5 years if the base load is chosen as the design load instead of the peak load. In this case, a short-term TES needs to be added in order to cover the hourly peak loads.

4.2. Integration of solar distillation plant with GHHD

There are a number of ways in which the integration of a solar distillation plant with a GHHD system could save costs and lead to more favorable economics. For example, certain components of a solar still such as the glazing and the base are provided for by the cladding and the foundation of the GHHD. In addition, there are a number of indirect cost savings that may be less obvious.

Chaibi [22] presented a model and derived performance parameters for a water desalination system of GHHD with roof integrated solar still. He studies the influence of solar irradiation, optical material properties and process parameters on the fresh water production and total light transmission. As about 40% of the solar irradiation has to be transmitted, the thermal efficiency is around one-third of the efficiency for tilted types of conventional stills. Estimated expansion water production capacities are in the range of 1–1.6 kg/d/m^2 [19]. Thus, the suggested system could be a self-supply one that could produce fresh water for crop irrigation.

Chaibi and Jilar [20] used the system shown in Fig. 4 to assess the studied concept compared to conventional, single glassed greenhouses using computer simulations and field experiments. A system integrated in 50% of the roof area had the capacity to cover the annual demand for a low canopy crop like lettuce with yield reduction is about 25% in relation to a conventional greenhouse case with a single glassed roof.

Ghosal et al. [21] analyzed a solar desalination system combined with a GHHD for different climate conditions of India. They The discussed the effects of various still and design parameters (water temperature, greenhouse room air temperature, glass cover temperature, flowing water mass over the glass cover, the hourly yield of fresh water and thermal efficiency) on its performances. The

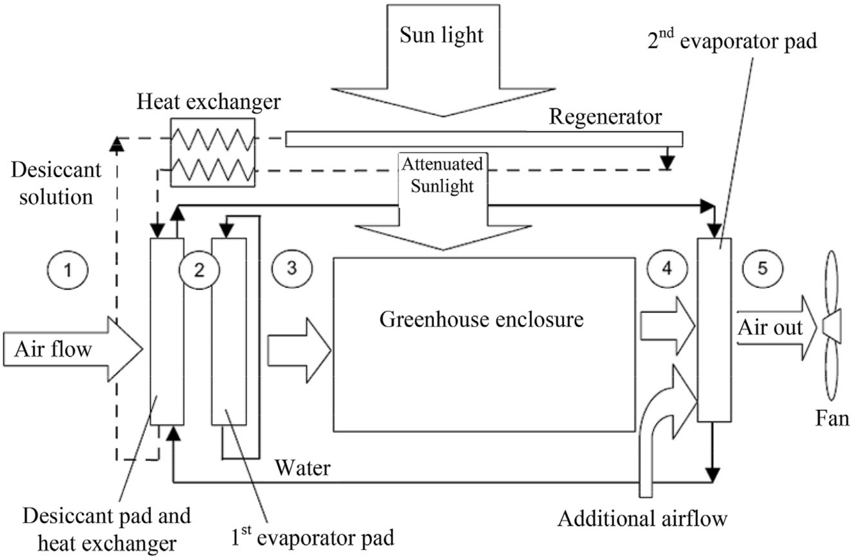

Fig. 2. The system used: an evaporative-cooled greenhouse with enhanced cooling by means of desiccation of the incoming air (figure is used with permission from [15]).

yield of fresh water was found to be higher in warm, humid climates than composite climate.

Mari et al. [22] studied experimentally the performance of a solar still integrated in a greenhouse. The system consists of 28 water basins located at the top of the greenhouse. The inner surface of the roof is used as a condensation surface and the fresh water produced is collected in a storage tank. Contrary to what happens in traditional solar stills, distillation took place after solar noon and during the night due to the low absorption of solar irradiation when the solar still is integrated into a greenhouse. Installing the solar still reduces the solar radiation and photosynthetic active radiation inside the greenhouse (about 52%).

4.3. *Possible techniques for GHHD reliability improvement*

Humidification and dehumidification processes by increasing dry air humidity ratio and cooling the moist (humidified) air for water extraction respectively are the keys to a successful application of GHHD. So, the development of humidifiers and condensers has a direct effect on the GHHD reliability. In the next section we will review possible techniques for GHHD performance and reliability improvement based on humidifiers and condensers for humidification and dehumidification technologies.

