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Can Integrated Aquaculture-Agriculture Systems Contribute to Food Security in Egypt – A Review

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Abstract
Aquaculture practices are in continuous development making it the fastest-growing food production sector in the world. However, the sustainability of the sector is at stake due to the predicted effects of climate changes on water resource availability and aquaculture activities. Therefore, the strategy to produce more food from every drop of used water is vital to face the challenges of climate change. The application of Integrated Aquaculture and Agriculture Systems (IAAS) is acknowledged as an efficient water use to increase water productivity, profitability, sustainability, and reduce risks associated with water scarcity. Such an application provides a chance for effective recycling of one waste product from aquaculture as input to a different agricultural component. Aquaponic is a type of IAAS that combines recirculating aquaculture system (RAS) and hydroponics into a single-loop recirculating system. This integration allows the crops to use the water's nutrients provided by the fish which improve water quality for fish use and then is emerging as a sustainable means of organic food production. However, income from aquaponic systems mainly comes from the sale of crops rather than fish. Egypt is the first in Africa and among the top ten countries in the world in the field of aquaculture, and has substantial experience in raising freshwater fish, mainly tilapia. Therefore, it is feasible to provide inexpensive technological solutions on various aquaculture practices. The paper provides an overview of the climate change impacts on the different IAASs that has great potential to increase food productivity and reduce risks associated with water scarcity.

Keywords: Aquaculture, Integrated farming system, climate change, water productivity, more crop per drop.

1. Introduction

The world population is expected to reach 8.1 billion by 2025 and 9.6 billion by 2050 [1]. Rapid population growth will increase global demand for food production, which is expected to increase by 60% by 2050. On the other hand, the per capita share of global agricultural land has gradually decreased from 0.44 to 0.25 ha over the last 50 years [2]. Population growth has long been linked to food security, climate change, and water resources. By 2050, our need for food will increase by more than 100 percent. Currently, 1 in 8 people, or 842 million people struggle with hunger every day. Furthermore, nearly 1 billion people in the world are food insecure, meaning they lack access to an adequate amount of affordable nutritious food [2]. Annually 7,130 km^3 of freshwater is required for global food production, and it is expected to increase to 13,500 km^3 by 2050 [3]. The effects of climate change may threaten global food production by increasing water demand, and reducing water availability and crop productivity [4],[5]. Therefore, increasing food production is one of the key challenges in feeding a growing global population.

In regions of the world where scarce water reserves are becoming scarcer, innovative approaches to growing food are crucial. Known for its heat and deserts, it is not surprising that the Near East and North Africa are located in these regions. Agriculture is essential for food security to meet the growing global population. Globally, agriculture consumes more than 69-70% of annual water withdrawals and 90% in some arid countries [1]. While agriculture has evolved to meet these exponentially increasing food demands, farmers will need to increase food production by 70-100% to meet global nutrition needs. Therefore, there is a necessity to produce higher yields using the same (or less) available lands than they use today while relying on fewer natural water resources [6].

On the other hand, with a global focus on environmentally and economically sustainable development of natural resources, it is logical to integrate appropriate farming practices, where possible, to enhance farm productivity and water-use efficiency (the concept of more crop per drop). A possible method to increase crops per drop would be through integrating aquaculture- into the existing agriculture systems (IAAS). IAAS has the privilege of

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augmenting food productivity and minimizing the menace correlated with water scarcity [7]. It is a form of intensification and sustainable development of agriculture, that is., producing more food from essentially the same area of land and water without (or less) environmental impacts [8].

This paper aims to (a) briefly explore the impact of climate change on aquaculture and more crops per drop. (b) present and highlight the different types if integrated Aquaculture - Agriculture systems (IAAS) as efficient solution to maximize water use efficiency, (c) assess the expected benefits from IAAS regarding water productivity and food security.

