Global Food Security 25 (2020) 100349

Contents lists available at ScienceDirect

Global Food Security

journal homepage: www.elsevier.com/locate/gfs

Towards sustainable food production systems in Qatar: Assessment of the viability of aquaponics

Sana A.A. Abusin[1], Brian W. Mandikiana[1,*]

The Social and Economic Survey Research Institute, Qatar University, P.O. Box 2713, Doha, Qatar

ARTICLE INFO

Keywords:
Aquaponics
Environment
Gulf
Food security
Qatar
Sustainability

JEL classification codes:
Q18 Agricultural Policy
Food Policy
Q20 General

ABSTRACT

Biophysical environments, socio-economic, and political shocks that hamper food production and affect access to food are a treat towards a country's capacity to achieve and maintain food security. Over the past couple of decades, food production at a commercial scale in non-traditional food production environments have been emerging. Among other agricultural systems, the opportunities aquaponics systems present are becoming more apparent. Nonetheless, aquaponics' ability to bring together hydroponics and aquaculture to produce nutritious food has prompted more attention in terms of its economic viability and sustainability. In this paper, we present the reasons why aquaponics might be part of the solution in arid countries with particular focus on the State of Qatar.

1. Introduction

The ability to access food at all times is enshrined in the Food and Agricultural Organization (FAO) definition of food security. Like most countries in the Gulf region, the State of Qatar faces several challenges, including biophysical environments, socio-economic, political shocks and, rapid changes in population growth, among others. Also, for the past two decades, most Gulf states, including Qatar, have experienced rapid economic growth resulting in higher demand for foods high in protein such as fish and vegetables rich in essential nutrients. Unlike the other countries in the Gulf region, the State of Qatar experienced the air and sea blockade of 2017 magnifying an already existing set of shocks that the country encounters. Action to address the risk of food insecurity, improve the resilience of the State of Qatar, and promote environmentally friendly food production systems is imminent.

The United Nations Sustainable Development Goals (SDGs) 2030 were formulated to facilitate addressing the most pressing issues of the past decade, mainly: population growth, climate change, soil degradation, water scarcity, and food security. Moreover, feeding the growing population requires more food production while minimizing food waste. Nonetheless, this has resulted in greater use of water and synthetic fertilizer in agriculture. Besides, agriculture uses the majority of available freshwater resources. Ensuring the sustainability of food production systems has become a high priority. Recent evidence suggests that water scarcity is already a pressing global issue that is affecting more than 40% of the worldwide population. Current future projections estimate that by 2025, an absolute water scare will affect approximately 1.8 billion people globally (Shomar et al., 2014).

Non-soil based production systems have emerged as sustainable options for food production. One such non-soil based system is Aquaponics, an agricultural production system that brings together aquaculture and hydroponics. The combination of the two food production systems simultaneously meets plants' need for essential nutrients for growth, while managing waste generated from fish production through aquaculture (Shaalan et al., 2018). Aquaponics is expected to participate in achieving some of SDG of having zero hunger and full accessibility to food and hence, food security. Among other food production technologies, aquaponics can compensate for the most critical animal protein of fish and essential nutrients from vegetables. In other words, aquaponics provides more benefits in comparison to when aquaculture and hydroponics produce food separately (Blidariu and Grozea, 2011).

Critics of aquaculture highlight its consumption of high volumes of water and fish waste management, which is not ideal for arid and water scare biophysical environments. On the other hand, hydroponics (planting of vegetables and fruits in a soil-less environment) is also one

* Corresponding author. The Social and Economic Survey Research Institute (SESRI), Qatar University, P.O. Box 2713, Doha, Qatar.
E-mail addresses: sabusin@qu.edu.qa (S.A.A. Abusin), bmandikiana@qu.edu.qa, bwmandikiana@gmail.com (B.W. Mandikiana).
[1] Author contributions: The authors whose names are listed above certify that they contributed to the manuscript equally.

https://doi.org/10.1016/j.gfs.2020.100349
Received 1 August 2019; Received in revised form 17 December 2019; Accepted 2 January 2020

of the innovative systems aim to solve water scarcity and soil degradation but also has the disadvantage of depleting the valuable and essential nutrients. As a result of these disadvantages of both systems, aquaponics as an innovative sustainable food production system emerges (Blidariu and Grozea, 2011). Recent studies have materialized that highlight the potential of aquaponics as an agricultural production system (Karimanzira and Rauschenbach, 2018; Li et al., 2019; Pinstrup-Andersen, 2018; Suhl et al., 2016). Nonetheless, very few papers focus on Qatar and the Gulf region. Given the recent developments in Qatar and the country's geographical location, we present the case for aquaponics. This is highly relevant given the importance of maintaining food access at all times and emerging evidence from commercial trials of aquaponics systems. This paper focuses on four aspects. We review the challenges facing the State of Qatar in addressing food security, the importance of aquaponics, highlight the merits and demerits of aquaponics, and lastly, we synthesize and recommend strategies that can support the successful establishment of a commercial aquaponics industry.

