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Review

Opportunities for Implementing Closed Greenhouse Systems in Arid Climate Conditions

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Abstract: The closed greenhouse is an innovative crop system in the horticulture sector, integrating appropriate climate control equipment and optimized techniques to collect, store, and reuse solar energy for heating and/or cooling the greenhouse. This concept aims to improve the crop yield and quality with energy efficient and water-saving technologies. A specific focus on the opportunities of implementing closed greenhouses under arid climate conditions is detailed in this work. Guidelines for selecting appropriate techniques and design parameters are investigated, aiming for profitable and sustainable greenhouse production. This paper provides an overview of the design aspects of the closed greenhouse and a state of the art of its applications in arid areas. Firstly, the microclimate parameters, including temperature, relative humidity (RH), light intensity, and CO_2 concentration are introduced. Then, an in-depth focus on the effects of these parameters on crop productivity, water, and energy efficiency are thoroughly discussed. Finally, the limitations of closed greenhouse applications are pointed out as opportunities for further research and development in this emerging agriculture field.

Keywords: closed greenhouse; arid regions; crop production; water recovery; energy saving

Citation: Jemai, N.; Soussi, M.; Chaibi, M.T. Opportunities for Implementing Closed Greenhouse Systems in Arid Climate Conditions. *Horticulturae* **2022**, *8*, 1102. https://doi.org/10.3390/horticulturae8121102

Academic Editor: Xun Li

Received: 14 October 2022
Accepted: 16 November 2022
Published: 24 November 2022

1. Introduction

Ensuring food security for an increasing population is becoming an urgent global challenge. This important increase will negatively affect the supply and demand of limited foods, water, and energy resources [1]. To meet the growing demand by 2050, food resources must be increased by 60%, water by 55%, and energy by 80% [2,3]. Agricultural production is affected by global warming, which affects climatic conditions by causing floods, droughts, and storms in different countries [4]. Arid regions are more affected by these changes, since they are characterized by high temperatures and water scarcity [5–7]. These climatic conditions are harmful to plant growth and the long-term viability of genetic resources [8–10]. In fact, extreme temperatures, drought, floods, high winds, and sandstorms damage agricultural systems in arid regions, especially spontaneous vegetation and plants with superficial root systems [5].

Arid and semi-arid regions (Figure 1) cover over 30% of the total world surface and are home to about 20% of the global population [5,11]. In Africa, these regions account for 24% of the total population, in Asia for 23%, the Americas for 17%, Europe for 11%, and Australia for 6% [5].

The climate in desert regions is characterized by a lengthy and hot summer season during which ambient temperatures can approach 45 °C with a very high daily variability, daily global solar radiation reaches 30 MJ m^{-2}, RH can dip below 10% at noon, and there is rare rainfall with high annual variability. During winter, these regions are characterized by a very high thermal amplitude with a strong variation in temperature between day and night. As a result, heating and cooling systems will be required. These systems are considered to be an important factor in reducing energy consumption [12,13]. For instance, in Tunisia

25% of geothermal resources used in agriculture are exploited for greenhouse-heating purposes [12].

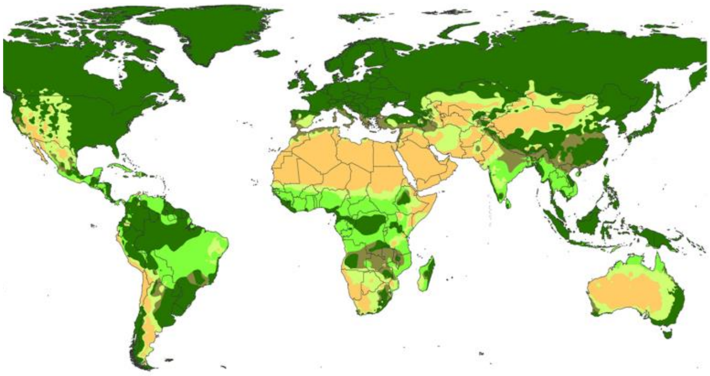

Figure 1. Climate classes for arid and semi-arid climates: tropical savannah, arid steppe, arid desert, temperate with hot dry seasons, and all others (Nor arid or semi-arid) [11].

Protected agriculture is a promising solution for improving the agricultural production system in arid areas to solve climate change issues. For instance, the Middle East and North Africa (MENA) region, one of the driest regions in the world, had 71,000 hectares of protected crops in 2014, with 13,000 hectares in the Gulf Cooperation Council (GCC) countries [13]. The adoption of greenhouses as a production system in this region has increased significantly in terms of area due to the challenging environment [13]. In arid regions, conventional greenhouses with passive ventilation or fan-pad evaporative cooling systems are the most frequently applied type to control the greenhouse climate. These cooling methods depend heavily on the ambient humidity and solar radiation levels. They have a number of drawbacks, such as a high risk of crop loss from pests and significant water and energy requirements [14]. For these reasons, the concept of closed greenhouses was introduced to maximize the benefit from solar energy and guarantee optimal growing conditions for plants [15,16]. Armstrong [17] defines a closed greenhouse as "A greenhouse, which is completely closed, no windows to open to release excess humidity or to cool the house when it is too warm". For instance, in closed greenhouses, mechanical cooling totally or partially replaces the conventional greenhouse's ventilation-based cooling system.