2. Factors affecting aquaculture's productivity

Regardless of all contradicting views, there is a general agreement that climate change is a fact and will have an impact on water resources, aquaculture, food production processes, and ecosystem balance as well as human well-being. These impacts include sea level rise, increased global temperature, frequency of extreme weather events and patterns [9],[10],[11]. Therefore, it is vital to promote sustainable water management practices, support resilient aquaculture systems, and implement innovative agricultural techniques that improve water-use efficiency (more crop per drop) and contributing to global food security. Implementing efficient irrigation techniques (e.g., drip irrigation, soil moisture sensors, improved crop varieties, mulching and conservation tillage, etc.) and sustainable water management practices help minimize the strain of climate change on water resources and promote environmentally sustainable agriculture. Climate change effects on water availability which varies from one region to another and can cause damage to people's health and ecosystems. In fact, climate change is a water issue and may disturb the water resources stability at local, regional, and national levels [12]. Many authors investigated and evaluated the impacts of climate change on aquaculture's different practices [9],[13],[11]. These impacts are expected to remain persistent and most probably irreversible with critical consequences on the aquaculture and concerned communities [14],[15]. The following are some of the changes that the climate will have impact. Changes in water temperature: Aquatic species have specific temperature ranges in which they thrive. Climate change alters water temperature, leading to shifts in the distribution and abundance of various species of aquatic organisms. Fish and shellfish are sensitive to temperature changes, and variations beyond their optimal ranges can reduce growth rates, alter reproduction patterns, increase susceptibility to diseases and potentially reducing aquaculture yields and survival [5],[16]. The following was depicted from the conducted literature review:

- Altered water quality: Climate change have an effect on water quality variables such as dissolved oxygen concentrations, pH levels, water salinity, nutrient concentrations, and the occurrence of harmful algal blooms. These changes can negatively impact the survival, health and productivity of aquaculture species [17].
- Disease outbreaks: Warming water temperatures can facilitate the spread of pathogens and harmful bacteria, thereby increasing the risk of disease outbreaks among farmed fish and other aquatic organisms. This can result in significant economic losses for aquaculture facilities [18].
- Loss of habitat and biodiversity: Climate change disrupts ecosystems, leading to the loss of critical habitats for aquatic species. Destruction of mangroves, coral reefs, and seagrass beds due to rising sea temperatures and ocean acidification lead to shifts in species distribution and can affect the overall biodiversity and productivity of aquaculture systems [19],[20].
- Ocean acidification: Increased carbon dioxide (CO_2) emissions in the atmosphere are not only warming the planet but also causing the oceans to absorb more CO_2. This leads to ocean acidification, which can hinder shell formation in mollusks, making them more vulnerable to predation, disrupting the food chain and potentially impacting the growth and survival of various species as well as other aquaculture operations (FAO 2009).
- Rising sea levels: The warming climate is causing ice caps and polar glaciers to melt leading to sea levels rising. This puts coastal aquaculture facilities at risk of flooding, salinization of freshwater sources, and increased vulnerability to storms and erosion [20].
- Extreme weather events: More frequent and intense storms, hurricanes, and typhoons can damage aquaculture facilities, disrupt production, and result in significant economic losses for the industry [21].
- Economic impacts: Disruptions in aquaculture production due to climate change can result in financial losses for farmers, processors, and related industries, thus affecting livelihoods and regional economies.

3. Adaptation strategies

To mitigate climate change impacts on water resources and aquaculture industry, specialists and stakeholders are exploring various adaptation strategies. These include developing efficient water management systems, such as recirculating aquaculture systems (RAS), reducing water consumption and minimizing the impact of changing water availability, implementing water-saving technologies, and diversifying aquaculture species to increase resilience to changing environmental conditions such as temperature-tolerant or disease-resistant varieties [11],[13]. Improved monitoring and early warning systems is crucial to detect and respond to any changes in water quality, disease outbreaks, and acute weather events. Adopting integrated multi-trophic aquaculture systems can help optimize resource utilization and reduce environmental impacts. By combining different species in a symbiotic relationship, these systems can enhance water quality and reduce the need for external inputs [11]. Several researches have indicated that the impacts of climate change on aquaculture may vary depending on many factors like geographical areas, economics, climatic zones, production systems, and farmed species [14],[22],[13]. Ultimately, climate change poses significant challenges to aquaculture, particularly regarding water resources. The industry must adapt and develop strategies to mitigate these impacts. Collaboration between policymakers, scientists, and aquaculture practitioners is vital to ensure the long-term sustainability and implement climate-resilient strategies for the sustainable use of water resources and the advancement of integrated agriculture and aquaculture industries.