2. Context

The State of Qatar is located in the Middle East region. The country only shares a land border with the Republic of Saudi Arabia to the South, and the Persian Gulf surrounds its coastline. The land area is approximately 11,000 km^2. Given that the land area in Qatar is a subtropical desert, dry and hot weather is typical during the summer season, and the winter season is mostly mild. The annual rainfall is an estimated 81 mm and an estimated absolute temperate above 45 °C. These extreme climate conditions increase the risks in food production, such as pests and plant diseases. As a result, production fluctuations due to crop losses, and food price volatility can be expected to be a common feature (Pinstrup-Andersen, 2018). Nonetheless, the benefits from enhanced control of the production environment will be even more apparent to assure the continuity of nutritious food supplies.

2.1. Supply-side

Arable land and freshwater are some of the critical resources in food production. The State of Qatar is an arid region with minimal arable land, and water scarcity is the norm. That means high levels of radiation the country experiences also further intensify water stress. These challenges prompted the use of desalinization of seawater to meet the country's water demands. Like other countries in the Gulf region, Saudi Arabia, Kuwait, and Bahrain, Qatar uses large amounts of non-renewable groundwater resources (Murakami, 1996). Siddiqi and Anadon (2011) estimate that Gulf countries use between 5% to 12% of total electricity consumption on groundwater pumping and desalination annually. Although this strategy helps meeting water demands, nonetheless, it causes depletion of groundwater resources and negatively affects the quality of water (Murakami, 1996). Furthermore, countries in the Gulf region that use irrigation face challenges of waterlogging and high soil salinity levels. As a result, limiting the already minimal freshwater and land area for food production (Pinstrup-Andersen, 2018). Thus, in the Gulf region, it is more appropriate to use water-saving technologies that simultaneously increase plants' nutrient efficiency and help reduce the environmental footprint.

2.2. Demand-side

Accelerated industrial development, coupled with population growth, has put pressure on Qatar's minimal water resources. Since 1995 when the population was an estimated 500,000 residents, it has grown by more than 400% to reach an estimated 2.6 million (MDPS, 2017). Moreover, not only has Qatar's population swelled, but the country has also experienced growth in per capita income. Given that population growth and per capita income are some of the main drivers of food demand, it is critical to consider a diverse set of sustainable options that enable furthers the country's food security. Furthermore, research has established that income growth affects the demand for food, not only terms of quantity but also quality. Unlike low earning consumers who mainly depend on carbohydrate-rich staples, high earning consumers demand quality diets composed of a large share of proteins, fats, and oils. Without suitable food security policy options, Qatar's development may negatively affect certain sectors especially, the need of Qatar to fill the fish production gap that estimated to be 6,000 tonnes per year in 2018 (Valin, 2014).

2.3. Political risk

Primarily at the national level, the State of Qatar, like the majority of countries in the Gulf region, depends on food imports to meet food demand. Before the 2008 global food crisis, Qatar depended on food imports. Estimates suggested that Qatar imported approximately 90% of its food. The recent blockade of Qatar and previous export restrictions that the country's suppliers imposed have raised concerns of alternative supply-side strategies to meet the country's food demands. Furthermore, Wright and Cafiero (2011) highlighted concerns over market access disruptions as a result of a blockade of the Straits of Hormuz. Recently, tensions in the Straits of Hormuz, a key channel for shipment of goods via the sea have emerged. Such tensions pose a severe threat to food access for Gulf countries. Alternative strategies for maintaining food security besides food imports have included foreign land acquisitions coupled with investments in research and development and technology that help improve the volumes of food and efficiency in supply (QNFSP, 2012).

To avoid significant vulnerability to food insecurity Strategies implemented include creating new routes for importing goods and bolstering the country's capacity to produce food products on its own. Some of the initiatives introduced include significant investment in agricultural production and the establishment of research centers aimed at supporting food production as well as agricultural extension. These initiatives suggest the importance of maintaining food security.

3. Agricultural systems for food security in arid region

Like many countries in the Middle East, currently farming systems in Qatar rely on irrigation. Nonetheless, the practice of non-soil based farming systems to supplement food supplies is gaining more momentum. Below we discuss non-soil based food production technologies that suit biophysical environments with limited arable land, namely; aquaculture, hydroponics, and aquaponics.

3.1. Aquaculture

Globally, the per capita fish consumption has risen significantly (FAO, 2014; FAO, 2018). Furthermore, the simultaneous increase in incomes, population growth, and urbanization has driven the demand for fish (Godfray et al., 2010). Among other techniques, aquaculture contributes significantly to meeting this demand. Thus, the role of aquaculture towards food security has been increasing over the past decades globally (FAO, 2014). In Qatar, aquaculture was formally introduced to the mix of agricultural production systems in 1988. Unlike the first government initiated aquaculture pilot program that was conducted at a small-scale, currently, aquaculture projects are undertaken at a broader scale (Falamarzi, 2009).

Aquaculture is the raising of aquatic animals (fish, shrimp, mussels, etc.) and aquatic plants (seaweed) for food. Proponents of aquaculture argue that it is an alternative, especially in areas, were conventional capture fisheries are weakened (Gengmao et al., 2010; Shaheen et al., 2013). The State of Qatar, similar to other countries in the Gulf region, have established aquaculture production centers. These aquaculture production centers are currently producing tilapia and shrimps.

Apart from supporting food access in arid biophysical environments, aquaculture enterprises are associated with negative impacts on the environment and natural resources. Water pollution is one of the vital environmental outcomes of aquaculture since aquaculture effluents contain non-ingested food and fish dregs that affect the receiving water bodies when discharged without any treatment.

