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Smart greenhouses as the path towards precision agriculture in the food-energy and water nexus: case study of Qatar

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Abstract
Greenhouse farming is essential in increasing domestic crop production in countries with limited resources and a harsh climate like Qatar. Smart greenhouse development is even more important to overcome these limitations and achieve high levels of food security. While the main aim of greenhouses is to offer an appropriate environment for high-yield production while protecting crops from adverse climate conditions, smart greenhouses provide precise regulation and control of the microclimate variables by utilizing the latest control techniques, advanced metering and communication infrastructures, and smart management systems thus providing the optimal environment for crop development. However, due to the development of information technology, greenhouses are undergoing a big transformation. In fact, the new generation of greenhouses has gone from simple constructions to sophisticated factories that drive agricultural production at the minimum possible cost. The main objective of this paper is to present a comprehensive understanding framework of the actual greenhouse development in Qatar, so as to be able to support the transition to sustainable precision agriculture. Qatar's greenhouse market is a dynamic sector, and it is expected to mark double-digit growth by 2025. Thus, this study may offer effective supporting information to decision and policy makers, professionals, and end-users in introducing new technologies and taking advantage of monitoring techniques, artificial intelligence, and communication infrastructure in the agriculture sector by adopting smart greenhouses, consequently enhancing the Food-Energy-Water Nexus resilience and sustainable development. Furthermore, an analysis of the actual agriculture situation in Qatar is provided by examining its potential development regarding the existing drivers and barriers. Finally, the study presents the policy measures already implemented in Qatar and analyses the future development of the local greenhouse sector in terms of sustainability and resource-saving perspective and its penetration into Qatar's economy.

Keywords Greenhouse technology · controlled environment agriculture (CEA) · Precision agriculture · Sustainable development · Food security · FEW nexus

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1 Introduction

Food security is a complex multidimensional phenomenon encompassed by the key dimensions of food availability, access, utilization, and stability of food supply for all people (FAO 2010). A country's food security status is the sum of its citizens' food security situation. Thus, food security is a global concern facing nowadays many challenges such as climate change, population growth, economic development, and the change in diet which consequently are putting pressure on resource availability (FAO 2020a). Climate change resulting in different weather patterns can threaten food production as both plant and animal productivity are affected. Crop yields are reduced, infectious diseases and pests are prevailing, frequent occurrence of environmental

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contaminants and chemical residues are observed along the food chain hampering food safety and security (FAO 2020b). As stated by the United Nations, the world's population is expected to increase by 2 billion people in the next decades, from 7.7 billion in 2020 to 9.7 billion in 2050 (United Nations Homepage 2020a) with a subsequent required increase of 60% in food production by then (FAO 2020a). However, an estimated 821 million people worldwide suffered from hunger in 2018, making hunger and malnutrition among the biggest risks to health. From a wider perspective, it is assessed that more than 2 billion people do not have consistent access to safe, nutritious, and sufficient food, including not only those suffering from hunger but also those who are affected by moderate levels of food insecurity (United Nations Homepage 2020b). Agricultural food production is a resource-intensive activity accounting for 70% of global water withdrawal including the need for irrigation, livestock, and aquaculture (FAO Aquastat Homepage 2020). Besides, approximately 75% of all industrial water withdrawals were used for energy production in 2014 (United Nations Homepage 2020c) and 25% of the energy used worldwide is utilized for food production and supply (FAO 2020a). Therefore, it is evident that traditional agricultural systems are insufficient to meet the increasing food demand. Consequently, there is an urgent need for a transition to sustainable and precision agriculture taking advantage of the technological progress to increase crop productivity while preserving the existing resources. Controlled Environment Agriculture (CEA) and smart greenhouses are key solutions to overcome these challenges as they can optimize crop production by manipulating the indoor climate while mitigating the climate change effect (Ouammi et al. 2020a). Moreover, they offer effective energy and water management solutions optimizing resource input while there have been recently developed innovative systems reaching nearly zero energy consumption and pesticide use with minimum water consumption (Bersani et al. 2020). Finally, the smart grid can play a significant role in enhancing the sustainable energy supply (Ouammi et al. 2020b). The term Controlled Environment Agriculture (CEA) refers to the growth and development of plants in a fully controlled environment with the use of modern horticultural techniques and technological advances resulting in achieving higher yields and improving product quality (Gómez et al. 2019). On the other hand, greenhouses are structures with transparent materials in which the microclimatic parameters are also modified to enhance plant growth and productivity and ensure all-year-round production (Shrawan Singh et al. 2008). CEA is a broader term that includes greenhouses, rooftop greenhouses, growth chambers, plant factories as well as vertical farms. This paper focuses on the technological advances in the greenhouse sector worldwide as well as in Qatar, as food production in the country is mainly realized in open fields and greenhouses.

Qatar is a small country in terms of land area located in the Arabian Gulf with an arid desert climate. The available land and resources are limited; therefore, the country was importing 90% of its food basket products until 2017 (Miniaoui et al. 2018). Agricultural food production in Qatar faces many challenges such as scarce freshwater, limited arable land and a climate that is not favoring agriculture as the summers are long, hot, and humid with low annual rainfall and often dust storms. Nonetheless, food security is a national priority for the State of Qatar and the government has launched many initiatives to boost local agricultural production while reducing its import dependency. Therefore, in the last decade between 2010 and 2019, the greenhouse and open field production of the most consumed vegetables in the country has increased from 31.573 tons to 66.500 tons, recording an approximate 110% increase (Planning and Statistics Authority in Qatar 2020a, 2014). Moreover, the Qatar greenhouse market is a developing sector, expected to mark double-digit growth during the near future and reach a value of approximately 259 million US$ by 2025 (Expert market research Homepage 2020).

The research method of this study includes a thorough review of the scholarly literature as well as data from gray literature (e.g., reports, discussion articles, policy documents) and databases (e.g., FAOSTAT, World Bank) from Qatar and other countries. The search included all the documents that were indexed up to the year 2015, so only recent studies were considered on the development of greenhouses and technologies worldwide as well as for the greenhouse sector development in Qatar.

Hence, the present paper provides an overview of the current status of greenhouse technology, aiming to offer effective supporting information to decision and policymakers as well as overall professionals and end-users in introducing new technologies and benefiting from the advances in monitoring techniques, artificial intelligence and communication infrastructure in the agricultural sector. Then, it focuses on Qatar, with the main objective to present a comprehensive understanding framework of the actual greenhouse development in the country, able to support the transition to sustainable precision agriculture meeting the country's food security and sustainability goals.

Specifically, this review paper:

- analyzes the actual development of greenhouses and technologies worldwide (Sect. 2);
- elaborates on smart greenhouses in the food-energy-water nexus focusing on the energy and water resources (Sect. 3);

- gives an overview of the greenhouse sector development in Qatar by analyzing the actual agriculture situation and examining its potential development regarding the existing drivers and barriers (Sect. 4); and
- presents the policy measures already implemented in Qatar while analyzing the future development of the local greenhouse sector in terms of sustainability and resources saving perspective as well as its penetration into Qatar's economy (Sect. 5).

2 Actual development of greenhouses and technologies

Global challenges linked to population growth, urbanization, and climate change have led to bringing innovative features to conventional greenhouse cultivation techniques (Specht et al. 2019). In fact, over the past few years, the greenhouse industry has been transformed to include modern technologies allowing farmers to grow a consistent product all year round using far fewer resources than conventional production (Tuomisto 2019). The main part of this transformation is the introduction of vertical systems that have been proposed as a concept to address the issue of sustainability (Graamans et al. 2018) and as a solution to improving food production involving land and water use optimization (Kalantari et al. 2020; Benke and Tomkins 2017; Bao et al. 2018; Yeşil and Tatar 2020). Vertical systems consist of growing crops in vertically stacked layers under a protected environment to limit the use of the agricultural land and therefore the ecological footprint of agriculture (Anda and Shear 2017). This concept, in addition to other major advances, has not only transformed the greenhouse industry but also led to new farming methods such as hydroponics (Al-Kodmany 2018), as well as the introduction and widespread adoption of full automation technologies and advanced lighting techniques.