4. The Integrated Aquaculture -Agriculture Systems (IAAS)

Aquaculture is one of the fastest progressing sectors of food production, with an annual growth rate of 5.3% in the period 2001–2018, ensuring an average of 46% of fish production worldwide up from 25.7% in 2000. Therefore, it is expected to fill the gap of fish demands [23],[24]. Integrated Aquaculture Agriculture Systems (IAAS) are innovative and sustainable farming systems that link the cultivation of aquatic organisms with other forms of agricultural crops in a symbiotic manner. Wastes generated from one system are recycled in IAAS as inputs to another system, thus decreasing pollution [25]. Therefore, these systems enhance resource utilization, waste recycling, and increase overall productivity.

From a broader context, the IAAS has been mentioned as part of managing integrated resources to improve natural resource efficiency and increase productivity, profitability, and sustainability [25]. The Following paragraphs briefly discuss water productivity in agriculture and aquaculture, and the different types and advantages of IAAS.

4.1 Water productivity

Water productivity, also called water use efficiency (WUE), is the amount of agricultural output (such as crop yield or industrial production) that is achieved per unit of water consumed or withdrawn (Fig.1).

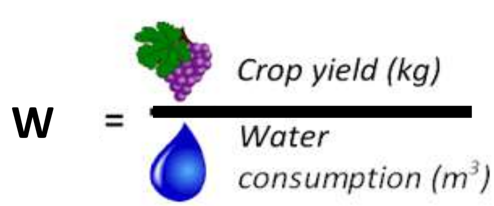

Figure (1). Relation between water productivity (WP), crop yield (kg) and water consumption (m^3), Source [26]

In other words, it's a measure of how efficiently water resources are utilized to generate a certain level of productivity or output [3],[27],[28]. Water productivity is a convenient concept to guide efficient water management implementations, improve irrigation techniques, boost sustainable agricultural practices and confront water scarcity challenges particularly in regions where water resources are finite. High water productivity implies that more output is generated for every drop of water used, which is essential for sustainable development, food security, and environmental conservation [29],[30]. Water productivity relies on different aspects which comprise varieties of the growing plants and crops, strategies of water application, farming techniques, soil quality, and other agricultural matters [31],[32].

4.2 Agriculture productivity based on water used

Water productivity in agriculture mainly refers to the quantity of agricultural output or crop yield that is obtained per unit of water used in the farming process. It measures how efficiently water resources are utilized to produce food and other agricultural products. Among agricultural crops, the highest average water footprint (i.e., volume of freshwater used throughout the entire production chain of a consumer item or service) has been recorded for rice production. Moreover, due to its popularity as a main food crop, rice is one of the highest consumers of blue water (i.e. surface water and groundwater) and green water (i.e. natural rainfall) in the world [33],[34].

Water productivity varies among major agricultural crops. The water productivity range of rice is averaged 0.74-1.10 $kg/m^{3,}$ for maize is 0.56–1.59 $kg/m^{3,}$ and for wheat is 0.94–1.10 $kg/m^{3.}$ A wider range of water productivity for rice, at 0.15– 1.60 $kg/m^{3,}$ and for wheat at 0.20–1.20 kg/m^3 was reported by [29]. Increasing water productivity in different agricultural practices is the main strategy to face the challenges of water scarcity and may abate the necessity for additional land and water resources. Water productivity in agriculture can be enhanced by adopting modern irrigation strategies, managing water efficiently, increasing soil fertility, selecting suitable crops, improve farming systems, and increase yield per volume of water used [29],[30],[31].