3.2. Hydroponics

Hydroponics is a form of an agricultural system that involves the production of plants using a nutrient-rich solution without any soil. The use of hydroponics for food production dates back to many decades (Benis and Ferrão, 2018). The nutrient-rich solution the plant's root system is submerged in is continuously circulated and monitored. That process is vital to maintaining the correct chemical composition in the nutrient-rich solution. In arid environments, assembling hydroponic systems inside protected environments such as buildings or greenhouses is common. An automated nutrient supply system supplies plants with nutrients. Thus, the process facilitates the supply of plants with optimal concentrations of nutrients.

An essential aspect of hydroponic systems in non-soil based food production is the management of nutrients. Flow-through systems make the management of nutrients more accessible. Nonetheless, for water scare areas, such systems raise concerns over water use and pollution.

Comparative analyses of aquaponics and hydroponics, notably the work of Suhl et al. (2016) focusing on a tomato production enterprise, demonstrated the overall merits of aquaponics over hydroponics.

3.3. Aquaponics as part of the solution

Food security, water security, and sustainability are closely connected and important, particularly in arid regions such as the Gulf. Aquaponics is a food production mechanism that brings together aquaculture and hydroponics to form a closed loop with the ability to reuse water and nutrients to support plant growth. There are various methods of integrating aquaculture and hydroponics to create aquaponics systems. Table 1 presents a typology of hydroponic components for plant production in aquaponics systems (Palm et al., 2018).

From the aquaculture side, the use of recirculated aquaculture systems (RAS) enables filtering water from the fish (or shellfish) tanks so it can be reused within the tank. This advanced technique for treating aquaculture wastewater involves continuous water re-use after bio-filtration. As a result, the amount of water and space required to produce seafood products intensively is significantly reduced (Delaide et al., 2019a).

In general, fish production wastewater acts as in input that supplies nutrients for plants in hydroponics. The range of products that can be produced using aquaponics includes but not limited to tomatoes, fruits, onions, tilapia, shrimp, lettuce. Furthermore, in cases where food production occurs in a controlled environment, such as a greenhouse, the seasonality of fruits and vegetables is minimized. This reveals that aquaponics is capable of addressing the seasonality, and the dietary diversity and food access aspects of food security (Pinstrup-Andersen, 2018). Aquaponics systems are capable of solving both challenges aquaculture (fish waste), and hydroponics (essential nutrients) present.

Single Recirculating Aquaponics System (SRAP) (One-loop/ Traditional Aquaponics System).

The most common or traditional aquaponics systems consist of aquaculture and hydroponic units involving recirculating water between both subsystems (Körner et al., 2017; Graber and Junge, 2009

. Furthermore, aquaponics systems with only a single loop demand trade-offs of optimal conditions between the aquaculture and hydroponic components. Given that fish and horticultural produce grow under the same ecosystem, pH, temperature and nutrient concentrations are shared at sub-optimal levels between the two systems (Delaide et al., 2019a; Goddek et al., 2015). Thus, having a single loop makes the management of fish, plants, and microorganisms challenging (Delaide et al., 2019a).

Decoupled aquaponics systems emerged as a means to overcome challenges in coupled aquaponics systems (Goddek et al., 2016; Goddek and Keesman, 2018; Suhl et al., 2016). Unlike coupled one-loop systems, decoupled double-loop aquaponics systems separate the recirculated aquaculture systems (RAS) and hydroponic units from one another. The splitting of the two systems results in separate ecosystems that are able to overcome the shortcomings of one-loop systems. This strategy promotes a healthy environment for both plants in the hydroponic and fish in the aquaponics components.

3.3.1. Merits of aquaponics

A decoupled aquaponics system, however, can reduce the need for tradeoffs by separating the components, thus allowing the conditions in each subsystem to be optimized. Utilization of sludge digesters is another key way of maximizing efficiency through the reuse of solid wastes (Emerenciano et al., 2017; Goddek et al., 2018; Monsees et al., 2015). Although many of the largest facilities worldwide are still in arid regions this technology is also being adopted elsewhere as design advances have increasingly made aquaponics evolve from more than a water-saving enterprise but also an energy efficient (De Graaf and Goddek, 2019) and nutrient recycling system (Goddek et al., 2019a).

Plant diseases are a common feature in conventional agriculture. In comparison to conventional agriculture, non-soil based components of hydroponics systems that form part of aquaponics systems present several biological advantages. First, dependence in water means plant growth and yield are independent of the soil type/quality of the cultivated area. Second, use of automation implies that there is better control of growth through a targeted supply of nutrient solution. Third,

Table 1
Typology of hydroponic systems in aquaponics systems.
Source: Maucieri et al. (2019).