Dawoud et al. [23] presented a theoretical study of possible cooling techniques for the condenser of GHHD. Applying evaporative cooling for a wider range of ambient relative humidity is to increase the temperature of air entering the condenser. In case deep seawater is used to cool the condenser, both the cooling capacities of cooling machines and the corresponding flow rates of deep seawater have been estimated for different condenser inlet and outlet temperatures.

Lychnos and Davies [24] carried out experiments and theoretical modeling to predict the performance of a solar powered liquid desiccant cooling system for greenhouses during the hot summer months in different climts conditions. They tested two components of the system in the laboratory using $MgCl_2$ desiccant: (i) a regenerator which was tested under a solar simulator and (ii) a desiccator which was installed in a test duct. They showed that the desiccant system lowers average daily maximum temperatures in the hot season by 5.5–7.5 °C compared to conventional evaporative cooling. The concept of the cooled greenhouse system is shown schematically in Fig. 5.

Mahmoudi et al. [25] developed a mathematical model for passive condenser in order to enhance the performance of a GHHD system with a condenser immersed in a water basin, and an external passive condenser connected to a basin of water placed on top of the cooling unit. They suggested that the passive condenser

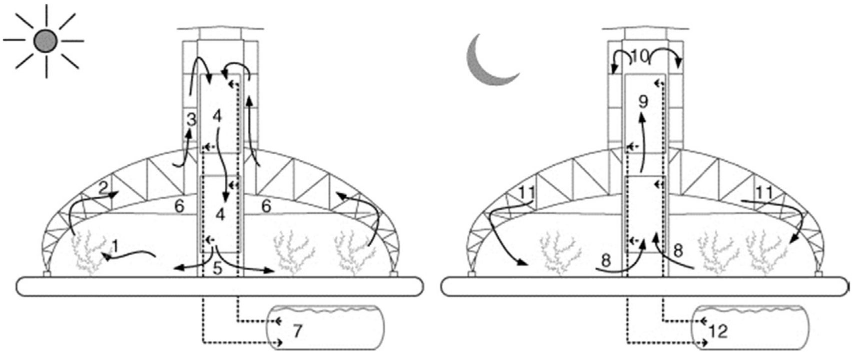

Fig. 3. Function of the greenhouse during the day and the night (figure is used with permission from [17]).

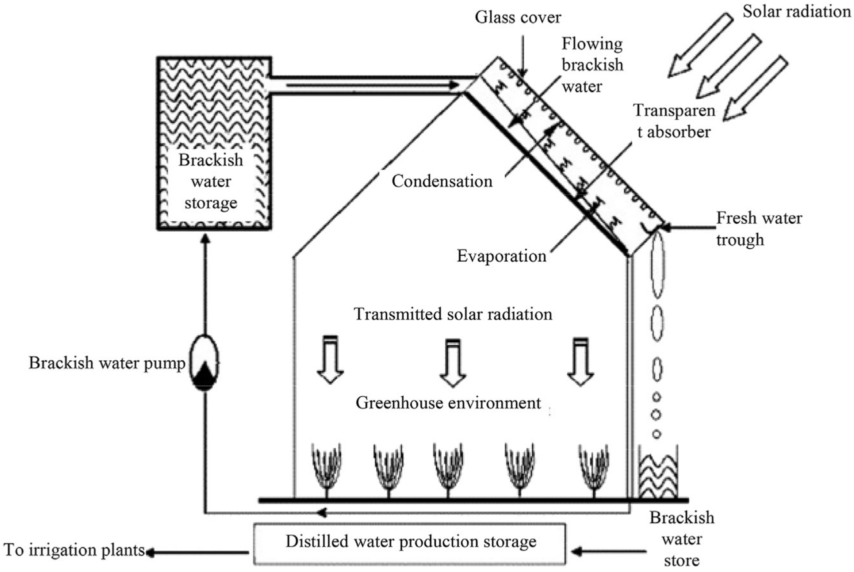

Fig. 4. A water desalination system integrated into a greenhouse roof (figure is used with permission from [20]).

has a much greater water production capacity than the existing pump driven system.