4.3 Water productivity in aquaculture

Aquaculture practice is considered non-exhaustive and non-consumptive regarding water use and therefore is a water - efficient food production system and does not compete with irrigation [35],[36]. Whenever water is available, aquaculture can be integrated with other crop production thus potentially increasing water productivity [34]. However, water productivity in aquaculture systems varies widely depending on location, culture method and fish species. Improving water productivity in aquaculture varies widely depending on culture method and the implemented strategies to maximize the yield of aquatic organisms while minimizing water usage and wastes. Improving aquaculture production will increase the economic water productivity of water especially when selecting high value fish [31].

Some key considerations for enhancing water productivity in aquaculture include water management, feed management, stocking density, recirculating aquaculture systems (RAS), integrated multi-trophic aquaculture (IMTA), polyculture and integrated systems, water quality and waste management, species, and site selection as well as monitoring and evaluation [29],[37],[38].

Efforts to improve water productivity in aquaculture can contribute to sustainable food production, reduce environmental impacts, conservation of freshwater resources, and the sustainability of the aquaculture industry.

4.4 Water productivity in Integrated Aquaculture - Agriculture system (IAAS)

Water productivity in integrated aquaculture-agriculture systems (IAAS) refers to the efficient use of water resources to produce both aquatic products (such as fish or shrimp) and agricultural products (such as crops) within the same integrated system. These systems aim to maximize the benefits derived from water use by optimizing the interaction between aquaculture and agriculture components. Water productivity in such systems involves measuring the combined output of both aquatic and agricultural products relative to the amount of water used [37].

Water productivity in well-managed pond systems is reported to be 0.21–0.37 kg/m^3 and in pond-based IAAS is 2.13 kg/m^3 for fish and maize production and up to 8.46 kg/m^3 for fish and vegetable production. Although water productivity in rice-fish farming is not well documented, IAA is reported to increase water productivity by at least 10 % [36]. Moreover, studies showed that water productivity could be improved in non-integrated farming system through integration and diversification of crops [31],[35].

4.4.1 Categories of IAAS

The integrated aquaculture-agriculture systems (IAAS) can be tailored to suit different geographical and environmental conditions, making them versatile and adaptable to various regions. However, successful implementation need proper management and awareness of the essential requirements of the integrated species involved. There are several systems of IAA practice, each combining different elements of aquaculture and agriculture. Some of these are as follows.

4.4.2 Integrated crop-aquaculture systems

It includes either rice, horticulture, sericulture, or mushrooms integrated with the fish system [39],[40],[41]. Integrated rice-fish farming is the most widely spread activity where fish (e.g., common carp, catfish, and tilapia) feed on weeds and insects particularly mosquitoes that carry malaria reducing the need for pesticides and herbicides [42]. In return, the fish waste acts as a natural fertilizer for the rice plants. The flooded rice paddies also provide an ideal habitat for fish growth, increasing overall productivity and local farmers' economic income [35]. Fish farming in rice fields increases the rice yield by 8-26%, as a result of the presence of fish [43]. Therefore, such an integrated system is better than rice monoculture in terms of high production and providing a more divergent and nourishing food supply. However, it requires about 26% more water than rice monoculture. In this context, the second aim of integrated fish and crop production applications is to eliminate aquaculture residues and provide organic fertilizers for agricultural crops [41], [44],[45]. Fish farming in rice fields is an extensive culture system that primarily relies on natural foods (e.g., plankton, periphyton, and benthos), accordingly, fish productivity is low (Table 1). To increase the production of the system, other livestock such as cattle are raised and fed rice straw, then dunk is used as fertilizer for homestead gardening. Duck rearing on rice fields is also practiced in many countries [7]; [61].