Type	Brief description
Deep Water Culture (DWC)/Floating Raft System	DWC has higher energy demands in comparison to NFT. DWC requires recirculation and oxygenation of the high volume of the nutrient solution.
Nutrient Film Technique (NFT)	This technique uses long narrow channels to grow plants. Plants' roots receive water, nutrients, and oxygen through the continuous flow of a thin layer of nutrient-rich water.
Flow-through Systems/Tidal/Flood and Drain	The water pump that is in a nutrient bath sends nutritional water to the growth medium or vessel until it is full enough. Then within a certain duration the nutrient shrinks slowly back to the water bath like a tidal cycle. Flow-through systems make the management of nutrients easier but raise concerns over water use and pollution.
Wick System	In this technique, the nutrient solution is pumped from the reservoir up the growing tray and delivered to plant roots via the capillary movement of the wick.
Drip Irrigation System	The drip system pumps the nutrient solution through the tube and drops onto plant roots via a network of drip lines. In general, a timer is used to automate this process.
Aeroponics	Plant roots are suspended in the air and are misted with the nutrient solution continuously. The misting interval is fairly short, done by a pump controlled by a timer.

the potential for reusing the nutrient solution enables for maximizing usage of resources. Lastly, better control of pests and other environmental parameters such as temperate and relative humidity improves the quality of produce (Delaide et al., 2019b).

In general, when compared to conventional agricultural practices, aquaponics systems are more environmentally friendly. For instance, Goddek et al. (2019b) reported that upflow anaerobic sludge blanket (UASB) reactors, when operated at low pH facilitate nutrient-recovery. In other words, aquaponics systems, when integrated with UASB reactors can use waste nutrients of fish or aquatic animals that could have been discharged into the environment and processes them into a form that plants can easily absorb. Furthermore, aquaponics facilitates the integration of smart energy opportunities such as biogas and solar power (De Graaf and Goddek, 2019; Delaide et al., 2019a). While this process limits the damage to the environment, it also leads to the production of useful by-products.

The uptake of most technologies is highly dependent on economic feasibility. Findings from a global survey on the profitability of commercial aquaponics enterprises reveal that more than half of the enterprises were profitable, yet approximately a third incurred losses (Love et al., 2015). This suggests that there is a high potential for running successful aquaponics ventures. Besides, there is a steady development of new technologies with the capacity to improve the profitability of aquaponics systems.

One of the major benefits of the aquaponics systems is that the fish in the aquaculture system provide supply nutrients to the plants. In most cases, plants receive a significant quantity of their required nutrients at a lower cost in comparison with conventional agriculture. As a result, time and money-saving opportunities. However, it is important to note that from an economic point of view, an aquaponics system requires a substantial initial investment, which is required to integrate the two productive systems (Tokunaga et al., 2015). Nonetheless, bringing the two sub-systems together presents gains in management costs and collective financial returns (Somerville et al., 2014). However, one condition is that the system has a suitable location. Furthermore, given that aquaponics systems address agricultural waste management, food production using aquaponics systems is ideal in places where there is a cost attached to waste disposal and nutrient emissions (Monsees et al., 2017).

3.3.2. Challenges in aquaponics systems

Indeed, the feasibility of aquaponics is becoming more evident across the globe. Nonetheless, similar to several emerging food production systems, the adoption of aquaponics systems at a significant scale faces some challenges. Goddek et al. (2015) categorize these challenges into economic, technical, and socio-ecological problems. These challenges are explained in detail in Table 2 below to help those who are planning to start aquaponics investment in Qatar and the other parts of the Gulf region to review and discuss these issues before they start.

4. Progress in technical, socio-ecological and economic aspects of aquaponics systems

Similar to several emerging technologies, challenges encountered in food production using aquaponics have options. Below we present recent findings from implementations of aquaponics systems in different parts of the world that address key technical, socio-ecological, and economic aspects of these systems. In addition, we present research results from simulation models of aquaponics systems.

4.1. Technical aspects

New technical developments in aquaponics are now focused on improving the efficiency of aquaponics systems using decoupled multi-loop aquaponics systems. An emerging technical solution is closing the nutrient loop and the introduction of re-mineralization (Goddek et al., 2016; Goddek et al., 2018; Yogev et al., 2016), and desalination (Goddek and Keesman, 2018) loops in the design. The technical set up of decoupled aquaponics systems includes a detached aquaculture and hydroponics components that creates advantages for fish and plants respectively. Detaching the two systems enables optimal environmental conditions for each loop to prevail and can lead to better growth performance (Delaide et al., 2019a; Goddek and Keesman, 2018). Additionally, decoupled multi-loop aquaponics systems introduce more potential for integration with renewable energy technologies (De Graaf and Goddek, 2019; Karimanzira, and Rauschenbach, 2018). De Graaf and Goddek (2019) found that integrating a neighborhood micro-grid with an aquaponics system improves the performance and enhances the economic viability of aquaponics systems. In general, the energy from the micro-grid can be used for cooling equipment, lighting, maintaining optimal water temperature, and other essential processes for the functioning of the aquaponics system. Thus applying this system can facilitate meeting energy demands of aquaponics systems while addressing the challenge of providing sustainable food, water and energy systems.

4.2. Socio-ecological aspects

Water quality is a high priority in aquaponics systems. Fish, plants, and nitrifying bacteria all depend on good quality water to support their growth and survival. Nonetheless, Goddek and Körner (2019) highlight that each geographical location has its own set of optimal conditions. In other words, the success of aquaponics ventures depends on proper water quality management, and that may be different from one geographical location to another. Food production techniques that address water scarcity are essential in the Gulf region. For water scarcity, recent studies have highlighted that aquaponics enterprises based on recirculating aquaculture systems (RAS) are better suited for food production in arid areas (Shaalan et al., 2018). Furthermore, a recent pilot study found that using a microbial system degrades wastes significantly and can help improve the water quality (Li et al., 2019).