2.1 Full automation technologies

Currently, greenhouse crop production is facing increased demand for automation and robotics. In fact, although the initial reason for using greenhouses was to grow crops in controlled environments, today the integration of smart systems can reduce reliance on labor and increase profitability while ensuring efficiency and sustainability. In this context, enormous progress has been made in the automation of greenhouses, mainly based on environmental sensors that play a key role in the programmed operation. Indeed, smart greenhouse solutions incorporating advanced sensor technologies have become widely used for crop growth environment monitoring. For example, different sensors of various environmental parameters have been used to support a greenhouse monitoring system consisting of a Programmable Logic Controller (PLC) and a Supervisory Control and Data Acquisition (SCADA) system which are different layers of automation in a system known as the Automation Pyramid (AP) (Ding et al. 2018). The different sensors and machines can communicate with each other by exchanging data, the so-called Cyber-Physical Production Systems (CPPS). These systems can fit into the existing farm decision-making tools and particular in the production processes as the database and information they offer is precise and constantly updated thus creating transparency in multifactorial decisions. A camera has been also used as part of the imaging platform of a greenhouse powdery mildew detection machine vision system (Wspanialy and Moussa 2016). Furthermore, huge steps forward have been also made in the field of Wireless Sensor Networks (WSN) as an effective solution to many problems associated with the conventional cabled sensors (Oliveira et al. 2016; Cenedese et al. 2012). Moreover, WSN has been developed under the Internet of Things (IoT) paradigm, by integrating web-based technologies, providing thus an interface to view the greenhouse status and remotely control the environmental parameters (Li et al. 2017a; Akkaş and Sokullu 2017; Danita et al. 2018). As an illustration, different sensors ranging from simple (temperature, humidity, pH, illumination, pressure, UV, CO_2, wind speed, solar radiation (Jahnavi and Ahamed 2015; Thirukkuralkani et al. 2018; Jiang et al. 2016; Erazo-Rodas et al. 2018) to complex [cameras (Hwang and Yoe 2016), mid-infrared spectroscopy (Wang et al. 2016)] have been used, and their measurements were communicated wirelessly to the host system using several technologies such as Zigbee (Chen et al. 2016a, 2017; Xing et al. 2017; Raheemah et al. 2016; Pascual et al. 2015; Luo et al. 2016; Liu and Bi 2017; Aiello et al. 2018; Rao et al. 2016; Ismail et al. 2016; Ibayashi et al. 2016; Erazo, et al. 2015; Çaylı et al. 2017), radio (Liang-Ying and Zhao-Wei, 2015; Achour et al. 2018; Mahbub 2020), GSM/GPRS (Liang-Ying and Zhao-Wei, 2015; Liu and Zhang 2017; Navarro-Hellín et al. 2015; Mat et al. 2016), 3G/4G (Zhou and Duan 2016; Chung et al. 2015; Zhang et al. 2015), Wi-Fi (Aiello et al. 2018; Chung et al. 2015; Mohapatra and Lenka 2016; Liang et al. 2018a) and Bluetooth (Hong and Hsieh 2016; Taşkın et al. 2018). However, to keep the greenhouse automation trouble-free, a secure protocol for wireless sensor networks has been proposed in the automated agricultural environment and has allowed more reliability (Sivamani et al. 2018).

The WSN's sensed data are processed and then used as multi-inputs to drive advanced control algorithms-based artificial intelligence to manage intelligently the greenhouse internal microclimate and to optimize the use of water and energy. These controllers can also vary from simple, such as feedback controllers (Mekki et al. 2015; Maher et al. 2016; Pawlowski et al. 2017), to modern ones such as fuzzy logic controllers (Rahmawati et al. 2018; Alpay and Erdem 2018; Xu et al. 2016; Pahuja et al. 2015; Márquez-Vera et al. 2016; Chen et al. 2016b; Wang and Zhang 2018; Li et al. 2017b, 2018; Ben Ali et al. 2018; Faouzi et al. 2017; Carrasquilla-Batista and Chacon-Rodrıguez 2017), artificial neural networks (Nicolosi et al. 2017; Huang et al. 2018; Francik and Kurpaska 2020; Singh 2017; Hongkang et al. 2018; Moon et al. 2018; Taki et al. 2016), genetic algorithms (Wang et al. 2017a; Mahdavian and Wattanapongsakorn 2017), model predictive controllers (Ouammi et al. 2020b; Liang et al. 2018b; Hamza and Ramdani 2020), sliding controllers (Khelifa et al. 2020; Oubehar, et al. 2016), adaptative controllers (Essahafi and Lafkih 2018), frequency controllers (Bagheri Sanjareh et al. 2021), and receding horizon controllers based on prioritized multi-operational ranges (Singhal et al. 2020).

Nevertheless, although WSN has been widely implemented as an automation technology offering numerous benefits, the research on applied robotics has also grown recently attaching great importance to mobile sensing as a sustainable solution for cost improvement (Li et al. 2019a; Roldán et al. 2016). On this basis, an autonomous mobile robot was developed to map the greenhouse and collect humidity, temperature, and light data (Durmus et al. 2016). Another improved robot, comprising ground and aerial vehicles, has been proposed to measure the temperature, humidity, luminosity, and carbon dioxide concentration in the ground and at different heights of the greenhouse (Roldán et al. 2016). However, robotic systems have not been used only for environmental monitoring, but also to perform greenhouse unsafe tasks like the UV-C treatment against powdery mildew (Mazar et al. 2018). In fact, robotic systems have been designed to help labor tasks such as pesticide spraying with path-planning and traveling-control abilities (Nakao et al. 2017; Mahmud et al. 2019), transplanting (Han et al. 2018), fertilizing (Yuan et al. 2016), phenotyping (Atefi et al. 2019) and harvesting (Wang et al. 2017b; Arad et al. 2020; Woo et al. 2020). In addition, they have been tightly related to image-based detection algorithms and near-infrared spectroscopy, and therefore, to crop disease detection (Rizk and Habib 2018; Schor et al. 2016, 2017), classification and picking (Zhao et al. 2016; Feng et al. 2015). But despite the fast development of these greenhouse robotic systems, there are several research challenges concerning the supervision, control and optimization of robots that must be addressed to ensure the competitiveness of this sector. Several steps have been made towards optimizing robots' efficacy, for example, heuristic and genetic algorithms have been implemented to reduce the duration of type-c ultraviolet radiation treatment performed by a battery-powered robot (Mazar et al. 2020). Moreover, a green pepper recognition method based on the least-squares support vector machine optimized by the improved particle swarm optimization (IPSO-LSSVM) has been proposed (Ji et al. 2019). And finally, a greenhouse layout optimization system that enables rapid and safe robot navigation has been developed (Uyeh et al. 2019).

2.2 Hydroponics

The introduction of hydroponics may be taken as a significant advance in modern greenhouses, where crops are grown in a soil-free environment, using only mineral nutrient solutions in water. The hydroponic techniques used to this end are mainly the deep flow technique (DFT) and nutrient film technique (NFT) (Son et al. 2020). Regarding the first one, panels are floating in a container filled with nutrient solution (10–20 cm deep), while for the second, a nutrient solution flows from the upper end to the lower end and passes through troughs of about 10 cm placed on trays at a slope of 0.5–2%. Generally, the choice of the DFT or NFT hydroponic system does not lead to important changes under greenhouse conditions (Santos et al. 2019). Nevertheless, DFT allowed an increase of 2.6 g in fresh weight of fresh basil compared to plants grown in NFT systems (Walters and Currey 2015).

Overall, compared to conventional greenhouses, hydroponics offers several advantages such as: improving the quality and nutrient content, increasing yield and conserving water. It has been documented in the literature that various plant species have been found to have better characteristics when grown hydroponically. For example, hydroponic strawberries were higher in terms of fruit yield and plant survival rate compared to systems traditionally grown in soil (Treftz and Omaye 2016). In addition, for hydroponic lettuce, the technique has offered 11 ± 1.7 times higher yields and 13 ± 2.7 times less water, but required 82 ± 11 times more energy compared to conventionally produced lettuce (Barbosa et al. 2015). However, to deal with the high-energy consumption issue, an innovative hydroponic greenhouse and a new solar air heater with latent storage energy have been assessed and have allowed an annual energy production reduction of over 4600 kWh. The innovation of this work is to guarantee an enhanced hydroponic greenhouse microclimate through a pilot unit with latent thermal storage using exclusively solar energy (Baddadi et al. 2019).

2.3 Advanced lighting techniques

The adoption of supplemental artificial lighting systems is a key solution providing important progress in modern greenhouses promoting agricultural production. Commonly, high-pressure sodium (HPS) lamps have been widely used as the main supplemental light source in greenhouses, because of their high electrical efficiency and high photosynthetically active radiation emission (Viršilė et al. 2017). However, recent developments have given rise to light-emitting diode (LED) due to their technological advantages, especially in terms of spectral output, light distribution, heat emission, lifespan, and control capabilities (Iersel 2017; Alsanius et al. 2017). In the literature, numerous comparative studies have been carried out to assess the effectiveness of each technology. For instance, three are different types of lighting, namely HPS standard lighting, HPS top lighting and LED inter-lighting, and 100% LED lighting have been tested in a lettuce greenhouse, and the results indicated that the efficiency of light use was the highest in the 100% LED combination and the lowest in HPS (Kowalczyk et al. 2020). Also, a comparison of 1000 W HPS lighting system versus 650 W LED lighting system has shown that LED lighting has 38%-47% less environmental impact in terms of global warming, ozone depletion, and acidification than HPS lighting system (Zhang et al. 2017). In fact, supplemental lighting by light-emitting diodes (LED) has shown further benefits in other studies, such as improving water use efficiency of greenhouse crops (Li et al. 2019b), increasing fruit weight and size (Paucek et al. 2020), enhancing lettuce growth and yield (Zhang et al. 2019) and reducing energy consumption (Wang and Wei 1956). In addition, extra studies have been conducted to determine the effects of LED colors on crop production, such as for lettuce where supplemental lighting with 80% red and 20% blue light has proven to be advantageous (Długosz-Grochowska et al. 2017), as well as for the artichoke where seedlings under red light condition were much better (Rabara et al. 2017). Furthermore, another important step consistent with the research is the design of an intelligent hybrid system for greenhouse plants by 3D supplementary lighting, which can be auto switched to sunlight or LED depending on weather conditions. This last has shown the ability to accelerate vegetables and fruits' growth rate (Tang et al. 2019).