Therefore, closed greenhouses enable farmers to better control inputs and outputs by controlling several parameters, such as temperature, humidity, CO_2 enrichment, and fertigation, leading to a more suitable environment for plant growth and development [18,19]. Furthermore, the use of closed greenhouses constitutes a solution to the problem of limited fresh water resources and rising groundwater salinity by using advanced desalination technologies [14,20].

This paper aims to better understand the closed greenhouse concept, introduce key parameters that impact the thermal behavior of a greenhouse located in arid climate conditions, and explain the major environmental factors that influence agronomical plant performance, such as temperature, humidity, light, and CO_2 concentration. It also discusses the major impacts of closed greenhouses on crop productivity, water, and energy efficiency.

2. Closed Greenhouse Concept

The closed greenhouse is a relatively new horticulture concept that has been in development since the late 1990s [21]. The first successful experiment in this type of greenhouse was conducted in the Netherlands in 2002, with the production of tomatoes, and the yield obtained was approximately 20% higher than that gained in a conventional greenhouse equipped with ventilation windows [22]. In 2004, the same company marketed the first closed greenhouse, known as "GeslotenKas" [23,24]. The "GeslotenKas" design was developed as a partially closed greenhouse with two compartments: a closed half that produces heat for a second conventional greenhouse part [25].

In the semi-arid region of El Ejido, Almeria, Spain, the first prototype of a closed greenhouse was installed in 2004. This greenhouse was designed to conserve water and ensure the recovery of up to 80% of the total irrigation water usage, as well as a reduction in total energy consumption when compared to a traditional greenhouse [20].

The concept of closed greenhouse operation is based on the management of temperature, relative humidity, solar radiation, and CO_2 concentration inside the greenhouse to save as much energy as possible while also improving the production and quality of protected crops. Different cooling and heating processes are used in closed greenhouses, mainly heat pump and heat exchanger systems (Figure 2). Passive cooling techniques are also applied, including efficient covering materials, shading, or reflecting devices that highly reduce solar heat gain [26].

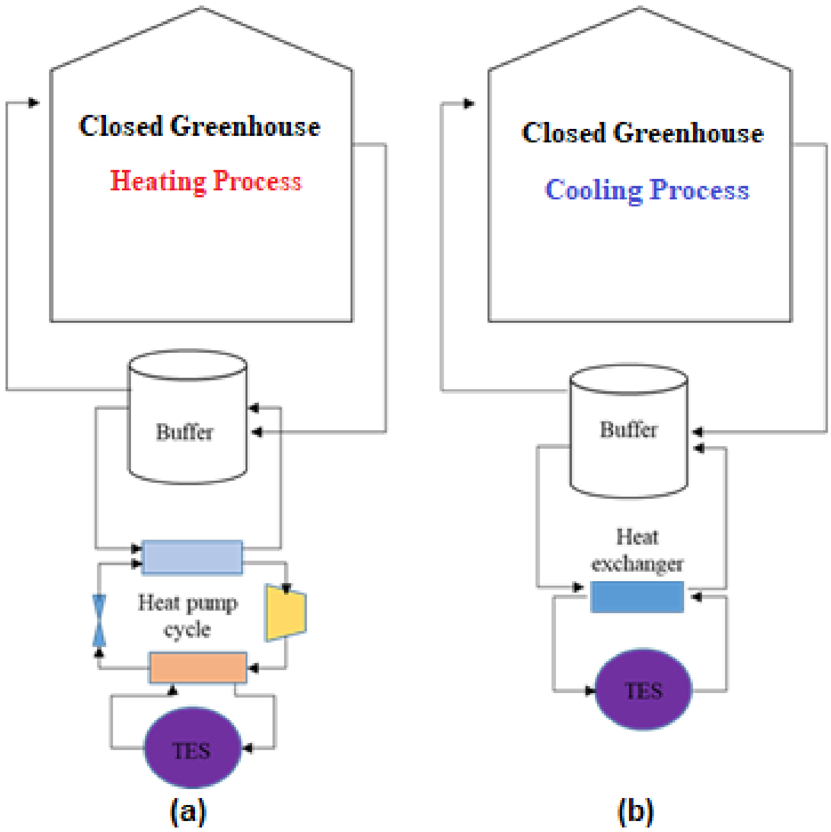

Figure 2. Heating and cooling processes in a closed greenhouse using TES system, (**a**) heating mode, (**b**) cooling mode.