Tahri et al. [26] presented an experimental feasibility analysis focused on the influence of operating parameters such as seawater temperature, moist air temperature, air relative humidity, speed of movement and intensity of solar radiation to estimate the optimal operation of GHHD prototype. The results demonstrate the positive impact of solar radiation on the flow of condensate to reach a speed of about 65 l/h for a solar radiation around 800 W/m^2 and that it reaches its minimum value, almost zero, at gloaming. They tested the impact of the temperature of cooling water (seawater) and note that the trend confirms the negative and shallow this parameter on the flow.

There are many indicators which may cause of discrepancies performance of the specific consumption of electricity in GHHD such as:

1. Applicability of sustainable considerations in greenhouse design, construction, components and plant size
2. Local climatic conditions and site selection.
3. Environmental control systems conditions such as temperature and humidity.

The above indicators must take in account to optimize and reduce the electrical power consumption.

Bulcka et al. [27] compared ventilated greenhouse to natural ventilated reference greenhouses during two years of operation. In the first year, the ventilated greenhouse resulted shows a 9.6% increase of energy consumption compared to the reference; most likely due to the greenhouse lay out. In the second year, the performance of the mechanical concept was improved and the energy saving was 12%. The used mechanical ventilation appeared to be insufficient as the need for natural ventilation is still noticeably present. The energetic performance can be enhanced by implementing a more efficient low temperature heating system for preheating of the supply air, whereas further improvements to the control strategies would benefit the system even more.

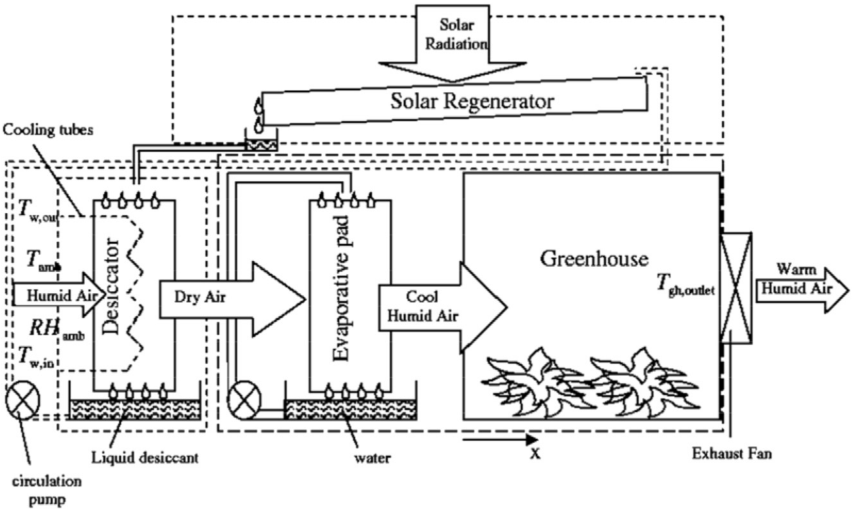

Fig. 5. Schematic of the proposed liquid desiccant cooling system and greenhouse with evaporative pad (figure is used with permission from [24]).

El-Awady et al. [28] constructed experimentally an integrated solar greenhouse (ISGH) for water desalination, plantation and waste water treatment to evaluate its thermal performance. The ISGH system uses the solar water desalination principle and works by saturating air with moisture vaporizing from brackish/seawater inside a greenhouse followed by dehumidifying, causing fresh water condensation. They indicated that the ISGH system can be used successfully to provide a low-cost solution in arid areas, where the fresh water is very limited. In addition, it is a relevant method of cultivation that provides desalinated water, cooling environment and humidifying environment in an integrated system and fulfills the safe disposal of treated waste water and to reduce the highly contaminated/polluted waste water discharged directly or indirectly on the ground water.

Gao [29] studied an economical method to achieve an effective controlling of relative humidity (RH) in greenhouses of cold regions. Han et al. [30] studied a dehumidification method using air to air heat exchanger to control the RH during cold weather condition inside the greenhouse. The results showed that heat exchanger controlled, but it was inefficient during humid and warm weather climate. Thus, the heat exchanger is a good choice for greenhouse dehumidification in cold and mild weather condition.