Table 2
Challenges in aquaponics.
Source: (Goddek, 2015; Goddek et al., 2019a,b)

Technical	Socio-ecological	Economic	Scientific and Technological
- A highly multidisciplinary approach, - The optimal pH stabilization - Integration of nutrient flows - Phosphorous management - Pest and Disease Management - Improve nutrient use efficiency - Balancing of nitrate levels in the system.	- Need for mineral recycling (phosphorous) - Energy demands - Overfishing - Water scarcity - Reduce of water use and discharge to the environment - Urban farming and short supply chains	- High human capital and financial capital to set up, - Limited ability to benefit from economies of scale, - Lack of crop diversification, - Consumer perceptions, - Volatile market prices of food products, - No standard aquaponics system - Location restrictions (urban) - Consumer perceptions	- Use of optimized reclamation and recycling of nutrients. - Utilization of condensers for reuse of nutrient-depleted water. - Need for solar-powered designs to improve energy savings.

4.3. Economic aspects

The uptake of most technologies is highly dependent on economic feasibility. Since their inception, the aquaponics systems have encountered the challenge of outperforming independent hydroponics and aquaculture systems. In particular, traditional one-loop aquaponics systems were less productive, given that there is a require trade-offs between the fish and plant (Graber and Junge, 2009). Furthermore, Delaide et al. (2016) argue that savings in the cost of fertilizer to support plant growth do not compensate for lower yields due to the suboptimal environments in the aquaculture and hydroponic subsystems. Nonetheless, using multi-loop decoupled aquaponics systems shown the potential to improve the profitability of aquaponics systems. In particular, multi-loop decoupled systems, unlike their predecessors, introduce recirculating loops that involve; fish, plants, and bioreactors (UASB) for sludge digestion and a unidirectional water (nutrient) flow. Recent studies have shown that this technique improves nutrient recovery, bioavailability, and water use (Goddek and Keesman, 2018). In addition, multi-loop decoupled systems make disease management easier, and they reutilize otherwise unusable sludge, converting it to valuable products such as biogas and fertilizer (Goddek et al., 2019b; Joyce et al., 2019; Li et al., 2019).

In other recent studies, the location of the aquaponics enterprise has also shown to have an influence on the profitability of aquaponics systems (Asciuto et al., 2019). Joyce et al. (2019) argue that a good location can facilitate cost savings of an aquaponics enterprise when land acquisition costs are low, setting up the system within the vicinity of urban and peri-urban areas. Furthermore, closer proximity to urban and peri-urban areas reduces transportation costs to markets and thus reduces emissions from fossil fuels and carbon dioxide footprint of production.

5. Implications of aquaponics for Qatar and the Gulf region

5.1. Environmental protection

Traditional soil-based agricultural systems are sensitive to high temperatures and rainfall variability. In addition, increasing productivity using soil-based methods commonly involves extensive use of fertilizers. Instead, more emphasis needs to focus on promoting soilless food production systems such as aquaponics systems that do not use chemicals and or pesticides as soil-based agricultural systems. Taking such action has the potential to improve the state of reservoirs, rivers, lakes, irrigation systems, and wetlands. On the other hand, Goddek et al. (2019a,b) established that while desalinization technology decreases the water and the environmental footprint of multi-loop aquaponics systems, it requires high amounts of thermal energy. Thus, not all regions in the world can benefit from this technology, but regions with high geothermal energy sources such as the gulf (Goddek et al., 2019b).

5.2. Institutional support

Sustainable food production in Qatar thrives when backed with good agricultural and environmental policy. One such plan includes the Qatar National Food Security Program (QNFSP). This food security strategy seeks to guide Qatar in achieving self-sufficiency by the year 2025. The Qatar National Food Security Program covers four key areas. First, domestic agricultural production reform. Second, diversifying trading partners and investment portfolio. Third, sustaining volumes of strategic food and water reserves. Lastly, reforming market governance. Also, improving the amounts of food and efficiency in supply through the QNFSP program has led to a surge in investments in research and development (QNFSP, 2012). This development suggests that Qatar acknowledges the importance of advancing the agricultural sector while at the same time, prioritizing guarding natural resources against depletion as a matter of national interest. In this regard, the State of Qatar and other governments in the Gulf region should coordinate efforts among relevant departments to champion integrated water-resources management of existing minimal sources of water resources such as groundwater is essential to ensure the availability of these much-needed water resources needs to support food production. Without proper water resources management, excessive water extraction will lower levels of groundwater resources and increase groundwater salinity levels.

5.3. Private-public partnerships

The commercial development of sustainable aquaponics systems requires specialized knowledge. Given the complexity of aquaponics technologies, finding expertise within one geographical location can be challenging. Nonetheless, retooling the existing workforce in the agricultural sector can help minimize the effect of skills shortage. Also, forming research alliances both at a regional and international level will help fill the gaps in knowledge and sharing of research findings. In Oman, the collaboration between local institutions and foreign private companies helped launch one of the few large-scale aquaponics systems in the Gulf region. The aquaponics enterprise currently produces large volumes of fruits and vegetables in systems integrated with the production of tilapia. Such initiatives can be replicated in Qatar as well as other parts of the Gulf region. Experience from other arid areas such as Egypt has found that private-public partners can assist fill critical gaps in knowledge in areas such as fish stock management, efficient use of fish feed, and disease management (Shaalan et al., 2018). Furthermore, public-private partnerships can be used as the cornerstone of developing programs that educate stakeholders with interest in aquaponics such as farmers, researchers, investors, and policy-makers.