In addition, closed greenhouses collect high amounts of solar energy estimated to approximately 80% according to Vadiee and Martin [25], which corresponds to three times its own annual heating requirements, as proved by Paksoy and Beyhan [27]. Thus, a high amount of the excess heat can be stored by means of thermal energy storage (TES) systems to be exploited later either for heating or cooling purposes. Figure 2 illustrates the general operation of a heat pump and TES-integrated heating and cooling systems. In heating mode (Figure 2a), hot water is pumped up from the TES to the heat pump that extracts the heat and transfers it to the greenhouse; the solar energy excess stored in summer is used for winter heating. The hot water supplied by the heat pump is stored in a short-term buffer used to level out the daily/hourly load in the closed greenhouse and the cooled water is then returned to the TES and loads the cold side of this system. In cooling mode

(Figure 2b), the cold water is circulated from the cold TES directly into the greenhouse and removes the heat via a heat exchanger system; hot water is then supplied to the hot TES to be stored and used in winter [28].

Several TES technologies have been developed in closed greenhouse systems during the last decades and a host of innovative scenarios coupling cooling and heating systems to TES technologies were investigated in the Netherlands, United States, Turkey, and many other countries (Table 1).

Table 1. Applications of the main thermal energy storage technologies in closed greenhouses [27].

Thermal Energy Storage Technologies		Seasonal Storage	Short-Term Storage	Heating	Cooling
Water storage			×	×	
Underground thermal energy storage (UTES)					
	Aquifer thermal energy storage (ATES)	×		×	×
	Borehole thermal energy storage (BTES)	×		×	×
	Cavern thermal energy storage (CTES)	×			
Phase change materials storage (PCM)			×	×	

Experimental analysis of TES integration in closed greenhouse systems revealed that they improve the efficiency of the heating and cooling systems, reduce their greenhouse gas emissions, guarantee higher yields, and lower energy consumption [24,27].

The integration of TES technologies offers various application options for use in closed greenhouses and requires the selection of the appropriate system parameters, such as the tank type and material, the insulation materials, the PCM thermophysical properties, and the characteristics of the heat exchanger connecting the TES to the greenhouse system [28–30].

3. Effects of Microclimate on Crop Growth in a Closed Greenhouse System

The greenhouse operating system should rely on techniques to regulate the inside environment parameters, including temperature, relative humidity, light, and carbon dioxide concentration, in order to maximize the production of the protected crops while preventing plant damage [31–35]. In closed greenhouse systems, it is expected that the average temperature, RH, and CO_2 concentration are increased, compared to a conventional greenhouse [36].

Optimal conditions for crop growth depend on a great number of factors changing from moment to moment and year to year and growing with uncertainty. As a result of this dynamic behavior, the greenhouse microclimate is considered as a nonlinear multi-input, multi-output system. Several interactions between the outside conditions, the greenhouse climate and the greenhouse crop exist with strong variation of the adjusted parameters according to the development stage of the crops [37]. So many control parameters in the greenhouse still need to be dynamically identified for suitable plant growth [38–40].

Most protected crops' product quality is greatly influenced by climatic variables. They have an impact not only on the physiological processes of the crops but also on the internal quality of the vegetables, both directly and indirectly. Sensory elements and ingredients, such as sugars, acids, and aromatic chemicals, which affect taste, as well as vitamins and secondary plant compounds, which are important for human nutrition and can be affected by changing climatic conditions in the greenhouse [41].

3.1. Air Temperature

Temperature is a major environmental factor that affects all stages of plant development, including germination, vegetative growth, flowering, and fruit ripening, as well as a number of physiological functions—such as transpiration—and biochemical functions—such as enzyme activity and photosynthesis [41–43].

The average temperatures, especially for the arid regions, are very high and generally exceed the optimum values with strong monthly, as well as daily, variation. For example, in the Saudi Arabian region, they can reach maximum values ranging between 39 and 46 °C, and for such values the relative humidity does not exceed 20%. The typical weather conditions of these regions require greenhouses equipped with cooling systems while maintaining optimal relative humidity for vegetable production [44]. Closed greenhouses can constitute, in this case, a suitable solution as climate control process can be less complicated and more precise, compared to conventional greenhouses.

Closed greenhouses are also characterized by vertical gradients of temperature (VGT) and humidity due to the location of the cooling ducts under the growing gutter. Temperature is increased by incident solar radiation at the top of the greenhouse, while it decreases at the lower part due to the cooled and dehumidified air [45].

Thermal amplitude also plays a relevant role in controlling the plant's physiological and biochemical parameters. The height, internode length, petiole elongation, leaf orientation, shoot orientation, chlorophyll content, lateral branching, and floral stem length of plants are all affected by this differential [46]. Damage to cell membranes, proteins, and nucleic acids is a direct result of high temperatures. Indirect effects include pigment inhibition and degradation, which causes sunburn symptoms [41,47].

Low temperatures below 13 °C, that differ depending on the species, have a negative impact on the pollination and flowering of protected crops during the winter. To overcome these deficiencies, several techniques have been employed by the farmers; for example, for tomato they use mechanical vibration or hormonal treatment of flowers with gibberellic acid capable of causing the flowers to set and the fruits to grow even if the pollen quality is poor [48].

