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

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ABSTRACT

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.

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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