5.4. Economic development

The push towards well-diversified economies is a top priority in Gulf countries. Qatar, like other Gulf countries, drafted the Qatar Vision 2030 national development plan. A policy document guiding the country's pathway towards a new wave of economic development. Among other goals, increasing the share of non-carbon resources' contribution toward the gross domestic product. These policy directions reflect the importance governments in the Gulf region are placing on economic diversification. In Qatar, promoting sustainable commercial aquaponics ventures has the potential to create new jobs through backward and forward linkages. For instance, it could lead to the emergence of fish feed companies, development of organic farmers markets, and agro-tourism ventures that champion sustainability among current and future generations alike. Furthermore, commercial aquaponics ventures can benefit from the high higher purchasing power of consumers in the local market and the growth in fish consumption.

6. Discussion and conclusion

Maintaining food security and using sustainable food production techniques to address this issue is a global concern (Godfray et al., 2010). In most Gulf countries, biophysical environments, socio-economic, and political shocks limit countries' capacity to produce food more sustainably pose a severe threat to food security. The 2017 air and sea blockade of the State of Qatar makes the country more unique and puts the country in a challenging position to address food security and makes strategies to address vulnerability to food insecurity a critical priority.

Although evidence exists of efforts to promote food self-sufficiency using both commercial and pilot implementations of aquaculture and hydroponics as independent agricultural systems, concerns about environmental sustainability in water scare areas like the Gulf region have emerged. Unlike stand-alone aquaculture systems, aquaponics systems treat nutrient-rich wastewater and use it for producing fruits and vegetables. The aggregation of aquaculture and hydroponics improves nutrient efficiency and reduces the environmental impact of these food production systems (Delaide et al., 2017). Furthermore, aquaponics can dampen the food security effect of the risks countries in the Gulf region encounter.

The prospects for addressing food security using commercial aquaponics systems seem favorable, yet there are other factors that are often overlooked or receive less attention in practice and aquaponics systems modelling. For instance, Turnšek et al. (2019) highlight that aquaponics systems are assembled in different ways. Thus, it is challenging to conduct accurate economic assessments that account for input and output levels in a robust manner. Furthermore, aquaponics systems assessments that only use higher outputs per area in comparison to conventional agriculture are misleading. Setting up an aquaponics system entails more energy, financial capital, and human capital input. Nonetheless, warmer locations such as arid regions of the Gulf are likely to be favorable locations for setting up aquaponics systems. Most countries in the Gulf region have lower energy costs and high levels of radiation (Turnšek et al., 2019).

Given that aquaponics systems depend on the establishment of optimized environments for fish and plant growth in the aquaculture and hydroponics components respectively, crop diversification using these systems entails compromising the best environments for plant growth. Alternative aquaponics systems that have been suggested to-date include large-scale commercial production of a few crops that require a similar set of parameters. This strategy ensures that the crops have exposure to similar growth conditions and limits the risk of sub-optimal yields. In other words, applying economies of scale decreases per unit cost of production, and in turn, improves the viability of aquaponics systems.

Agricultural marketing policy is essential in promoting the viability of aquaponics systems. In particular, producers of agricultural products such as fish and vegetables can benefit from marketing strategies that highlight the sustainability features of aquaponics systems. In Qatar, introducing rules and regulations in support of sustainability-focused food production techniques in mainstream agricultural policy strategies has the potential to leverage the growth of aquaponics systems. For instance, in the United States, food produced organically can get organic certification based on federal law. In the same way, there is potential for producers of vegetables produced organically using aquaponics systems to fetch a premium on the market (Miličić et al., 2017). On the other hand, for consumers addressing perceptions is critical. Consumers are more likely to pay a premium when materials used to market agricultural produce coming from aquaponics systems highlight the issues these food production systems address, for instance, sustainability. Thus, producers will have a better chance to breakeven, especially given the initial high capital investment aquaponics systems require.

While many proponents of aquaponics usually compare yield and other productivity features of aquaponics with those of conventional agriculture, the two systems are distinct. In particular, horticultural production is a small component of the agricultural sector usually done in controlled environments such as greenhouses. To state this differently, the horticulture side of agriculture is only a very small part of it. While aquaponics systems have an important role in supporting food security, the contribution of conventional land-based commercial agriculture cannot be underscored, especially given its role in providing key staples that aquaponics systems have not yet proven capable of producing optimally to-date.