Gruda [41] reveals that night temperatures, below 14 °C, highly affect flowers, especially if combined with high humidity rates. This results in reducing the number of pollen grains, their release, and their germination capacity, as well as fruit set and shapes. Low temperature combined with low solar radiation causes swelling and blotchy ripening in tomato, as well as deterioration of taste due to lower sugar content [49].

The majority of protected crops are adapted to an average temperature, ranging between 20 °C and 30 °C (Table 2), with lower and upper limitations of 10 °C and 35 °C, respectively [50].

Table 2. Temperature requirements for selected greenhouse crops.

Crop	Optimal Day Temperature (°C)	Optimal Night Temperature (°C)	References
Tomato	25–30	16–20	[51]
Pepper	21–30	16	[52]
Melon	32	13–18	[51,53]
Green Bean	16–30	-	[51]
Eggplant	22–30	18–24	[51,52]
Cucumber	25–30	17–20	[51]
Cabbage	15–16	2	[51,52,54]
Lettuce	18–23	7–11	[51,52,54]

Maintaining greenhouse temperatures at optimal values is only possible for closed greenhouses, since it has no ventilation windows and no air exchange with the outside [45].

3.2. Relative Humidity

The relative humidity of the air is the ratio of the partial pressure of water vapor contained in the air to the saturation vapor pressure at the same temperature. This parameter affects the water status of plants, which, in turn, influences all processes related to transpiration and water balance, since it is responsible for the functioning of stomata [41,55,56]. Vapor pressure deficit (VPD) also influences the photosynthetic rate through leaf stomatal conductance, which decreased with increasing VPD level [57].

Plant transpiration is driven by the VPD, which varies exponentially with ambient temperature [58]. The potential to increase plant growth and productivity through VPD control has long been recognized [59]. Grange and Hand [60], claim that the growth and development of horticultural crops are generally unaffected by VPD values between 0.2 and 1.0 kPa (at 20 °C). Most plants can grow at a VPD that ranges from 0.5 to 0.8 kPa, according to J. C. Bakker [61]. The recommended ranges for VPD for plants are between 0.5 and 1.2 kPa, as stated in the advice provided by Zhang et al. [62]. The optimal VPD levels, though, change depending on the development stages of the plant. For instance, research recommends an ideal VPD of 0.8 kPa for clones, roughly 1.0 kPa for the vegetative stage, and around 1.2 to 1.5 kPa for the flower stage [63].

Plant transpiration is enhanced by high VPD (more than 1.0 kPa), in addition to low humidity and high temperature, whereas low VPD in combination with high humidity and low temperature results in dehydration, wilting, and necrosis [50]. Compared to conventional greenhouses, closed greenhouses typically have lower VPD and, as a result, lower transpiration rates [64].

Humidity levels above 90% (VPD more than 0.32 kPa at 25 °C) have an adverse effect on plant development and fruit quality, as well as stimulating disease attacks [42,65].

In addition, excessive humidity causes stomatal dysfunction in a variety of cropping systems and plant species. According to Arve et al. [66], stomatal pore opening and length were greater in plants cultivated under high RH (90%) than in plants grown under moderate RH (60%) conditions (Figure 3), which make it difficult to regulate the process of stomatal opening and closure for gas exchange and drought or darkness stress control.

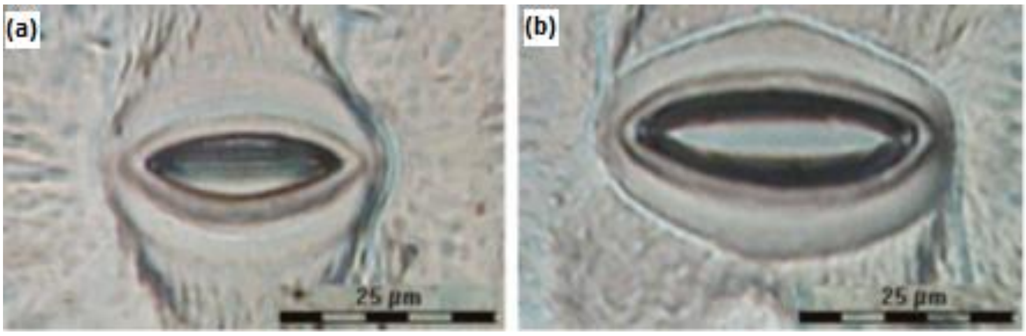

Figure 3. Light microscope images of stomata in 60% relative air humidity (RH) (**a**) and 90% RH (**b**). The images are of imprints of the abaxial side of the leaves during the light period [66].