3 Smart greenhouses in the food-energy-water nexus

Due to the intensive exploitation of energy, water, and food resources, induced by population growth and rapid urbanization, increasing interest has been given to the preservation of these resources and leading to the introduction of the food-energy-water nexus (FEW) as an approach to the sustainable development of agriculture among other practices (Li et al. 2019c). The FEW nexus is a holistic approach to the resources of food, energy and water examining their interrelatedness and interdependencies rather than considering each resource individually (United Nations University 2022). Hence, sustainable FEW systems can be defined as systems that can meet their food, energy, and water demands with sustainable sources rather than using non-renewable inputs. They aim at effective management of natural resources, optimization of potential conflicts and reinforcement of multisectoral integration (Lahlou et al. 2020; El-gafy 2017). In this context, agricultural technologies like smart greenhouses have been increasingly encouraged as means to achieve regional food security and reduce the stress on water and energy resources. They can be considered as FEW systems able to yield food while minimizing energy and water consumption and maximizing economic productivity (Karan et al. 2018).

As part of this paradigm, a decision-making framework based on the approach of the FEW nexus for the development of new greenhouses has been introduced and has led to a reduction in CO_2 emissions and an economy of water resources (Al-Ansari et al. 2018). In addition, a novel decision-making methodology in greenhouse cultivation has been proposed using the FEW nexus approaches, which assesses the investment and operating costs and the potential for global warming, for food production based on economic and environmental performance (Namany et al. 2019). Moreover, an approach based on both GIS, analytical hierarchy process and resource assessment has been proposed to improve water and energy efficiencies (Haji et al. 2020). However, the performance of the FEW nexus has been conventionally analyzed through energy and water indicators.

3.1 Energy considerations in smart greenhouses

From the energy viewpoint, smart greenhouses focus consideration on integrating different types of renewable energy to support sustainable growth. Solar energy remains the primary renewable source used to generate electricity in greenhouses to economically meet the electrical load of any actuating machine. Solar technologies used for this purpose can be divided into three categories: photovoltaic systems, solar thermal collectors, and hybrid photovoltaic/thermal (PV/T) modules. Classically, solar thermal collectors have been adopted in greenhouses to accumulate the maximum amount of solar energy (Patil and Gawande 2016; Awani et al. 2015), especially for drying purposes, where their use has allowed a remarkable reduction in drying hours from 24 to 17 h for red pepper compared to open sun drying (ELkhadraoui et al. 2015). As for photovoltaic systems, they have also been highly integrated into greenhouse applications to cater in a clean way to energy-consuming activity (Trypanagnostopoulos et al. 2017; Marucci and Cappuccini 2016; Fatnassi et al. 2015; Marucci et al. 2018; Gao et al. 2019). Moreover, by combining these two technologies, photovoltaic/thermal (PV/T) systems have gained popularity by increasing the use of solar energy (Good 2016; Achour and Zejli 2018; Kim et al. 2016). They have been used for several greenhouse applications such as crop drying (Tiwari and Tiwari 2016a, b; Shyam et al. 2015; Tiwari et al. 2018, 2016a) and biogas heating (Tiwari and Tiwari 2017; Tiwari et al. 2016b). Differently, another example of renewable energy implemented in greenhouses is geothermal energy. It consists of circulating fluid in the depths of the earth to use its underground temperature as a source of energy. Its employment in greenhouses includes space heating and cooling, agricultural drying, and ground-source heating pumps (GSHP) (Ha et al. 2015; Roumi et al. 2017; Ozturk 2017; Andritsos et al. 2015; Papachristou et al. 2016; Urbancl et al. 2016).

In addition, the implementation of energy supply optimization strategies is another aspect of efficiently improving the water, energy, and food security in greenhouses. The optimization strategies have varied from feedback conventional controllers to advanced ones based on artificial intelligence such as: fuzzy logic controllers (Su et al. 2017), hybrid particle swarm optimization and genetic algorithms (Chen et al. 2015), model predictive controllers (Ouammi et al. 2020a, b; Lin et al. 2020) and optimal controllers (Beveren et al. 2015, Beveren et al. 2020; Singh et al. 2015). Their common goal is to maximize production yield by tracking the desired trajectories of the controlled variables while minimizing the use of available water and energy resources.

In another way, the optimization of energy consumption can be done by implementing high-tech solutions that facilitate the development of smart greenhouses. In this context, new innovative hardware technologies have been studied to ensure the safe and sustainable use of resources such as LED and novel covering materials. In fact, recent developments have opened a new perspective for LEDs as a light source technology having more technical advantages for greenhouse cultivation over traditional light sources, in terms of high-energy efficiency, low maintenance cost and longevity (Singh et al. 2015). In addition, innovative covering materials have gained a significant amount of attention in the research community as promising technologies. By way of illustration, a material based on TiO_2 mixed with low-density polyethylene in the form of heterogeneous granules, developed as an alternative material to face up to the high heating and cooling energy requirements showed improved thermal insulation characteristics (Kavga et al. 2018). In addition, a feasibility study of many combinations of different types of glass with different types of F-Clean plastic films showed that the double covering material has high insulation levels, saving 50% energy compared to single glass (Kempkes et al. 2017).

While considering the energy needs of a greenhouse it is important to include the energy demands for the desalination of water for irrigation purposes. The salinization of water resources is a progressive phenomenon mostly affecting coastal and delta areas, as well as arid and semi-arid regions. This is due to natural and anthropogenic sources such as climate change and overexploitation of groundwater resources (Mastrocicco and Colombani 2021). Especially in the case of hydroponics, the regulation of salinity levels is imperative as it can detrimentally affect plant growth and development. Although desalination increases water resources and improves water quality, the general problem with this process is the relatively high-energy requirement and the associated CO_2 emissions in the case of conventional energy supply (Hussein and Lambert 2020). Specifically, the energy required to desalinate seawater could be between 2.5 and 4 kW-h/m^3 (Pearce 2008) depending on salinity levels and other factors, such as operating conditions, prevailing temperature, recovery, etc.

3.2 Water considerations in smart greenhouses

From a water-saving point of view, although there is consensus that smart greenhouses are sustainable in terms of their water use, they remain undoubtedly the sector of activity where the consumption of irrigation water is very intensive. For that, smart greenhouses are challenged to save more water without compromising their economic viability (Warner et al. 2020), by adopting effective management strategies aiming at conserving water while maintaining satisfactory production and water use efficiency levels.

Smart greenhouse water management techniques include water conservation practices (Warner et al. 2018), scheduling strategies (Nikolaou et al. 2019) and desalination processes (Kabeel and El-Said 2015; Martínez-Alvarez et al. 2016). Regarding water conservation practices, drip irrigation was the method justifying the most efficient use of water and has been widely used for many species, like tomato (HongJun et al. 2015), muskmelon (Li et al. 2016), pepper (Sharma et al. 2017; Rameshwaran et al. 2016), sugar beet (Kiymaz and Ertek 2015) and cotton (He et al. 2018). In fact, dispensing small amounts of water at high frequencies has shown a significant increase in water use efficiency (Yao et al. 2019), but greater efficiency has been achieved with water pillow irrigation. The latter is a new irrigation method incorporating mulching techniques to drip irrigation through flexible plastic pipes (Fang et al. 2018). In this context, many studies have been carried out to assess the superiorities of water pillow irrigation over the drip irrigation method under greenhouse conditions. For example, for the tomato crop, the exploitation of water pillows has proven to have more efficient water use by saving 52% of water compared to drip irrigation (Gerçek et al. 2017; Altunlu et al. 2017). As well as for eggplant, the use of colored water pillows and mulching treatments has demonstrated a decrease in the irrigation water amounts of 22% and 16%, respectively (Gerçek and Demirkaya 2020). For lettuce also, the results suggested that using plastic film mulching was interesting for increasing the biological water use efficiency (Chen, et al. 2019). Overall, the benefits of the mulching effect in maintaining the water amount in the root area made this technique yield better outcomes than drip irrigation regarding crop water consumption and irrigation water use efficiency.

Always within the framework of water conservation practices, an alternative water source for greenhouse crop production is the use of rainwater harvesting systems that are demonstrated to reduce the consumption from the water supply network by 80–90% in the case of a rooftop greenhouse. Otherwise, for a standard greenhouse, the application of drainage water blended with water of low electrical conductivity has allowed savings of 17% of the water in comparison to the standard nutrient solution treatment (García-Caparrós et al. 2018a, b).

Also, deficit irrigation, defined as an optimization strategy consisting of irrigating the root zone with water below the evapotranspiration requirements (Aly et al. 2015), has proved to be a success in water saving for a wide range of crops. Indeed, many studies have been carried out to investigate the effects of applying different amounts of water on crop yield and water use efficiency under greenhouse conditions. A summary of the most recent studies, since 2015, is presented in Table 1.