Revisiting alternative strategies for meeting Qatar's food requirements has become more urgent. In this policy paper, we sought to unpack the issues related to the current state of the potential to produce food sustainably using aquaponics in Qatar and other Gulf countries. Furthermore, we discuss the importance of the institutional environment in supporting commercialization aquaponics. Aquaponics offers opportunities to tackle food security and sustainability objectives. Qatar will particularly benefit from aquaponics given; its arid climate, lack of an extensive amount of arable land, the need to diversify the economy while meeting food self-sufficiency, and the urgent need to reduce its environmental footprint. At the same time, we have to consider that, aquaponics is an emerging innovating system at its early stage and needs more research based on a highly multi-disciplinary approach. We can conclude that the competitiveness of aquaponics systems with traditional food production is yet to be proven extensively. Nonetheless, several studies have confirmed that aquaponics systems address the goal of sustainable food production while partially contributing to vital nutritional needs, such as essential vitamins, fiber and proteins.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors whose names are listed immediately above certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Asciuto, A., Schimmenti, E., Cottone, C., Borsellino, V., 2019. A financial feasibility study of an aquaponic system in a Mediterranean urban context. Urban For. Urban Green. 38, 397–402.
Benis, K., Ferrão, P., 2018. Commercial farming within the urban built environment–Taking stock of an evolving field in northern countries. Glob. Food Secur. 17, 30–37.
Blidariu, F., Grozea, A., 2011. Increasing the economical efficiency and sustainability of indoor fish farming by means of aquaponics-review. Sci. Pap. Animal Sci. Biotechnol. 44 (2), 1–8.
Delaide, B., Monsees, H., Gross, A., Goddek, S., 2019a. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G. (Eds.), Aerobic and Anaerobic Treatments for Aquaponic Sludge Reduction and Mineralisation. Springer International Publishing, New York, pp. 247–266.
Delaide, B., Teerlinck, S., Decombel, A., Bleyaert, P., 2019b. Effect of wastewater from a pikeperch (Sander lucioperca L.) recirculated aquaculture system on hydroponic tomato production and quality. Agric. Water Manag. 226, 105814.
De Graaf, F., Goddek, S., 2019. Smarthoods: Aquaponics Integrated Microgrids. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G. (Eds.), Aquaponics Food Production Systems. Springer International Publishing, New York, pp. 379–392.
Delaide, B., Delhaye, G., Dermience, M., Gott, J., Soyeurt, H., Jijakli, M.H., 2017. Plant and fish production performance, nutrient mass balances, energy and water use of the PAFF Box, a small-scale aquaponic system. Aquacult. Eng. 78, 130–139.
Delaide, B., Goddek, S., Gott, J., Soyeurt, H., Jijakli, M.H., 2016. Lettuce (Lactuca sativa L. var. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. Water 8 (10), 467.
Emerenciano, M.G.C., Martínez-Córdova, L.R., Martínez-Porchas, M., Miranda-Baeza, A., 2017. Biofloc Technology (BFT): a Tool for Water Quality Management in Aquaculture. Water Quality; InTech, London, UK, pp. 91–109.
Falamarzi, M., 2009. National aquaculture sector overview fact sheets. Food and agriculture organization of the United Nations (FAO). Online. http://www.fao.org/fishery/countrysector/naso_qatar/en, Accessed date: 23 July 2019.
FAO, 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals. Food and Agriculture Organization of the United Nations (FAO), Rome.
FAO, 2014. The State of World Fisheries and Aquaculture – Opportunities and Challenges. Food and Agriculture Organization of the United Nations (FAO), Rome.
Gengmao, Z., Mehta, S.K., Zhaopu, L., 2010. Use of saline aquaculture wastewater to