Closed greenhouses have a higher relative humidity estimated to be more than 20%, compared to conventional greenhouses [36]. Excessive humidity can also cause condensation on crop plants, which can stimulate the spread of fungal infections [66–68]. Heuvelink et al. [22] reported that *Botrytis* infestations on tomato and cucumber crops resulted in 10% and 40% production losses, respectively, at the start of cultivation, as a result of excessively high humidity in closed greenhouses. The recommended VPD for greenhouse crops ranges between 0.32 and 1.58 kPa (at 25 °C) (Table 3). The excess of humidity inside closed greenhouses can be reduced through water recovery monitoring techniques that apply closed or semi-closed air cycles in the greenhouse design. Humid air condenses at its contact with a surface at a temperature that is lower than its dew point; the condensate is then collected and used depending on whether water is suitable for irrigation. This controlled condensation is either ensured by heat pumps, heat exchangers, or finned pipes (Figure 4) [42,69,70]. Thus, water recovery techniques offer an interesting solution in terms of taking advantage of high humidity inside closed greenhouses and reducing irrigation water consumption, especially in hot and arid regions that suffer from water scarcity.

Figure 4. Dehumidification and water recovery system using finned pipes [75].

Table 3. VPD requirements (at 25 °C) for selected greenhouse crops used in arid regions.

Crop	VPD (KPa)	References
Tomato	0.95–1.58	[71]
Pepper	1.11–1.27	[72,73]
Eggplant	0.95–1.27	[73]
Cucumber	0.32–0.95	[73]
Lettuce	0.63–1.11	[57,74]

3.3. Light Intensity

Light is the most significant primary environmental component that controls plant growth and the development of plants [76]. The plant uses only about 1% to 5% of the transmitted radiation; the remainder is absorbed and re-emitted as thermal radiation (heat) [77].

The photosynthetically active radiation requirements measured as photosynthetic photon flux density (PPFD) of the main greenhouse vegetables are summarized in Table 4.

Table 4. PPFD requirement for selected greenhouse crops grown used in arid regions.

Crop	PPFD (µmol $m^{-2}s^{-1}$)	References
Tomato	400	[78]
Pepper	504	[72,78]
Cucumber	400	[72,78]
Eggplant	504	[78]
Lettuce	260–290	[74,78]
Bean	336–420	[78]

Excessive lighting influences both the external and internal quality of crop production. This excess of light can be beneficial to the development of certain plants, for instance, it can increase the content of essential oils in medicinal plants [65,79]. However, excessive illumination can also be harmful to a wide range of crops, such as tomatoes and peppers, as it causes organoleptic quality problems, such as pigmentation loss, tissue collapse, and cellular death [47,80].

Lack of radiation causes plant quality issues, including stunting and vegetative development at the expense of fruiting organs; malformed organs, such as high-oval tubers in kohlrabi or radish; tomato flower abortion; or radish tuber production failure [41].

Arid and semi-arid regions are characterized by abundant solar radiation, which seems to offer these regions great potential for agricultural operations and especially for closed greenhouses constructed with adequate covering materials. These greenhouses guarantee a better exploitation of this abundance, either for improvement of the productivity by increasing the rate of photosynthesis or for reducing energy use by storing extra heat to be used for heating the greenhouse in cold periods.

Arid regions have the disadvantage of having a dusty environment that causes dust accumulation on the greenhouse's roof and reducing light transmission through the glazing. In this situation, providing cleaning devices in these areas is critical to resolve this problem [10,13]. Several improvements have been made to the covering materials of closed greenhouses in arid environments in order to have an adequate microclimate for the development of the crops. Baeza et al. [7] investigated the possibilities of using near infrared (NIR) reflective filters to improve the optical properties of closed greenhouse in Morocco, Malaysia, and the Netherlands. They demonstrated that using these filters results in a 36 % energy savings, a 40% reduction in maximum cooling power, and a 15% increase in potential tomato production when compared to using standard glass as a covering material.

3.4. Carbon Dioxide Concentration

The increase in yield is mainly attributable to higher rates of photosynthesis in closed greenhouses, resulting from higher CO_2 concentrations, compared to open and semi-closed greenhouses. CO_2 concentrations constitute the main characteristic that distinguish closed greenhouses [67]. They are often maintained at up to 1000 ppm in the summer when solar radiation is high, while they are about 400 ppm in conventional greenhouses due to ventilation losses [21]. The optimal CO_2 concentration is determined by solar radiation, as well as the rate of photosynthesis and rate of ventilation [12,81].

It has been shown that elevated CO_2 concentrations result in an increase in the rate of photosynthesis even under low light conditions, as well as a reduction in the transpiration rate by decreasing stomatal conductance, which is valuable to the plant by protecting it from dehydration [82]. It may also improve energy efficiency by 5–10 percent without affecting photosynthesis or growth [38]. High CO_2 concentrations have a short-term favorable effect on photosynthesis; however, a long-term positive effect was not proved, as maintaining a CO_2 concentration of 1000 ppm for several weeks has not guaranteed a continuous rise in leaf photosynthetic rate [83].

Several studies have demonstrated the positive impact of CO_2 enrichment on plants, concluding that raising the concentration in a greenhouse helps the plant to grow in height, weight, biomass, and lateral branches. Furthermore, high CO_2 concentrations have an impact on the optimal temperature, humidity, and light levels [14]. Higher CO_2 concentration also means a higher optimum growth temperature, which can lead to an increase in the plants overall growth rate, particularly in hot regions where high solar resources are available [14].