However, to further improve water conservation techniques, greenhouse irrigation scheduling has been widely promoted as an effective tool in attempting to prevent water wastage. The main technique used for this purpose is the use of soil and plant sensors (Çakir et al. 2017). Indeed, although several technological innovations based mainly on thermal infrared imaging systems have been introduced in humidity sensors (Wang et al. 2020), the tensiometer remains the most common sensor due to its low cost, simplicity of use, high accuracy, and direct measurement of matric potential (Garcia-Caparros et al. 2107; Montesano et al. 2015; Contreras et al. 2017). It offers a better use of the water resource without being influenced by the temperature and the osmotic potential of the soil (Buttaro et al. 2015). The main interest of this functionality is to provide the opportunity to integrate tensiometer based sensor networks in the classic irrigation systems, like what was reported in numerous researches carried out on wireless sensor networks, proving this to be an alternative way to solve the water resources optimization and to support the decision making (Hamouda and Elhabil 2017; Harun et al. 2015; Montesano et al. 2018; Nawandar and Satpute 2019; Lea-Cox et al. 2017; Khan et al. 2018; Ferentinos et al. 2017; Silva et al. 2018). Besides, the tensiometer demonstrated the ability to assist the development of smart autonomous precise irrigation control systems that can lead considerably surpass the conventional approach in terms of water consumption (Angelopoulos et al. 2020; Kim et al. 2015).

A resource-saving method as it maximizes overall output and minimizes the use of space, soil, water, and other resources is hydroponics, a soilless cultivation technique. Hydroponic crop production apart from the low land and chemical fertilizers use, requires less water as the nutrient solution can be recirculated. Hence, the hydroponic production of lettuce can result in 64% water savings than the soil cultivation (Majid et al. 2021) or even higher, as it needs 13 ± 2.7 times less water compared to conventionally produced lettuce (Barbosa et al. 2015). Fully automated hydroponic systems for smart farming (Shetty et al. 2021) and the use of internet of thing (IoT) technology (Aliac and Maravillas 2018), results in even less amount of water resource consumption when compared to traditional methods. Further water use optimization in hydroponics can be realized by the implementation of the circular economy concept. A two-level cascade cultivation system using the drainage solution of a primary crop to irrigate a secondary crop significantly improved water use efficiency as it reduced by approximately 30% the freshwater consumption of the second crop plants in comparison to plants irrigated with freshwater (Elvanidi et al. 2020).

4 Overview of greenhouses development in Qatar

4.1 Market growth

Qatar is a small peninsula with a set of islands located in the Arabian Gulf with a total area of approximately 11.628 km^2 including the islands (Planning and Statistics Authority in Qatar 2013a). Food production faces many challenges in hot arid countries like Qatar, which is marked by sparse rainfall with an annual average of 83.4 mm in 2019, high temperatures in summer (> 45°C) starting from June till the middle of September, high humidity and strong winds as reported in Figs. 1 and 2 (Homepage 2020). The harsh climate, the limited freshwater availability with the dependency on the desalination treatment as well as the limited available arable land, with 65.000 ha or 5.6% of the total area being arable (Al Yousef et al. 2000) are reflected in the limited agricultural sector in the country, which provided 0.2% of Qatar's GDP in 2019 (Planning and Statistics Authority in Qatar 2018).

The main component driving the progress of the greenhouse market in Qatar is the capability to maximize crop production contrasted to the traditional cultivation practices. To expand the self-sufficiency of agricultural production, the need for greenhouses has been increasing in Qatar. As Qatar has a harsh climate throughout the year, consequently, new technologies, methods and practices are introduced to ensure the quality the continuous crop production as well as

Table 1 Works carried out on the impact of irrigation regimes on water use efficiency (WUE) under greenhouse conditions

Irrigation regimes	Observations	Crop	Location	References
0% 50% 75% 100%	The WUE increased from the fully irrigated to the dry treatment, proving that water is more efficiently used under stress conditions	Tomato	Mediterranean environment	Lovelli et al. (2016)
50% 75% 100%	The yield was affected by the irrigation regime implemented. The highest was obtained under 100% and the lowest under 50%	Tomato	Agadir, Morocco	Alaoui et al. (2015)
25% 50% 100%	The accurate control of the water stress level improved the irrigation water use efficiency	Cherry tomato	Sevilla, Spain	Coyago-Cruz et al. (2019)
70% 85% Randomized design	The regulated deficit irrigation has shown no significant difference compared to randomized irrigation treatment in terms of WUE	Tomato	Ahvaz, Iran	Hooshmand et al. (2019)
50% 75% 100%	The obtained WUE was 16.5% lower in 75% than that in 50%	Tomato	Northwestern China	Du et al. (2017)
40% 60% 80% 100%	The combination of plastic mulch with 80% of the irrigation level was considered the most suitable in terms of WUE with a recorded water saving of 20%	Muskmelon	Riyadh, Saudi Arabia	Alenazi et al. (2015)
50% 70% 100%	The regulated deficit irrigation improved agronomic WUE compared to full irrigation without a significant reduction in yield	Papaya	Rio de Janeiro, Brazil	Lima et al. (2015)
50% 70% 90% 110%	Both yield and WUE increased under 90% and 70%	Tomato	Xinxiang, China	Liu et al. (2019)
50% 75% 100% 125% 150%	The optimal strategy in terms of water saving, yield and fruit quality was obtained under 75%	Tomato	Jiangsu, China	Ullah et al. (2017)
60% 80% 100%	The highest water use efficiency (WUE) of 55.8 kg/m^3 was obtained under 80% with the application of 360 kg/ha of N	Cucumber	Shaanxi, China	Wang et al. (2019)
Different irrigation regimes	The optimal water use efficiency was obtained under 77%	Watermelon Hot pepper Tomato	Wuwei, China	Yang et al. (2017)
75% 100% 125% 150%	Both yield and biomass WUE increased under 75%	Rocket	Policoro, Italy	Schiattone et al. (2018)
50% 75% 100%	The water use efficiency under 50% was 27.3% and 18.7% higher than that under 100% and 75% respectively	Tomato	Shijiazhuang, China	Xiukang and Yingying (2016)

Table 1 (continued)

Irrigation regimes	Observations	Crop	Location	References
Regimes for both vegetative and reproductive growth stages: 75–75% 75–55% 65–65% 55–75% 55–55%	The water use efficiency and the crop yield were the highest under 75–55%	Muskmelon	Wuhan, China	BaoZhong et al. (2015)
70% 100%	The highest water use efficiency and the highest crop yield was obtained under 70%	Cucumber	Tulkarm, Palestine	Rahil and Qanadillo (2015)
70% 100%	The regulated irrigation resulted in higher water use efficiency of 15% compared to full irrigation	Tomato	Taastrup, Denmark	Pazzagli et al. (2016)
50% 100%	The deficit irrigation increased the water use efficiency of both fresh and dry tomatoes	Tomato	Belgrade, Serbia	Djurović et al. (2016)
0% 50% 100%	The deficit irrigation caused a decrease in biomass and yield water use efficiencies	Cherry tomato	Bari, Italy	Cantore et al. (2016)

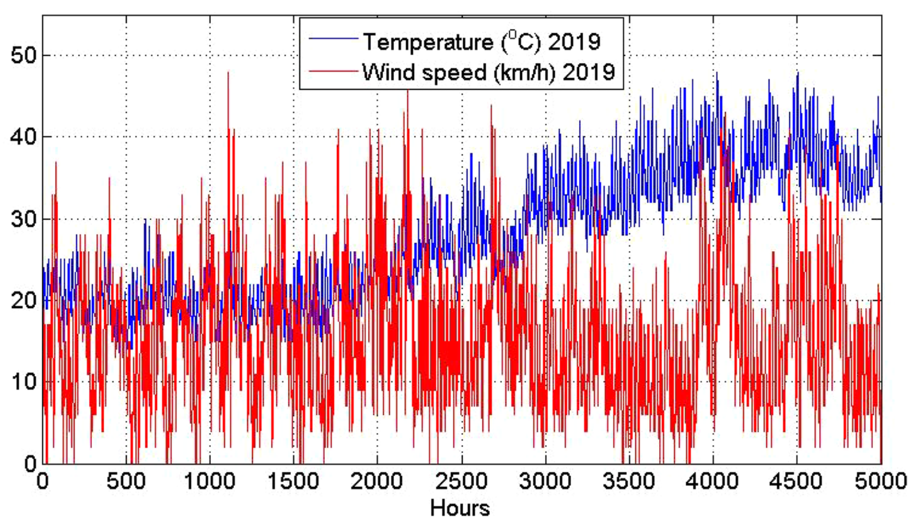


Fig. 1 Hourly temperature (°C) and wind speed (km/h) in Qatar in 2019 (Homepage 2020)

increase their conservation periods. Furthermore, the Ministry of Municipality and Environment (MME) declared 34 new strategic investment projects-based greenhouses technology in 2018 (Gulf Times Homepage 2020). Additionally, the adoption of hydroponic greenhouse and the collaborations with Spanish companies in Qatar have offered a variety of valuable businesses in the country (Businesswire Homepage 2020). On the other side, many factors like an elevated investment and import-dependent agriculture in Qatar favour the expansion of the market. Therefore, the Qatar greenhouse market reached a value of US$ 97.9 million in 2018, a value of 112 million US$ in 2019, and it is anticipated to mark a value of US$ 216 million by 2024 (IMARC Group Homepage 2020) as stated in Fig. 3.