4.5 Aquaponics

Aquaponic is a popular highly efficient and sustainable IAAS technique where a recirculating aquaculture system (RAS) and hydroponics are merged to grow plants and fish in a closed system, thus increase economic efficiency and water productivity [62]. The basic principle of aquaponic involves cultivating fish in a tank and using the nutrient-rich water from the fish tanks to nourish plants grown in a soil-less medium. The fish waste contains ammonia, which is converted by beneficial bacteria into nitrates and nitrites. These nutrients serve as natural fertilizers for the plants, providing essential elements for their growth. The plants, in turn, act as a biofilter by taking up these nutrients, purifying the water, and returning it back to the fish tanks. This symbiotic relationship creates a self-sustaining ecosystem where both fish and plants thrive (Fig.2) with a large reduction in water use and thus will mitigate and alter the negative environmental impacts of the system [62], [64],[65].

Aquaponic system supports food security and is equally effective in places with drought or poor soil quality resulting in local food production, boosting the local economy, and reducing food transportation. Aquaponics have the advantage of being sustainable and environmentally safe compared to other aquaculture practices because no agrochemicals are required and there is a continuous natural supply of organic fertilizers (Table 2). Current studies on aquaponics sustainability gave a lot of information on its applicability. These studies revealed that, although the system is apparently simple, it can only be sustainably managed through the availability of enough knowledge and experience of the fish, bacteria, and plant components at the individual and systems levels [62],[64],[66].

Table (1). Productivity of rice (crop) and fish in IAA among different countries

Farming system	Country	Fish species	Productivity(kg/ha)		Reference
			Fish	Crop/rice	
Pond-based IAA	Bangladesh	Prawn, Carp & Mola	1,983	1,470	[39]
	China		13,575	Not documented	[46]
	Egypt	Tilapia	350	5400	[47]
	India		3,000	800	[48]
	Malawi	Tilapia	2,017	1,976	[41]
	Tanzania	Tilapia- catfish	2460	2460	[49]
	Thailand		2,307	Not documented	[50]
	Vietnam	Common carp, silver carb, kissing gourami, tilapia, and catfish	474	1,618	[51]
Rice-fish* farming	Bangladesh)	C. carpio, B. gonionotus, O. niloticus	259	5,261	[35]
	China	Cyprinus carpio	372	6,290	[52]
	Ghana	Nile tilapia (Oreochromis niloticus)	201	4,410	[53]
	India	C. catla, C. carpio, C. mrigala, L. rohita	906	3,629	[54]
	India	Rohu, Catla, Silver carp, Common carp, & Mrigal	1230	5800	[25]
	Indonesia		0.8–625	7,800	[55]
	Nigeria		2,376	1,656	[56]
	Philippines		233	2,750	[57]
	Thailand		146–363	1,630–2,651	[58],[59]
	Vietnam	carpio, B. gonionotus O. niloticus	326 C.	4,209	[60]

**Fish production from rice fields is low because they only depend on natural foods (e.g., plankton, periphyton, and benthos)*