irrigate salt-tolerant Jerusalem artichoke and sunflower in semiarid coastal zones of China. Agric. Water Manag. 97 (12), 1987–1993.
Goddek, S., Espinal, C., Delaide, B., Jijakli, M., Schmautz, Z., Wuertz, S., Keesman, K., 2016. Navigating towards decoupled aquaponic systems: A system dynamics design approach. Water 8 (7), 303. https://doi.org/10.3390/w8070303.
Goddek, S., Joyce, A., Kotzen, B., Dos-Santos, M., 2019a. Aquaponics and global food challenges. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G. (Eds.), Aquaponics Food Production Systems. Springer International Publishing, New York, pp. 3–17.
Goddek, S., Joyce, A., Wuertz, S., Körner, O., Bläser, I., Reuter, M., Keesman, K.J., 2019b. Decoupled aquaponics systems. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G. (Eds.), Aquaponics Food Production Systems. Springer International Publishing, New York, pp. 201–229.
Goddek, S., Körner, O., 2019. A fully integrated simulation model of multi-loop aquaponics: a case study for system sizing in different environments. Agric. Syst. 171, 143–154.
Goddek, S., Delaide, B.P., Joyce, A., Wuertz, S., Jijakli, M.H., Gross, A., Morgenstern, R., 2018. Nutrient mineralization and organic matter reduction performance of RAS-based sludge in sequential UASB-EGSB reactors. Aquacult. Eng. 83, 10–19.
Goddek, S., Keesman, K.J., 2018. The necessity of desalination technology for designing and sizing multi-loop aquaponics systems. Desalination 428, 76–85.
Goddek, S., et al., 2015. Challenges of sustainable and commercial aquaponics. J. Sustain. 7 (4), 4199–4224. https://doi.org/10.3390/su7044199.
Godfray, H.C.J., et al., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818.
Graber, A., Junge, R., 2009. Aquaponic Systems: nutrient recycling from fish wastewater by vegetable production. Desalination 246 (1–3), 147–156.
Joyce, A., Goddek, S., Kotzen, B., Wuertz, S., 2019. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G. (Eds.), Aquaponics: Closing the Cycle on Limited Water, Land and Nutrient Resources. Springer International Publishing, New York, pp. 19–34.
Karimanzira, D., Rauschenbach, T., 2018. Optimal utilization of renewable energy in aquaponic systems. Energy Power Eng. 10 (6), 279–300.
Körner, O., Gutzmann, E., Kledal, P.R., 2017. A dynamic model simulating the symbiotic effects in aquaponic systems. Acta Horticulturae 1179, 309–316.
Li, C., et al., 2019. Performance of a pilot-scale aquaponics system using hydroponics and immobilized biofilm treatment for water quality control. J. Clean. Prod. 208, 274–284.
Love, D.C., Fry, J.P., Li, X., Hill, E.S., Genello, L., Semmens, K., Thompson, R.E., 2015. Commercial aquaponics production and profitability: findings from an international survey. Aquaculture 435, 67–74.
Maucieri, C., Nicoletto, C., van Os, E., Anseeuw, D., Van Havermaet, R., Junge, R., 2019. Hydroponic technologies. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G. (Eds.), Aquaponics Food Production Systems. Springer International Publishing, New York, pp. 77–110.
Miličić, V., Thorarinsdottir, R., Santos, M., Hančič, M., 2017. Commercial aquaponics approaching the European market: to consumers' perceptions of aquaponics products in Europe. Water 9 (2), 80.
Ministry of Development, Planning, and Statistics (MDPS), 2017. Qatar in figures. Doha, Qatar. Online. https://www.mdps.gov.qa, Accessed date: 19 January 2019.
Monsees, H., Keitel, J., Kloas, W., Wuertz, S., 2015. Potential reuse of aquacultural waste for nutrient solutions in aquaponics. In: Proceedings of Aquaculture Europe. Rotterdam, Netherlands.
Monsees, H., Keitel, J., Paul, M., Kloas, W., Wuertz, S., 2017. Potential of aquacultural sludge treatment for aquaponics: evaluation of nutrient mobilization under aerobic and anaerobic conditions. Aquacult. Environ. Interact. 9, 9–18.
Murakami, M., 1996. Managing Water for Peace in the Middle East: Alternative Strategies. The United Nations University Online. http://archive.unu.edu/unupress/80858e/80858E09.htm, Accessed date: 19 January 2019.
Palm, H.W., Knaus, U., Appelbaum, S., Goddek, S., Strauch, S.M., Vermeulen, T., Kotzen, B., 2018. Towards commercial aquaponics: a review of systems, designs, scales and nomenclature. Aquacult. Int. 26 (3), 813–842.
Pinstrup-Andersen, P., 2018. Is it time to take vertical indoor farming seriously? Glob. Food Secur. 17, 233–235.
Qatar National Food Security Program (QNFSP), 2012. Qatar National Food Security Program. Online. http://www.qnfsp.gov.qa/, Accessed date: 18 January 2019.
Shaalan, M., El-Mahdy, M., Saleh, M., El-Matbouli, M., 2018. Aquaculture in Egypt: insights on the current trends and future perspectives for sustainable development. Rev. Fish. Sci. Aquacult. 26 (1), 99–110. https://doi.org/10.1080/23308249.2017.1358696.
Shaheen, A., Seisay, M., Nouala, S., 2013. An Industry Assessment of tilapia Farming in Egypt. African Union, International Bureau for Animal Resources (AU-IBAR).
Shomar, B., Darwish, M., Rowell, C., 2014. What does integrated water resources management from local to global perspective mean? Qatar as a case study, the very rich country with No water. Water Resour. Manag. 28, 2781. https://doi.org/10.1007/s11269-014-0636-9.
Siddiqi, A., Anadon, L.D., 2011. The water-energy nexus in Middle East and North Africa. Energy Policy 39 (8), 4529–4540.
Somerville, C., Cohen, M., Pantanella, E., Stankus, A., Lovatelli, A., 2014. Small-scale aquaponic food production. Integrated fish and plant farming. FAO Fisheries and Aquaculture Technical Paper No 589 (2014).
Suhl, J., et al., 2016. Advanced aquaponics: evaluation of intensive tomato production in aquaponics vs. conventional hydroponics. Agric. Water Manag. 178, 335–344.
Tokunaga, K., Tamaru, C., Ako, H., Leung, P.S., 2015. Economics of small-scale commercial aquaponics in Hawaii. J. World Aquac. Soc. 46 (1), 20–32.
Turnšek, M., Morgenstern, R., Schröter, I., Mergenthaler, M., Hüttel, S., Leyer, M., 2019. Commercial aquaponics: a long road ahead. In: Goddek, S., Joyce, A., Kotzen, B., Burnell, G. (Eds.), Aquaponics Food Production Systems. Springer International Publishing, New York, pp. 453–485.
Valin, H., et al., 2014. The future of food demand: understanding differences in global economic models. Agric. Econ. 45 (1), 51–67.
Wright, B., Cafiero, C., 2011. Grain reserves and food security in the Middle East and North Africa. Food Secur. 3 (1), 61–76.
Yogev, U., Barnes, A., Gross, A., 2016. Nutrients and energy balance analysis for a conceptual model of a three loops off grid, aquaponics. Water 8 (12), 589.