More specifically, the cooled greenhouse area increased from 49 ha in 2017 to 73 ha in 2018, with a subsequent increase in vegetable production from 4.814 tons to 6.500 tons in the same years (Table 2). Similarly, the no-cooled greenhouse area increased from 200 to 220 ha from 2017 to 2018 with an increase in vegetable production from 17 thousand tons to 20 thousand tons during the same period. The same trend is recorded for the open field vegetable

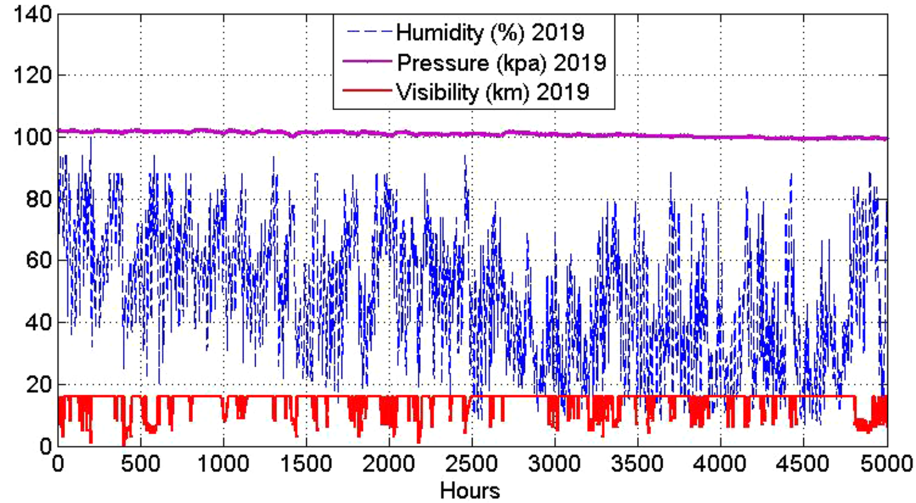


Fig. 2 Hourly humidity (%), pressure (kPa) and visibility (km) in Qatar in 2019 (Homepage 2020)

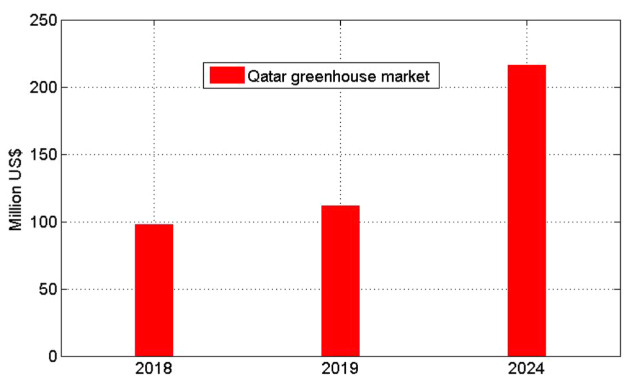


Fig. 3 Greenhouse market evolution (million US$) from 2018 to 2024 in Qatar (IMARC Group Homepage 2020)

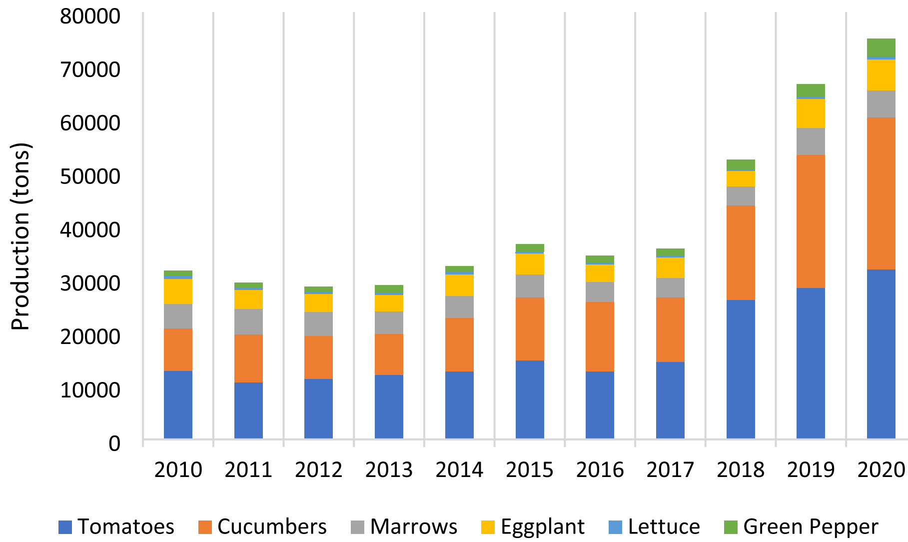
cultivation where the cropped and production area increased from 1,910 ha to 2,484 ha and from 33,000 tons to 36,000 tons, respectively. Therefore, according to Table 2, the total vegetable production in Qatar has been significantly increased within one year (2017–2018) from 54,814 tons to 62,500 tons and it is noteworthy that the land-use efficiency, in terms of land resource input and production output varies among the three crop production systems. In the case of vegetable greenhouse production, the land-use efficiency is much higher when compared to open field cultivation. However, there are small differences between the cooled and the non-cooled greenhouse production.

According to market experts, the Qatar greenhouse market is a dynamic sector, and it is expected to mark double-digit growth during the next five years and reach a value of almost 259 million US$ by 2025 (Expert market research Homepage 2020). This trend is reflected in the increased domestic production of vegetables in the country, as shown in Fig. 4. During the last decade, the greenhouse and open field production of the most consumed vegetables, like tomatoes, cucumber, marrows, eggplants, lettuce, and green pepper, has increased from 31,573 tons in 2010 to 75,063 tons in 2020, marking an approximate 138% increase. It should be highlighted that after 2017, domestic vegetable production has more than doubled, reaching a more than 100% increase within three years, from 2017 to 2020 (Planning and Statistics Authority in Qatar 2020a, 2014). The main driver behind this remarkable increase in local food production was a 3.5-year land, air and sea blockade imposed on Qatar by neighboring countries and allies in the region between June 2017 and January 2021, making the issue of food security a fundamental national security concern. Till then, the state of Qatar imported approximately 90% of its foodstuffs from other countries while 27.4% of the imports came from the blockade imposing countries such as Saudi Arabia and the UAE (Miniaoui et al. 2018). After the blockade, Qatar was forced to develop new suppliers for food products and begin to implement local production of perishable goods such as vegetables and milk while nearly tripling local production (Collins 2018; Hassen and Bilali 2019). Self-sufficiency in

Table 2 Vegetable production area (ha) and production amount (tons) for greenhouse and open field cultivation in Qatar for 2017–2018 (Qatar International Islamic Bank 2019)

Vegetable production method	2017		2018	
	Area (ha)	Production (tons)	Area (ha)	Production (tons)
Cooled greenhouse	49	4,814	73	6,500
No-cooled greenhouse	200	17,000	220	20,000
Open field	1,910	33,000	2,484	36,000

Fig. 4 Production (tons) of main vegetables (greenhouse and open field cultivation) in Qatar over the period 2010–2020 (Planning and Statistics Authority in Qatar 2020a, 2014)



many goods like meat, dairy products and vegetables has increased in the country since 2017 and although the blockade has ended, the government of Qatar together with the Ministry of Municipality and Environment has set solid targets to increase up to 70% self-sufficiency on greenhouse vegetables and reach the size of 110 hectares with high-tech greenhouses by 2023 (Ministry of Municipalities and Environment 2020).

The main companies and competitors in the Qatari greenhouse market are the NAAAS Agricultural Consulting & Greenhouse (Naaas Group), the Arab Qatari Agricultural Production Company (QTFA), the Qatari Agricultural Development Company (Agrico), the Al Rayyan Agricultural and final the Pergola Contracting & Green Houses company.

4.2 Technologies implemented

Greenhouse design in hot arid climates should tackle challenging climatic conditions such as the high temperature and humidity levels and the abundant sunshine. The types of greenhouses found in Qatar can be segmented into categories by the type, the used material and technology. Amongst free-standing and gutter-connected greenhouses, the latter represents the leading type, holding the largest share (IMARC Group Homepage 2020). As Qatar has mild winter, the most important function is cooling than heating and consequently, most greenhouses have cooling systems with the evaporative cooling system with pads and fans being the most frequently used. Moreover, the most common greenhouses in the country have plastic or net as covering material, instead of glass. This is because glass is mostly used in countries with colder climates since the temperature inside is higher than the ambient. The following three types of greenhouses could be distinguished according to the used technology:

- Low-tech: uncooled and unheated plastic houses or net houses.
- Mid-tech: greenhouses with evaporative cooling and with/without air-conditioning for night cooling.
- High-tech: computer-controlled greenhouse microclimate i.e., temperature, humidity, CO_2 concentration and lighting.

For Qatar, the most frequent types are the low-tech uncooled, reaching 220 ha total area, followed by the cooled greenhouses with 73 ha area, as shown in Table 2. The number of high-tech greenhouses is gradually increasing with technologies adapted to the country's specific geo-climatic conditions (Businesswire Homepage 2020). Thus, CO_2 enrichment of the greenhouse environment and artificial light are not common practices in Qatar, as most greenhouses are not fully closed, for ventilation purposes and sunshine is abundant. The methods of natural and forced ventilation and external shading are effective and low-cost ways to control the greenhouse climate in hot areas, with the most optimal method being the evaporative cooling pads (Ghani et al. 2019). However, the evaporating cooling method, has its limitations in the summer months, as the high levels of humidity are reducing its effectiveness (Hassabou and Khan 2019). Besides, this type of cooling requires a significant amount of water which in most cases exceeds the amount of water needed for irrigation purposes, especially during the hot season from April to June.