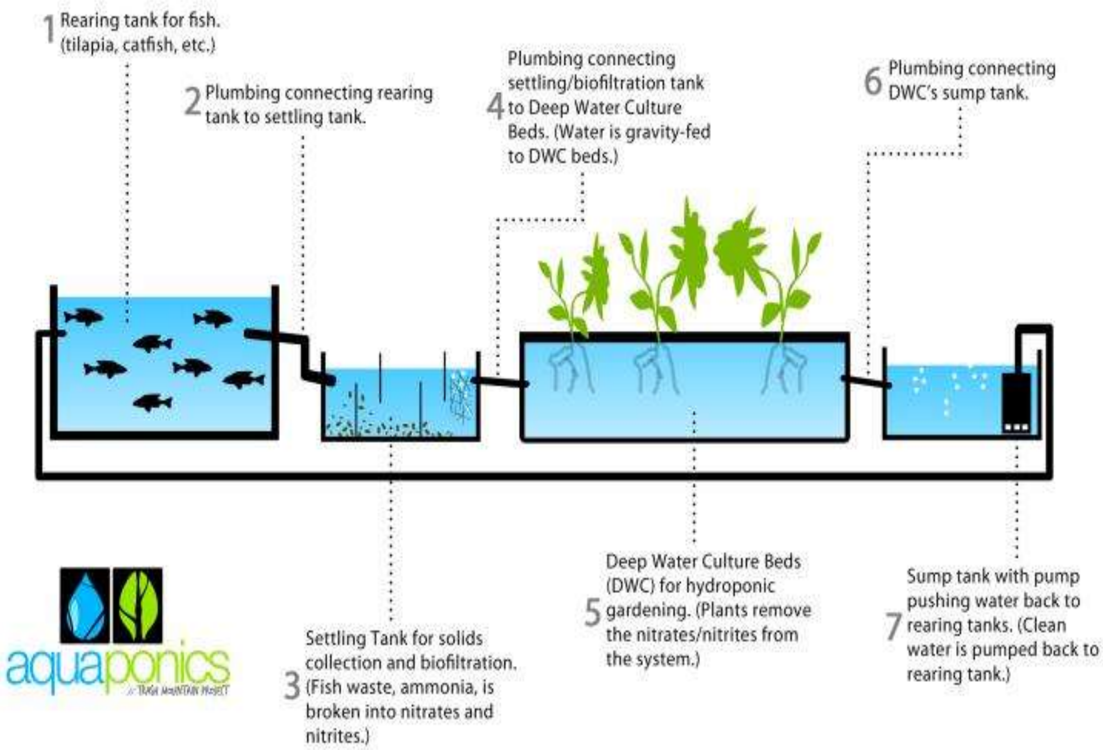

Figure (2). General setup of an aquaponic system (source: [61])

Table (2). Comparison between hydroponic, aquaculture and aquaponic systems

System	Advantages	Disadvantages
Hydroponic	• Produces a high crop yield in a small space. • Highly water use efficient for crop production	• Using expensive fertilizers.
Aquaculture	• Produce a large number of fish in a small space.	• May fail if high fish stocking density. • Fish produce toxic wastes that should be continuously removed.
Aquaponic	• No pesticide, thereby environmentally safe and reducing carbon footprint. • Plants get their automatic nutritional supply from the fish's water as they filter water for fish.	• Management requires expertise in both growing fish and plants. • High initial and operational costs compared to soil culture. • The system requires high energy and maintenance. • Numerous ways in which the entire system can break down.

5. Aquaculture in Egypt

Aquaculture in Egypt has been a significant and growing industry for several decades. The country's favorable climate, access to water resources, and historical reliance on the Nile River have all contributed to the development of aquaculture as an important economic sector. Aquaculture is considered as the only practical resource for decreasing the current gap between production and consumption of fish in Egypt. Egypt has continued to be a significant player in the global aquaculture industry. It is now number one in Africa, number six worldwide in aquaculture production and number three in tilapia production globally [67],[68],[69]. In Egypt, the aquaculture is practiced in almost all different production systems that have been described in previous paragraphs [67],[70].

Egypt's total fish production increased by 17.64 % from 1.7 million metric tons (MMT) in 2016 to 2.0 MMT in 2020 [71]. Aquaculture's share grew from 1.37 MMT in 2016 to 1.62 MMT in 2020 which representing about 81% of total fish production. Moreover, there is an increase of 18.2 % growth from 2016, followed by production from lakes with 10 %, seawater with 4.4 %, freshwater with 3.8 %, and finally rice fields with 0.8 % of the total production [69],[72].

5.1 IAA systems in Egypt

According to [28], there are several commercial farms implementing the IAAS and producing finfish particularly. The most common fish are Nile tilapia (Oreochromis niloticus), African catfish (Clarias gariepinus), carps, flathead grey mullet (Mugil cephalilus), European seabass (Dicentrarchus labrax) and gilthead seabream (Sparus aurata). The water source comes from groundwater reserves and/or agricultural drainage. The majority of these farms have applied the integrated techniques that allow them to maximize water productivity through producing three different crops (fish, plant and sheep) at specific period. Some other farms have applied the recirculation aquaculture system (RAS) and produce tilapia in densities of 20–30 kg/m^3 to market size of 250–400 g in 6–8 months. This production was attainable due to the suitable climate and available warm groundwater present throughout the year [73]. Moreover, brackish groundwater with salt concentration of 25g/L is also used in IAAS as Salicornia crops (a halophytic vegetable with an array of potential health benefits) is combined with intensive European seabass and gilthead seabream aquaculture. The yearly production of both fish species is about 100 tones/year [47], [73].