4.4. Produced water quality and environmental impacts

High quality water for agricultural and drinking use is becoming limited. Runoff and irrigation return flow from containerized greenhouse facilities may contain fertilizer, certain pesticides, various salts, and trace metals. This has stimulated many different studies on water and pest management. Traditional greenhouse irrigation practices recommend watering to 10% excess, with application scheduled just prior to incipient wilting [9].

Sammons et al. [31] present an engineering solution to the current human health hazards involved in spraying potentially toxic chemicals in the confined space of a hot and steamy glasshouse. They designed and constructed of an autonomous mobile robot for use in pest control and disease prevention applications in commercial greenhouses. The effectiveness of this platform is shown by its ability to successfully navigate itself down rows of a greenhouse, while the pesticide spraying system efficiently covers the plants evenly with spray in the set dosages.

Osorio et al. [32] proposed a solar disinfection system, based on a solar collector that uses solar radiation to heat the water and profits of the naturally occurring UV radiation. In two field experiments, the reservoir of the collector was filled with drainage water obtained from a commercial greenhouse. Heating treatment was effective in bacteria elimination with a thermal time requirement of 240 °C h for total aerobic and 217 °C h for coliform bacteria. A thermal time of 268 °C h is needed to achieve a reduction to 10% of the initial total aerobic bacterial concentration, whereas, to reduce the concentration of coliform bacteria to the same amount, requires a thermal time of 241 °C h.

The environmental impacts of desalination processes are intrinsically related to system efficiency; per water-unit produced loads have constantly decreased over the past decades. The main environmental impacts of the desalination technology are caused by energy and extensive brine discharge; unavoidable desalination sub-product that may heavily affect marine biota. Environmental loads of any desalination process can be considerably reduced when integrated with renewable energy production systems (adapted from [33]).

5. Application of GHHD in cold regions

Greenhouses in cold regions often exhibit conditions of low temperature and high relative humidity [34]. In the cold regions, it is needed to an energy source to power GHHD desalination unit 24 h a day. Geothermal energy as a natural resource is needed to heat the underground water and to warm the greenhouse by means of the hot vapor leaving the first evaporator. Underground water is pumped and sends into a ground heat exchanger to increase its temperature to an acceptable level. Hot salt water is fed to the humidifiers. The air leaving the humidifier and passes over a condenser immersed in a water basin [35].

In standard greenhouses, the use of thermal mass materials (concrete, water barrels, etc.), can help maintain temperatures by absorbing heat from the winter sun during the day, and radiating that heat at night.

GHHD systems also work well in combination with power generating infrastructure, especially where there is a need to remove heat. With concentrated solar power facilities, our systems can use waste heat generated to increase fresh water production.

6. Economical and sustainable aspects of GHHD

The economic factor is an important role for the decision makers in any field. Cost analysis of GHHD systems usually aims to estimate the cost of a one liter or a cubic meter of fresh water, and calculates the contribution of each cost item to the total cost of agriculture. This identifies immediately the most significant cost items and attracts the attention to what should first be examined for possible improvement and cost reduction [29]. The GHHD is today a proved technology, although it has not yet realized its potential in those areas of the world most indicated. Design specifications vary according to climatic conditions, grower requirements, irrigation system, local materials and labor. Greenhouse cladding can be polythene, rigid plastic or glass. This means that the overall cost of salt water greenhouse becomes low.

The economics of GHHD system depend on a number of factors. These factors are the local climate, growing methods and greenhouse styles. While GHHD system economics are influenced by these factors, they also benefit from several key advantages, regardless of the crop, market or region.

Davies et al. [36] scoped for energy saving in fan-ventilated greenhouses through low speed operation. Measurements of electricity usage as a function of fan speed, shown that the fan speed reducing can cut the energy usage per volume of air moved by more than 70%. To minimize the capital cost of low-speed operation they built in a cold greenhouse which the fan speed responds to sunlight such that full speed is reached only around noon. The energy saving is about 40% compared to constant speed operation. On comparing the net present value costs of the different systems over a 10 year amortization period (with and without a carbon tax to represent environmental costs) they find that sunlight-controlled system saves money under all assumptions about taxation and discount rates. So, the greenhouse fan manufacturers can improve the availability of energy-saving designs by expanding their product range to include such solutions.