Dong et al. [84] studied the effect of carbon dioxide enrichment on fruit quality and found that fruit quality does not necessarily correlate with increased yield. They proved through a meta-analysis that rising CO_2 concentration increased fructose, glucose, total soluble sugar, total antioxidant capacity, total phenols, total flavonoids, ascorbic acid, and calcium in the food part of vegetables, but they also decreased protein, nitrate, magnesium, iron, and zinc concentrations. They proposed several techniques to solve this problem based on selecting species or cultivars that respond better to high CO_2 concentrations, maintaining optimal environmental conditions at the same time as high CO_2 levels, harvesting late-stage vegetables and combining this factor with mild environmental stress (e.g. salinity or Ultraviolet-B radiation).

3.5. Combined Effects of Climatic Factors

The impact of these climatic factors on plants is sometimes described as a dynamic mixture of two or more factors, and many studies have documented their interaction [50,65].

The temperature affects VPD by varying water availability in the plant and its ability to regulate water absorption. In this case, exposure of plants to high relative humidity and high temperature reduces stomatal functions, thus, affecting plant growth, transpiration, and photosynthesis [50].

Low temperatures affect the absorption of solar radiation by interfering with the photosynthetic cycle in a greenhouse environment, and light levels influence both ambient and plant leaf temperatures [42]. The combined effects of light, CO_2, and temperature affect the rate of photosynthesis. This rate is affected by the greenhouse's temperature, and it reaches its optimum value when light intensity and CO_2 concentration are both high [45]. The increase in CO_2 concentration, according to Dannehl et al. [64], compensates for the reduction in photosynthesis caused by low light intensity. They found that a concentration of 1000 ppm in the photosynthetic flux density (PPFD) range of 303 to 653 mol $m^{-2}s^{-1}$ will compensate for a 40% loss in light, a 51% increase in net photosynthesis, and a 5–8% drop in transpiration. The reduction in transpiration caused by high CO_2 levels can, under a high light intensity, be useful for plants by protecting them from dehydration or can be harmful by restricting the amount of latent heat the plant can dissipate through evaporation. Additionally, increased CO_2 content reduces the effects of ethylene produced by plants [82].

The combination of all of these parameters, including optimal temperature, VPD, high light intensity, and a high CO_2 concentration at about 1000 ppm, leads to enhanced crop productivity in closed greenhouses [67].

4. Effects of the Closed Greenhouse System on Crop Productivity and Water Use Efficiency

Given the accurate, optimal microclimate they maintain, closed greenhouses have a number of benefits, including significantly higher agricultural yields and increased irrigation water efficiency. In this regard, Dannehl et al. [85] compared tomato output in Berlin, Germany between a closed greenhouse and a traditional one with a 307 m^2 total area. According to their study, a closed greenhouse's microclimate increased mean plant height by 1.5 m, which, in turn, increased overall production by 21.4%. Closed greenhouse climate conditions have also improved the fruit quality as they promoted the accumulation of primary and secondary plant compounds, such as soluble solid by 9%, lycopene by 22%, ß-carotene by 21%, phenolic compounds by 8%, and ascorbic acid by 26%.

According to Heuvelink et al. [22], tomatoes grown in a closed greenhouse under Dutch climatic conditions had a 17% higher yearly production than those grown in a conventional greenhouse. This increase in crop production resulted from high CO_2 concentrations of about 1000 ppm during the summer, with optimal temperatures ranging between 16 °C and 24 °C, as well as light intensity of around 1380 µmol m^{-2} s^{-1} PAR. Furthermore, [22] showed that to reach the same average fruit weight in a closed greenhouse, a higher planting density of more than 17% than that utilized in a conventional greenhouse could be maintained. De Gelder et al. [67] studied a closed greenhouse in the Netherlands and revealed that high solar radiation and high CO_2 concentrations, as well as optimal relative air humidity and temperature are achieved and allowed for a 10–20% increase in production. This increase in yield is mostly attributable to increased photosynthetic rates in closed greenhouses, compared to conventional ones.

It is also important to highlight the important role of the climate control inside closed greenhouses on avoiding pests and crop diseases. Applying effective environment conditions inside closed greenhouses prevent the appearance of fungi, as well as other serious diseases and considerably minimizes the usage of pesticides [10]. The closed greenhouses also address a major issue in dry regions in terms of water shortage and lack of fresh water supplies, as well as groundwater salinity. Several studies proved that the reduction in irrigation water consumption achieved in closed greenhouses ranges between 50 and 80% [20].

Different techniques are used when aiming to reduce water consumption, particularly integrating processes that guarantee the condensation of water produced by plant evapotranspiration. The recovered water is subsequently reused for irrigation. In this cultivation system, water losses are minimal and occur through small leaks in the greenhouse cover, allowing an increase in water efficiency by a factor of 20 [13].

Solar potential, which is the most important characteristic of hot and dry regions is captured in closed greenhouses and commonly valorized through desalination processes that guarantee water supply for irrigation purposes [13,20,86,87]. Several experiments have been undertaken to develop water desalination technologies for greenhouse irrigation in dry environments using humidification and dehumidification processes [20,86].