Furthermore, aquaponic is a relatively new technique in Egypt for growing aquatic species and soilless plants in a single integrated system. Commercial aquaponic is still developing and practiced on a pilot scale. The predominant challenge is to balance the conditions required for the growth of multiple species which eventually may lead to a complex dynamic system. In Egypt, some trials have been initiated by national institutions and the private sector to highlight that aquaponic could be an ally or alternative to traditional agriculture and land reclamation [72], [73],[74]. Although aquaponic presents a great opportunity, especially for developing countries like Egypt, it still requires further studies, researches and trainings to be prepared for the unexpected challenges.

5.2 The innovative Heliopolis University's IAA system

Heliopolis University developed its aquaponic station, in which the marriage of aquaculture (raising fish) and hydroponics (the soil-less growing of plants) that grows fish and plants together in one integrated system. The fish waste provides an organic food source for the growing plants and the plants provide a natural filter for the fish live in the water. The micro nitrifying bacteria do the job of converting the ammonia from the fish waste first into nitrites, then into nitrates and the solids into vermi-compost that are food for the plants. The hydroponics provide 80% water efficient than the traditional agriculture. The system could be close to the market to avoid transportation as cost and pollution. Also the system could establish in desert to give the chance for green the farmland. Limited labor needed for the system but most trained is recommended. In sunny countries like Egypt, the source of renewable energy could be used to operate the mechanical equipment or even for the desalination unit. Heliopolis University considered its aquaponic station as an integrated environmental project that provides three basic elements: WEF Nexus of Water, food and clean energy. The university's aquaponic station applied as an integration of three Erasmus projects aimed to energy efficiency, water and agriculture. Heliopolis University is a leader in the field of aquaculture using solar energy as a research project more than economic benefit, provide all the services and technical assistance to its specialized researchers [75].

6. Conclusion and recommendations

This review highlighted the potential effects of climate change on aquaculture production and implications on the sector's sustainability. It is also discussed the IAAS as a combined activity between aquaculture and agriculture to increase farm productivity, waste recycling, maximize resource use efficiency and as an effective mean of using the same land resource to produce both agricultural products and animal protein.

Globally, aquaculture is considered one of the most efficient solutions to meet the increasing demands for aquatic products. However, this sector is under threat from climate change's negative and positive effects, although the negatives outweigh the positive ones. Even though climate change poses a universal threat to food production, the correlated risks on aquaculture are predicted to vary according to geographical or climatic zones, national economy, rearing environment, production system scale, cultured species and their feed ingredient availability.

Because of the continues growth of aquaculture sector while climate impacts become more evident, there is a necessity to adopt a comprehensive approach in anticipating the impacts of climate change on aquaculture and in addressing these impacts. Therefore, developing mitigation and adaptation strategies and action plan would be more effective. Integrated aquaculture agriculture system (IAAS) is perceived as efficient use of water to increase its productivity and reduce the risks associated with water shortages. Therefore, IAAS is considered to produce “more crop per drop” and play a crucial role in food security. Aquaponic depicts a promising practice for producing both fish and vegetables in ways that use less land and water. It also reduces the chemical and fertilizer inputs that are used in conventional food production. Aquaponic has the ability to be a cost-effective business, while the substantial challenges are the high initial and operational costs, available skill and knowledge from two separate fields, daily maintenance, limited plant selection, monitoring water quality for fish and plants, as well as marketing. There are multiple ways the entire system can fail. The topic of water resources availability and management must be carefully addressed before the adoption of the IAAS in the national country strategy. These encompass the efficient use and better management practices of blue and green water.

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