Eslamimanesh and Hatamipour [37] made an economical study of HD desalination pilot plant in order to estimate the benefits of the process in comparison with a small-scale reverse osmosis (RO) system.

The cost-estimation of solar desalination systems is reported by Delyannis and Belessiotis [38]. They noted that solar energy conversion plants are capital-intensive enterprises. For solar distillation plants, the problem is compounded with the fact that most of them are constructed from inexpensive local materials using local personnel. In such a situation, prices differ considerably from one location to another.

Fiorenza and Sharma [39] studied an economic assessment performed to estimate the expected water cost, which is the ultimate measure of the feasibility of the two solar powered standalone membrane distillation units (compact and large).

The discharge of brine from largest desalination plants located around the world continues to seriously damage large areas of coastal systems. Importantly, instead of discharging high salinity water back into the sea, the GHHD can recover sea-salt and make it a sought-after, saleable product as mentioned above.

Chaibi and Bourouni [40] introduce the effect of water cost production on crops yields. They showed that the water desalination use in irrigation could be profitable for farmers, particularly to produce high commercial value. The solar desalination in irrigation is only worthwhile if higher crop production is adopted and assuming a high qualification of farmers.

The remaining high salinity water from the desalination may conducted in ponds where salt and other minerals (such as Calcium, Potassium and Magnesium) are extracted for use in production or sold to other interests [41].

The GHHD systems consume power from 1 to 5 kWh/m^3 [2]. As the modest demand for electrical power for fans and pumps is proportional to sunlight, researchers propose in future to meet this need with photovoltaic panels, without the need for batteries and inverters. In addition to carbon dioxide savings, this will enable off-grid, and remote communities, to produce crops and fresh water.

Less than 1% of the world's deserts, if covered with concentrating solar power plants, could produce as much electricity as the world now uses. By using these technologies, there is huge commercial potential to restore forests and create a sustainable source of fresh water, food and energy. If the scheme were located upwind of higher terrain than the air carrying this ‘lost’ humidity would be forced to rise and cool, contributing additional water to the mist or cloud. By using a location that lies on below sea level, seawater pumping costs may be eliminated [7].

The sustainable aspects such as materials used in the construction of the GHHD are both low cost and 100% recyclable [42].

Much research has been directed at addressing the challenges in using renewable energy to meet the power needs for desalination plants. Wind energy and solar energy are clean and renewable fuel sources. Mahmoudi et al. [43] selected and investigated five typical areas of traditional agriculture to analyze the feasibility of using wind energy to power brackish water GHHD systems. They indicated that the wind energy is a suitable resource for power production and can be used to provide the required electricity for the GHHD systems using brackish water.

7. Conclusions

In this paper a technical and economical discussion is presented for irrigation and water desalination using greenhouses assisted by a humidification dehumidification desalination system (GHHD). The researcher's efforts in GHHD systems economics and sustainability are reviewed with explained its effects on developments and applicability of the method. Based on the review and discussions, the following could be concluded;

1. Most researchers did not care to clarify the economic feasibility for GHHD technology developments that have proved their efficiency.
2. The distilled water production from GHHD systems showed a significant effect when they enhance through technological aspects compared with conventional systems under the same operational conditions.
3. GHHD indicates a potential reduction of fixed costs of 10–15%, lower operating costs of 10–25% and improved returns of 15–35% against a traditional greenhouse of the same size (clad in plastic or glass). A thermodynamic model is used to predict the most effective solution.
4. Condenser design and airflow velocity appears to be the bottleneck of the dehumidification process and fresh water productivity in GHHD system.
5. CFD model can be a useful tool in designing and evaluating greenhouses with various configurations.
6. Further research and technical development are needed in order to optimize the thermal and optical performance of the GHHD concept through better design of the shape and more selective absorbers.
7. The integration of solar still with greenhouse makes distillation takes place after solar noon and during the night due to the low absorption of solar irradiation contrary to what happens in traditional solar stills. In addition, it reduces the solar radiation and photosynthetic active radiation inside the greenhouse (about 52%).

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