According to the collaborative research report of important agricultural companies in the field of greenhouse crop production, fertilizer and plant products in Qatar, Agrico, Qatar Fertilizer Company (QAFCO) and Yara International

Table 3 General characteristics of some of the different greenhouse types used in Qatar in 2019 (Enikeeva and Khadra 2019)

Greenhouse type		Growing season	Recommended crops	Crop yield (kg/m^2)	CAPEX (QR/m^2)
Low tech	Multispan net house	October-June	Tomatoes, eggplants	Tomato (12)	194
Mid tech	Multispan plastic greenhouse with evaporative cooling and night cooling air-conditioning	September-July	Tomatoes, cucumbers, sweet peppers	Tomato (33.2)	624
	Multispan plastic greenhouse with evaporative cooling and shading	September-June	Tomatoes, cucumbers, sweet peppers	Tomato (29)	534
	Plastic tunnels with evaporative cooling and shading	October-June	Tomatoes, cucumbers, sweet peppers, eggplants, leafy greens, beans	Tomato (18.6) Cucumber (22.6)	227

ASA conducted in 2019 (Enikeeva and Khadra 2019), the low-tech net houses have low cost and a 10-month growing period per year for winter crops. However, the growing season can be extended in summer for crops like okra and melon. The mid-tech greenhouses have a growing period of 10 months per year; nonetheless, the air-conditioning night cooling function can extend the summer growing season. The most productive system is the multi-span plastic greenhouse equipped with evaporative cooling and air-conditioning for night cooling, which can reach a tomato yield of 33.2 kg/m^2, followed by the same type of greenhouse without night air-conditioning with a tomato yield of 29 kg/m^2. Nevertheless, the first greenhouse type has a higher capital expenditure (CAPEX) compared to the latter, as shown in Table 3.

Greenhouse cultivation includes soil and soilless cultivation systems, like hydroponics and recently in 2021, aquaponics. Soilless cultivation methods are more suitable for arid climates with limited arable land, like Qatar, as they overcome the limitations of soil and water availability. As agriculture is one of the main water consumers in Qatar, consuming almost 1/2 of the total gross water supplied by the water supply industry which is 310 out 671 million m^3 per year in 2019 (Planning and Statistics Authority in Qatar 2019), water-saving hydroponic and aquaponic systems are a possible solution reducing agricultural water use (Barbosa et al. 2015). There are many pilot projects in Qatar initiated mainly by the Ministry of Municipality and Environment aiming to improve yields and consequently increase self-sufficiency in various crops (Qatar International Islamic Bank 2019). According to researchers, aquaponics is indeed a viable solution to address both food security and sustainability issues in the country but as is an emerging innovative system, it needs more research and development (Abusin and Mandikiana 2020). Nonetheless, it is a promising sector and the first aquaponic farm in Qatar by Agrico Agricultural Development started producing tilapia and lettuce in 2021 (Doha News Homepage 2022).

4.3 Capacity and potential development

Greenhouse cultivation is an effective way of getting over the limitations in agricultural production in Qatar, which are the harsh climate and the resources scarcity of water, land, and soil. Therefore, the greenhouse sector has significant potential for development. This rise of course is following

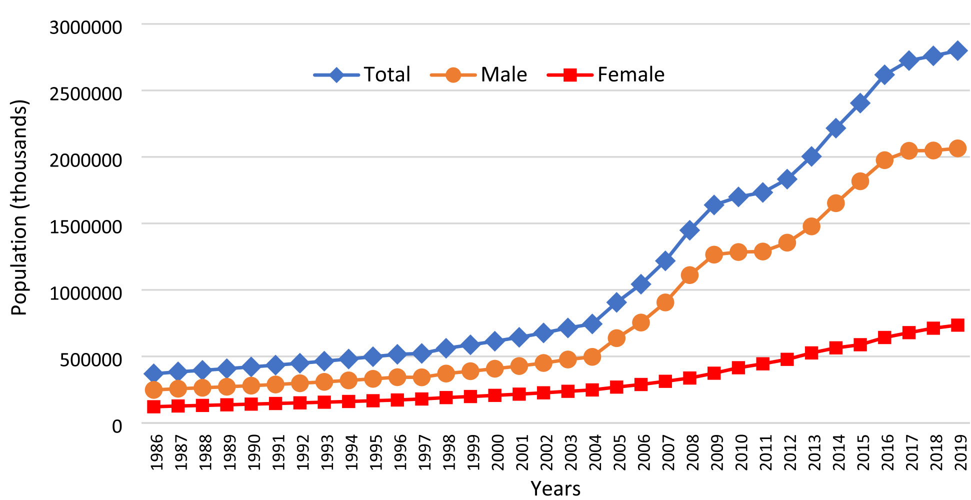


Fig. 5 Recorded population growth (thousands) from 1986 to 2019 in Qatar (Planning and Statistics Authority of Qatar Homepage)

the country's efforts to increase food and nutrition security by reducing at the same time import-dependent agriculture. Other factors that seem to favor the sector's rise are economic welfare and population growth with a consequent increase in food demand. Qatar is among the richest countries in the world with a 66.622 US$ GDP per capita and a 0.1% unemployment rate for 2019 (Focus Economics Homepage 2020). The country has witnessed unceasing variations in the population size and its growth rates as reported in Fig. 5, showing the estimation of the yearly population growth (Planning and Statistics Authority of Qatar Homepage). According to the Planning and Statistics Authority of Qatar, the population has augmented to reach 2.733.624 in September 2020; 1.969.032 of them being males and 754.592 females (Planning and Statistics Authority of Qatar Homepage).

The greenhouse industry could be further developed with the help of knowledge and innovation and the introduction of new techniques for modernizing the agricultural sector across the value chain. Greenhouse production can become smarter and less resource-intensive while integrating dynamic technologies such as hydroponics, aeroponics, and aquaponics and adapting advanced cooling technologies to increase crops' shelf-life (Embassy of the Kingdom of the Netherlands in Doha 2019; Karanisa et al. 2021). The government's attitude can enable the greenhouse sector to advance even further, in cooperation with educational institutes, researchers and the private sector on a national and international level. Thus, in summary, the following research areas could boost the agricultural sector and domestic production (GDA 2017) and subsequently achieve food security up to a certain level:

(1) Greenhouse research on hydroponics, aquaponics and vertical farming.
(2) Smart agriculture focused on increasing agricultural productivity.
(3) Resources management research on soil, water, and energy to optimize their use avoiding depletion while enhancing conservation.
(4) Marine, fisheries, and aquaculture research to develop innovative technologies to produce fishes, shrimps, seaweeds, etc.
(5) New crop varieties that are heat and humidity-resistant and less water-intensive.
(6) Post-harvest technology to increase crops' shelf-life.

4.4 Policies and regulations

Food security and sustainable development are high priorities in the Qatar National Vision 2030 (General Secretariat for Development Planning 2008), thus the Qatari government has launched different initiatives and strategies for boosting the local food production, as the further development of Qatar's agricultural industry is fundamental to ensuring food security in the country. Consequently, some of these initiatives are focusing on the greenhouse market as it represents the second major agricultural production method in the country (Qatar International Islamic Bank 2019). Additionally, the government's attention is engaged in resource security by improving their use efficiency and ensuring their conservation. Therefore, special attention is given to the use of groundwater, as without appropriate water resource management, the aquifers will be depleted while the salinity levels of groundwater water will be increased.

According to the Ministry of Municipality and Environment (MME), Qatar is aiming to double the number of farms in the near future to cover 8% of Qatar's surface area compared to 4% in 2019 (Qatar International Islamic Bank 2019). These farms will include animal and livestock farmlands along with vegetable production. That is in alliance with the Qatar National Food Security Strategy (QNFSS) 2018–2023, which has set a target to increase up to 70% domestic self-sufficiency in greenhouse vegetables and reach the size of 110 hectares with high-tech greenhouses by 2023. This strategical and policy guidance aims to achieve a high level of food security while regulating local production, improving crop yield, and protecting the country's food supply from external shocks. Moreover, special attention is given to environmental protection by preserving water resources and reducing food waste. These targets will be achieved by finalizing greenhouse cluster infrastructure plans and by developing bid guidelines and subsidy programs (Ministry of Municipalities and Environment 2020). Besides, the local government had launched agricultural strategic investment projects in 2018 and had been jointly working with companies from Spain to install state-of-the-art greenhouse facilities spread across 100 hectares of land, which required an initial investment outlay of about 430 million QR (117.6 million US$) (Businesswire Homepage 2020; Alpen Capital 2019). Moreover, 350 greenhouses, cooled and non-cooled, were installed on 85 local farms in 2019 by the Department of Agricultural Affairs of MME with all the necessary equipment and agricultural supplies to enhance agricultural production (Qatar Tribune Front 2020). In addition, Qatar Development Bank launched a ''Greenhouse financing program'' in 2019. Urban scale greenhouses can be financed by 100% of the value with a maximum of 70.000 QR, developing the culture of agriculture and enhancing self-sufficiency among the local community (Qatar Development Bank Homepage 2020). Although there have been considerable steps enhancing the agricultural and greenhouse sector, Qatar should strengthen even more synergies among government, industry, academic circles, and community. The lack of agricultural legislation in the State of Qatar is a big challenge for the local farmers and agricultural companies because the legislation would support marketing and monitor production more effectively.