Chaibi and Jilar [88] experimented the integration of a desalination system on the roof of a closed greenhouse in Tunisia to take advantage from incident solar radiation on the sloping part of the south façade. The roof transmission is decreased as solar radiation is absorbed by flowing water in a sealed box, covered by clear glass on the top and a semi-transparent glass on the bottom. Fresh water is evaporated, condensed on the top glass, and then collected to guarantee plants water supply with a rate that ranges from 1 to 1.6 $kgday^{-1}m^{-2}$ [89]. Chaibi and Jilar [88] recommended the use of covering materials with dynamic and active control of the light absorption to reach higher system efficiency rates and to improve crop yields in arid areas.

El-Awady et al. [90] developed an integrated solar greenhouse (ISGH) for water desalination, planting, and wastewater treatment to evaluate its thermal performance under real-world weather conditions in Giza, Egypt. ISGH uses the principle of desalination of water using solar radiation and works by saturating the ambient air with moisture vaporized from brackish water or seawater inside a greenhouse, then dehumidifying it, causing fresh water to condense. This system provides desalinated water and a cooled and a dehumidified environment while also reducing highly contaminated wastewater discharged directly or indirectly to groundwater. They suggested that the ISGH system offers a low-cost solution in arid regions that suffer from water scarcity.

5. Effects of the Closed Greenhouse on Energy Use

In addition to agricultural production, energy consumption is one of the main criteria of greenhouse efficiency. In some cases, it accounts for half of the cost of the greenhouse production [21]. For these reasons, the closed greenhouses concept was commonly used to integrate a range of techniques aimed at lowering energy consumption. For instance, Tantau et al. [91] investigated the effect of combining energy-saving methods, including the use of thermal screens and solar energy storage for reuse in heating. Double or triple glazing that can reduce light reflection due to their anti-reflective properties and high light transmittance (PAR) (over 96%) were also employed as covering materials. Combining these technologies resulted in a 90% reduction in energy use. Stanghellini et al. [92] have also proved that the passive method of using NIR-filtering plastic films as a covering material to reduce greenhouse temperature also reduced energy consumption by 8%.

Buchholz et al. [14] developed the "Watergy" closed greenhouse prototype that integrated a new cooling tower and a secondary heat collector to use low night-time temperatures as a cooling source, using natural convection. The Watergy prototype achieved satisfying results as it allowed water recovery, solar thermal storage, and energy savings. Opdam et al. [23] evaluated the efficiency of a closed greenhouse system using tomato cultivation and found that when this cultivation system was compared to a conventional greenhouse, it provided a 20% reduction in fossil fuel use, a 20% increase in crop yield, an 80% reduction in chemical inputs, and a 50% reduction in irrigation water consumption.

According to Maslak and Nimmermark [93], implementing an air-to-air heat exchanger for dehumidification reduced energy use in a closed greenhouse in Sweden by up to 17%.

It was proved through these pieces research that energy efficient greenhouses must integrate appropriate techniques that improve all crop growth conditions, which is a compromise. For instance, some covering material solutions, such as double glazing with an anti-reflective coating, increase the inside temperature of the glazing, leading to less water vapor condensation and higher humidity inside the greenhouse. As a result, the covering materiel solution requires a costly microclimate control system [91].

In conclusion, the integration of energy-saving techniques should be combined with an efficient microclimate system control to guarantee significant energy savings and yield increases.

6. Limitations Facing Closed Greenhouses in Arid Regions

The high initial cost of the closed greenhouse is the main concern for the majority of small farmers in dry regions with limited income [25]. This has compelled them to use conventional greenhouses, potentially at the expense of efficient operation and performance management.

Since closed greenhouses are equipped with high-tech materials, they require a greater investment in advanced technologies than conventional greenhouses, specifically for climate management. The goal for farmers, particularly in arid regions, is to find a compromise between appropriate greenhouse technology, increasing costs, and economic yield. Given that, the use of plastic film as a greenhouse-covering material could be a solution, since it is designed on the principles of minimal capital and technology input, as well as low operating costs [94].

The greenhouse's cooling system has the highest investment cost [13,95]. The size, type of TES used, and related equipment all affect how much a closed greenhouse will cost [21,25]. For instance, according to a cost–revenue analysis of a desiccant greenhouse in arid land [13], it was shown that the investment cost of the cooling system is estimated to be 40 EUR m^{-2}, which is approximately 56% of the total investment cost. In terms of total investment and annual cost, a closed greenhouse costs slightly less than twice as much as a conventional greenhouse, with an area of 20 ha. However, it provides a much higher income, which compensates in some way the high initial investment cost [13].

The educational level of the main farmers in arid developing countries may emerge as a barrier to the advancement of technology in new production practices, such as closed greenhouses. In fact, the installation of this type of greenhouse, which is equipped with high technology, with systems of effective climate control, requires the diffusion of the know-how and the transfer of technology for the farmers. To more effectively manage the greenhouse environment and to make it viable, significant efforts are required to strengthen extension services before implementing these technologies [96,97].