5 Food security-greenhouses interaction in Qatar

5.1 Climatic and socioeconomic barriers to sustainable GHs development in Qatar

The barriers to sustainable greenhouse development in Qatar, in terms of continuation and technological advancement, are geo-climatic and socioeconomic. Qatar's climate is characterized by a hot summer starting from May till October with recorded temperatures as high as 34–37.2°C between 2010 to 2020, whereas winter starts from December till the end of February, and it is generally mild (Fig. 6). Rainfall is low and humidity is high; 71.4 mm recorded average rainfall between 2010 and 2020

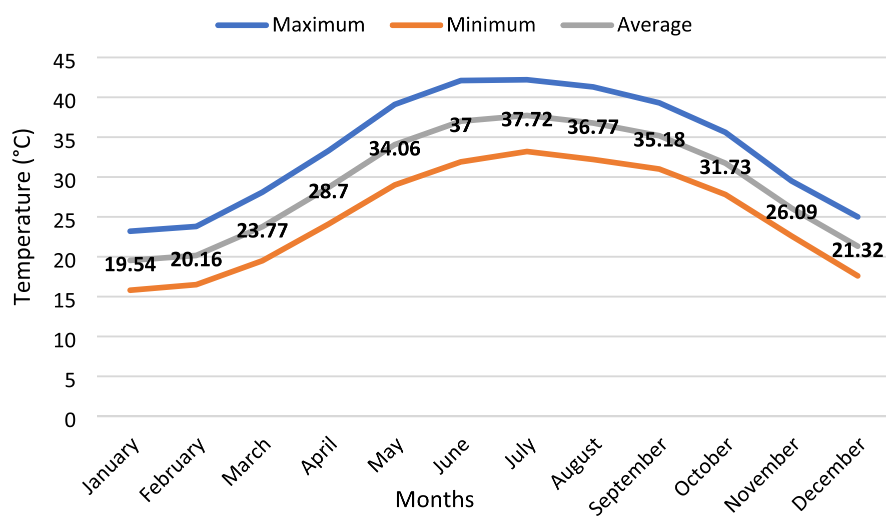


Fig. 6 Temperature (°C) per month in Qatar from 2010 to 2020 (Planning and Statistics Authority in Qatar 2013a, 2015a, 2020b)

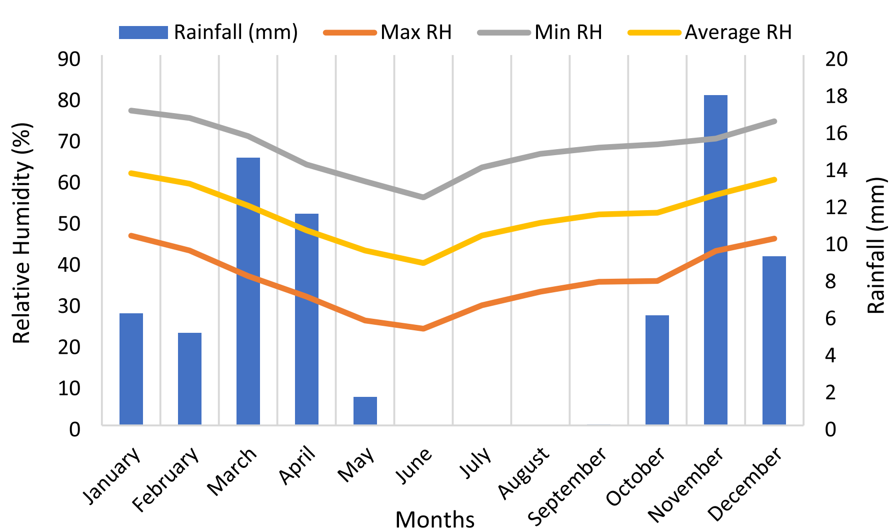


Fig. 7 Relative Humidity (%) and rainfall (mm) per month in Qatar from 2010 to 2020 (Planning and Statistics Authority in Qatar 2013a, 2015a, 2020b)

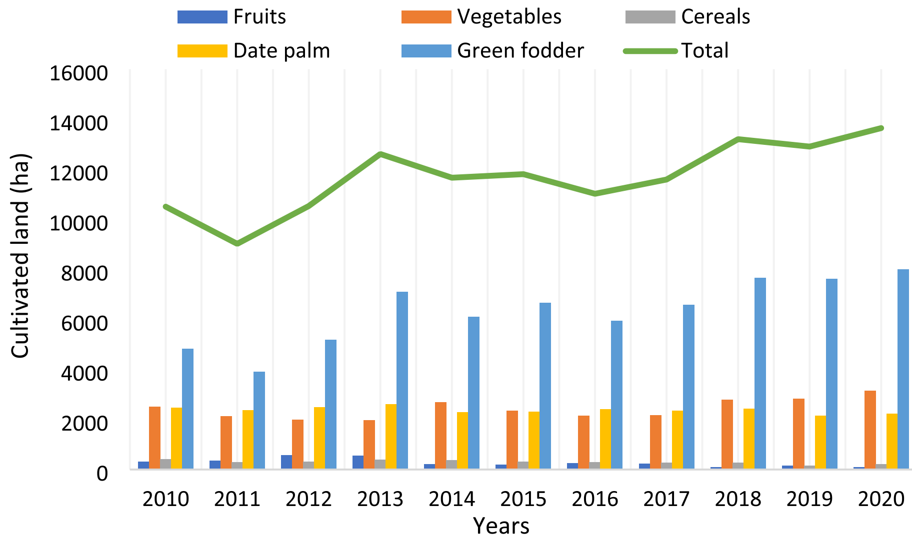


Fig. 8 Land utilization of crops (ha) in Qatar from 2010 to 2020 (Planning and Statistics Authority in Qatar 2014, 2020a)

and 51.4% average annual relative humidity during the same period, as shown in Fig. 7.

Qatar's total arable land is a stable area of 65.000 ha and represents only 5.6% of the total country's area (Planning and Statistics Authority in Qatar 2013a). In the years between 2010 and 2020, the cultivated land was between 14 to 21% of the total arable land while most of the land is used for green fodder production followed by date palm and vegetable production (Fig. 8).

These factors have hindered the development of the greenhouse and the agricultural sector in general in the past and might prevail the further development of the sector, as they limit the crop production period and the land availability. Greenhouse cooling systems like the pad and fan system, which are widely used in Qatar, are not operating effectively in the summertime due to high humidity levels, causing big stress in plants thus having a negative yield impact.

The socio-economic barriers to the future development of the greenhouse sector are mainly the acceptability and the adaptability of the existing high technology by the farmers and the agricultural professionals, followed by the initial high greenhouse capital investment, the lack of awareness and the need for the expertise in labor force.

It is very often that agricultural professionals are reluctant to adopt new methods and technologies as opposed to the traditional ones, with the main barriers being the risk and the cost they might face. The research on the greenhouse sector has been making great advances as proved by the number of published research articles on agriculture, which has an increased average annual rate of 0.4% between 1999 and 2018, while the greenhouse technology articles have increased by 1.1%, which highlights the advancement of the sector (Aznar-Sánchez et al. 2020). Therefore, it is evident that the research institutions have resources and facilities to support the farmers in adopting new technologies, however, there is a gap between scientific knowledge and its implementation. On one hand, adoption of new technologies by the farmers is mostly influenced by their personal characteristics such as their age, educational level, income, their general attitude towards technology which is influenced by the level of accessibility they have (Li et al. 2020), and on the other hand, it is also often negatively influenced by perceptions of being a costly and risky investment. Thus, it is recommended that the economic-financial feasibility of the novel applications should be addressed together upon introduction for their successful adaptation by the end-users (Aznar-Sánchez et al. 2020).

Moreover, farmers should be well trained and experienced enough to manage efficiently the agricultural farms, thus achieving the highest possible yields. The highly skilled farmers are even more important in the case of the hydroponic cultivation system, which requires specialized knowledge. Additionally, hydroponics has expensive infrastructure costs related mainly to irrigation. As most of the water used in agriculture in Qatar is abstracted fresh groundwater (Planning and Statistics Authority in Qatar 2017a), it should be desalinated before use in the hydroponic cultivation system, because of elevated levels of salinity, ranging between 6 to 10 g/l. The high salinity levels in the groundwater are caused by overexploitation; the excessed extraction of aquifers causes seawater intrusion (Ahmad and Al-Ghouti 2020). Thus, a desalination system investment including reverse osmosis water filtration system and water reservoirs is crucial, and these high costs are contemplated only in large-scale investments.

5.2 Energy and water savings potential in Qatar

Greenhouse crop production consumes large amounts of energy and water resources. In countries with a similar climate as Qatar, most of this energy is required for cooling and ventilation while the agricultural sector is the first biggest water consumer using 92% of the total abstracted groundwater (Ahmad and Al-Ghouti 2020). Besides, a considerable amount of water is needed for cooling purposes apart from irrigation as the evaporative cooling system, which is the most prevalent cooling system in Qatar, is significantly water intensive. Notably, the groundwater abstraction rates in Qatar substantially exceed the rate of rainfall-induced recharge, leading to decreasing aquifers levels and deterioration of groundwater quality. Indeed, the groundwater salinity levels have been increased due to over pumping and subsequent seawater intrusion affecting negatively not only the crop yield but also the used equipment such as water pipelines and irrigation drippers. Consequently, the increasing groundwater salinity levels will make groundwater not suitable for direct irrigation use without pre-treatment in desalination systems. In turn, this will increase the total energy needs as desalination is a process with relatively high-energy requirements and there are associated CO_2 emissions in the case of conventional energy supply (Hussein and Lambert 2020).

For energy needs, the greenhouse sector in Qatar depends mostly on fossil fuels, which have a big environmental impact on the country. Fossil fuels emit high CO_2e (carbon dioxide equivalent) gases, making Qatar amongst the top countries with high carbon emissions per capita, recording 35.640 metric tons in 2020 (Knoema. 2022). The biggest share of emissions in 2019 came from the natural gas sector with 42.7%, followed by the manufacturing sector with a 21.7% share while the domestic power sector contributed 16% of total net emissions (Doha News 2016). Although only 0.1% of the total GHG emissions were from the agricultural sector in 2015 in Qatar (Sayeed 2016), nonetheless, this number is expected to have increased with the subsequent growth of the sector despite the lack of more recent data. Besides, the whole food chain including transportation and processing is energy-intensive, along with production itself.

The greenhouse sector could be more sustainable if alternative sources were used for water consumption and energy production, shifting away from fossil fuel use such as petroleum and carbon energy and natural groundwater resources. Namely, the use of Treated Sewage Effluent (TSE) and recycled water for irrigation purposes as well as the use of renewable energies like solar, wind, hydro and geothermal, respectively, in combination with innovative resource-saving technologies and greenhouse designs adapted to the local conditions, could contribute to lower carbon emissions and save the groundwater resources of Qatar. Practices and standards from other regions such as Europe and America cannot always be applied in hot arid countries like Qatar due to climatic differences which affect energy efficiency and consequently the operation cost (Alkhalidi et al. 2020). Pakari and Ghani (Pakari and Ghani 2019) have proposed a new greenhouse design that limits the available solar radiation thus reducing the high cooling demand during the hot season in subtropical countries like Qatar. The innovative thermally insulated greenhouse can reduce approximately 80% of the cooling load in comparison with a conventional greenhouse. Other researchers (Hassabou and Khan 2019) have developed a Passive Solar greenhouse in Qatar with roof PV panels, which can have a grid zero carbon footprint. The energy and ventilation needs are covered with solar cooling, achieving more than a 77% reduction in annual

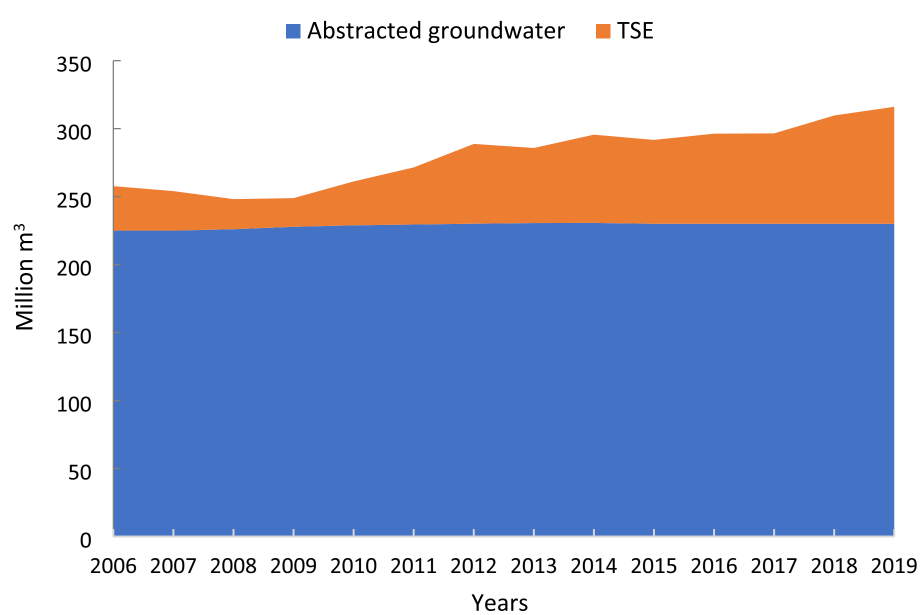


Fig. 9 Agricultural water sources for Qatar (million m^3) from 2006 to 2019. TSE: Treated Sewage Effluent (Planning and Statistics Authority in Qatar 2019, 2017a)

energy consumption, in comparison with a conventional greenhouse design.

The use of TSE for irrigation purposes in agriculture and landscaping in Qatar had already started back in 2004 with 25 million m^3 (5%) and increased by about 3 times from 32.69 m^3 in 2006 to 86.0629 million m^3 in 2019, as shown in Fig. 9. There have been considerable efforts to increase the use of TSE in agriculture and landscaping from different sectors, thus in 2017, 30% of the TSE was used for agriculture irrigation by the agricultural sector and 27% was used for green space irrigation by the government sector (Planning and Statistics Authority in Qatar 2017a).

5.3 Impacts of greenhouses penetration on the national economy

Open field farming in Qatar is suitable only for a limited type of crops while the growing season is limited to certain months per year, from October to June approximately. Therefore, during the hot summer season, the country is relying exclusively on food imports to cover the local market needs. Additionally, the environmental impact of this type of farming is high, as it consumes large amounts of resources such as water, pesticides, and fertilizers with substantial losses, compared to greenhouse farming (Marucci et al. 2011; Bartzas et al. 2015; Planning and Statistics Authority in Qatar 2017b).

Greenhouse production could lead Qatar in achieving higher levels of food security since it can overcome all the limitations that hindered the development of agriculture in the past, such as water scarcity, limited land availability, and the harsh climate. Additionally, it can achieve higher yields than open-field farming with significant product quality increase, while offering the possibility of year-round production, therefore changing the balance between exports and imports of foodstuff in the country. In the last decade, from 2010 to 2020, Qatar's imports in basic agricultural plant products for human consumption such as cereals, fruits, dates, and vegetables were 10,909,591 tons whereas the exports and re-exports were 132,396 tons. Simultaneously, the local production of the same products reached only 994.932 tons, as shown in Fig. 10. Vegetable production under greenhouse cultivation can boost domestic production while reducing the reliance on exports and increase Qatar's resilience to supply shocks and disruptions in the future.

6 Conclusion and policy implications

Considering climate change, shortage of resources, population growth, and harsh climate, the agricultural sector in Qatar is encountering several challenges in ensuring its growing food needs. Advanced technological solutions such as active smart greenhouses, IoT and precision agriculture, as well as alternative sources for water and energy, can support the state of Qatar to achieve its National Vision 2030, particularly the food security, environmental and sustainability challenges.

This paper aims to generate the knowledge, innovation, technologies, and practices needed to boost the local food production as well as increase the self-reliance of communities in four aspects:

(1) lead to a state-of-art deep understanding of the actual situation of agriculture in Qatar as well as introducing smart greenhouses as a key solution to overcome agriculture challenges at the national level;
(2) develop win–win business opportunities for massive portfolios assets that are beneficial for consumers, farmers, and industrials;

Fig. 10 Agricultural supply (tons) of cereals, fruits, dates, and vegetables in Qatar from 2010 to 2020 (Planning and Statistics Authority in Qatar 2012, 2013b, 2014, 2015b, 2017b, 2020a)

(3) contribute to the modernization and transition to precision agriculture through adoption of smart greenhouses, integrating effective energy us, and water into agri-technology, as well as promoting the incorporation of pertinent technologies in the agricultural sector and
(4) may offer researchers and scientists with knowledge, which encourage them to develop advanced solutions and practices to answer the challenges linked to the transition to sustainable and precise agriculture.

Therefore, the areas of greenhouse development that could potentially lead to higher food security levels while meeting the sustainability goals of Qatar are:

- innovative greenhouse designs adopted to the Qatari climate characterized by high temperatures, humidity and solar radiation;
- new technological systems for food production like hydroponics, aquaponics and vertical farming;
- innovative cooling systems allowing all-year-round crop production especially during summer months while being less water intensive than e.g., the evaporative cooling system;
- advanced technological solutions such as the Internet of Things (IoT), metering and communication infrastructure, artificial intelligence, advanced monitoring and control techniques and smart greenhouses targeting ways to optimize resource use, maximize agricultural productivity, adaptation and mitigation against climate change;
- use of alternative energy sources like solar, wind, geothermal, etc. to cover the needs of irrigation, cooling and desalination while reducing the associated carbon emissions of the use of fossil fuels and
- use of alternative water sources other than fresh groundwater like TSE or recycled water in agriculture.

These greenhouse advancements will generate local socio-economic and environmental advantages. Besides, they will provide an attractive occasion for fostering sustainable development, guaranteeing the high-performance abilities and thus promoting the renovation of the agricultural sector. This is of incredible significance for the efficient design and expansion of the next-generation agricultural sector in terms of self-monitoring, self-control, and optimal operation.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

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