7. Conclusions and Recommendations

Improvements made in the field of protected cultivation have contributed to the development of closed greenhouses as a new cultivation system provided with high technology equipment and offering better and simultaneous control of temperature, VPD, solar radiation, and CO_2, resulting in a more profitable method of crop production. The use of closed greenhouse technology in arid areas has many advantages, which are summarized in Table 5. They enable farmers to improve crop yields throughout the year due to high levels of radiation and high CO_2 concentration, and they protect crops against pests and diseases. Additionally, this technology guarantees water and energy savings through several techniques, mainly due to the use of thermal energy storage systems (TES) that maximize the use of solar energy gain either for heating or cooling the greenhouse. However, closed greenhouse investments are considerable, and thus a potential increase in profit should make using this technology justified. The closed greenhouse concept is anticipated to be used primarily in greenhouse projects where the necessity for high productivity and the desire to reduce risk can offset the high investment costs.

Table 5. Main advantages of closed greenhouses, compared to conventional greenhouse systems.

		Conventional Greenhouse	Closed Greenhouse	References
Water effeciency	Water desalination production (kg day^{-1} m^2)	-	1–6	[86,89]
	Reduction in water consumption (%)	-	50–75	[14,23,35,64]
Energy efficiency	Energy savings (%)	-	20–50	[7,22,23,67]
	Annual heating demand (KWh m^{-2})	223–300	60–115	[21,28]
	Annual cooling demand (KWh m^{-2})	84–104	165–308	[21,28]
Crop production yield (kg m^{-2}) (At specific everage CO_2 concentration, type of crop)		55 (600 ppm, tomato) 24.4 (600 ppm, tomato) 11.5 (300 ppm, cucumber) 74 (600 ppm, cucumber)	60 (1000 ppm, tomato) 32.6 (800 ppm, tomato) 13.7 (650 ppm, cucumber) 148 (1100 ppm, cucumber)	[98–101]
Economic aspect	Total investment (EUR m^{-2})	40	70	[13]
	Annual profit (EUR m^{-2})	5	10	[13]

Despite the high expectations for this novel concept in terms of environmental control and further water saving, research is required to gain a better understanding of the factors that are needed for the adoption of closed greenhouse technology in arid areas, such as the greenhouse design, the selection of component technical specifications and performance, structure, and materials. The outcome of such research would help horticulture farmers with integrating this technology into their farming practices.

Numerous innovative high-tech closed greenhouses are also emerging as viable solutions for hot and arid regions, notably when they are powered by renewable energy systems, such as solar collectors, PV modules, concentrating collectors, or geothermal systems. Although the opportunities to use renewable energy sources to power closed greenhouses may increase the energy independence of limited fossil fuel resources, there are still considerable economic and technological challenges to be addressed with further research and experimental work.

Considering greenhouse farmers need to be informed about new technologies and how they should adapt as the closed greenhouse concept matures, further instructional information and investment are required with a specific focus on the technical and economic aspects of this emerging technology. Greenhouse farmers in arid regions will be encouraged to use the closed greenhouse concept for sustainable agricultural systems if appropriate knowledge and awareness of its benefits and features are widely communicated. Considerable thought should be given to the establishment of regional or community learning hubs, which would provide training and opportunities for skill development in dealing with this innovative technology. These hubs could serve as a useful method for supplying farmer organizations and companies with practical information on successful case studies.

Author Contributions: Conceptualization: N.J. and M.S.; methodology: M.T.C. and N.J.; validation: M.T.C.; investigation: N.J. and M.S.; writing—original draft preparation: N.J. and M.S.; writing—review and editing: M.T.C.; supervision: M.T.C.; project administration: M.T.C. and M.S.; funding acquisition: M.T.C. All authors have read and agreed to the published version of the manuscript.

Funding: The project leading to this work has received funding from the Tunisian Ministry of High Education and Scientific Research with the support of the PRIMA program (CONSIRS project).

The authors acknowledge funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 101000801 (Project LC-FNR-06-2020 TheGreeFa, G.A. 101000801).

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
CTES	Cavern thermal energy storage
CO_2	Carbon dioxide
EVA	Ethylene vinyl acetate
E-W	East–West
GA	Gibberellic acid
GCC	Gulf Cooperation Council
HD	Humidification and Dehumidification
ISGH	Integrated Solar Greenhouse
LDPE	Low Density Polyethylene
NIR	Near InfraRed
N-S	North–South
PAR	Photosynthetically active radiation
PC Polycarbonate	
PCM	Phase change materials storage
PE	Polyethylene
PMMA	PolyMethyl MethAcrylate
PVC	Polyvinylchloride
PVF	Polyvinyl fluoride
RH	Relative humidity
TES	Thermal energy storage
UTES	Underground thermal energy storage
UV	Ultra violet
VGT	Vertical Gradients of Temperature
VPD	Vapor pressure deficit

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