Integrated Aquaculture-Agriculture System: A Tool for Sustainable and Optimum Water Management

Chapter · July 2025

DOI: 10.1007/978-3-031-93587-9_5

Wael M. Khairy
Heliopolis University

Citation:

Salah El Deen, M.A., **Khairy, W.** (2025). Integrated Aquaculture-Agriculture System: A Tool for Sustainable and Optimum Water Management. In: Correia Leitão, J.C., Khairy, W., Pereira, D., Zascerinska, J., Gaspar, P.D. (eds) Sustainable Water Management and Irrigation Systems. Natural Resource Management and Policy, vol 62. Springer, Cham. https://doi.org/10.1007/978-3-031-93587-9_5

Chapter 5

Integrated Aquaculture-Agriculture System, A Tool or Sustainable and Optimum Water Management

Prof. Dr. Magdy A. Salah El Deen[1] and Prof. Dr. Wael M. Khairy[2]

Abstract:

Aquaculture practices is 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 resources availability and the different 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 integration of aquaculture and agriculture (IAA) has long been implemented by rural communities in many Asian and African countries as part of integrated resources management for enhancing the efficiency of natural resources and the livelihood of the farming community. In this context, the system of integrated fish - livestock and fish - crop farming includes raising fish besides with livestock and crop for maximizing the farm productivity. These systems are particularly relevant for developing countries where the capacity of the farming community for intensive aquaculture is limited. Some case studies are presented and discussed in this chapter. Generally, the application of IAA is acknowledged as an efficient water use to increase water productivity, profitability, sustainability and reduce risks associated with water scarcity. Moreover, such application provides a chance for effective recycling of one waste product from aquaculture as input to a different agricultural component. Aquaponics is a type of IAAS that combines the components of recirculating aquaculture system (RAS) and hydroponics into a single-loop recirculating system. This integration allows the plant to use nutrients from the water provided by the fish which improve water quality characteristics for fish use and emerging as a sustainable means of organic food production. However, income from aquaponic systems is mainly come from the sale of

[1] Professor, National Water Research Center (NWRC), Ministry of Water Resources and Irrigation, P.O. Box 13621/5 Kalubia - Egypt, Tel.: +20 (0)2 4 218 33 26, +20 (0)12 24 55 79 26 (mobile), Fax: +20 (0)2 4218 3326, E-Mail: magdyeldeen@hotmail.com

[2] Responsible Author: Professor, Head, Civil Engineering Department (Water Program), Faculty of Engineering, Heliopolis University for Sustainable Development, Mob. +20 201224798846 & +20 1119922544, E-mail: wael.khairy@hu.edu.eg & wkhairy00@hotmail.com

plants 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 contribute and provide straightforward and inexpensive technological solutions on various aquaculture practices.

The present chapter provides an overview of the impact of climate change on water resources and the different integrated aquaculture agriculture (IAA) systems 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 (United Nations 2017). Rapid population growth will increase global demand for food production, which is expected to increase 60% by 2050. On the other hand, the per capita share of global agricultural land has gradually decrease from 0.44 to 0.25 ha over the last 50 years (FAO 2013).

Population growth has long been linked to of food security, climate change and water resources. By 2050, the world's population is expected to grow to nearly 9 billion; thus, our need for food increases 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 (FAO 2013).

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 (Molden 2007). The effects of climate change may threaten global food production by increasing water demand, reducing water availability and crop productivity (Hanjra and Qureshi 2010; Turrel et al. 2011). 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 (United Nations 2017). While agriculture has evolved in order to meet these exponentially increasing food demands, farmers will need to increase food production by 70-100 percent 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 (United Nations 2019).

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 augmenting food productivity and minimizing the menace correlated with water scarcity (Ahmed et al. 2012). 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 (Godfray et al. 2010).

The aim of this chapter is to (a) briefly explore the impact of climate change on water resources, 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. Impacts of climate change on water resources and aquaculture

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, increase global temperature, frequency of extreme weather events and patterns (De Silva 2013; United Nations 2020; Elsheikh 2021).

Therefore, it is vital to promote sustainable water management practices, support resilient aquaculture systems, and implement innovative agricultural techniques that improving 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.

2.1 Impact of climate change on water resources

Climate change effects on water availability which vary from one region to another and can cause damage to people health and ecosystems. In fact, climate change is a water issue and may disturb the water resources stability at local, regional and national levels (Sukanya and Sabu 2022). The following are some of the climate change impacts on water resources:

- Changes in precipitation patterns: Climate change can cause alterations in rainfall in terms of distribution and quantity, leading to more recurrent and drastic droughts in some regions and increased rainfall in others. These changes can disrupt water availability and cause water scarcity, affecting both freshwater sources and groundwater reserves both of which can disrupt water resources for various uses, including agriculture and aquaculture.

- Rising temperatures: Higher temperatures accelerate evaporation rates, reducing the amount of water available for different uses. This phenomenon contributes to the depletion of surface water bodies and reduces soil moisture, impacting agricultural productivity.

- Melting glaciers and snowpack: In many regions, water supplies are dependent on the gradual melting of glaciers and snowpack. With rising global temperatures, glaciers are melting at an accelerated rate, affecting the timing and quantity of water flows in rivers and streams.

- Saltwater intrusion: Rising sea levels can cause saltwater intrusion into coastal aquifers, contaminating freshwater sources used for drinking, irrigation, and aquaculture.

2.2 Impacts of climate change on Aquaculture

Many authors investigated and evaluated the impacts of climate change on aquaculture different practices (De Silva 2013 2017; Maulu et al. 2021; Elsheikh 2021). These impacts are expected to remain persistent and most probably irreversible with critical consequences on the aquaculture and concerned communities (Barange et al. 2018; Dabbadie et al. 2018). The following are some of the changes that the climate will have impacts. Moreover, Potential positive and negative effects of some climate effects on aquaculture are summarized in table (1).

- 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 (Troell et al., 2017; Guyondet et al.,2018).

- 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 (Ngoan, 2018).**

- 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 (Sae-Lim et al.,2017).

- 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 (Kibria et al.,2017 and Rutkayova et al., 2017).
- 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 (Rutkayova et al.,2017).

- 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 (Seggel et al.,2016).

- 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.

Table (1) Potential effects of climate change on aquaculture systems

No.	Element	Negative effects	Positive effects
1.	Rising Temperature	- Slow growth rate and viability of cold-water species. -Water quality deterioration. - Fragile immunity in cold water species. - Slow down carbon absorption capacity in the oceans. -Enhance thermal stratification. - Increased severity of disease-causing agents in warm waters	- Prolong growing seasons of warm-water species. - Promote the possibility of developing genetic traits .
2.	Diseases and harmful algal blooms	-Slow growth and survival rates -Water quality deterioration - Increase disease outbreak which lead to increase production costs - Increased incidence of unfamiliar diseases	-Possibility of eradicating cold-water pathogens - May develop disease tolerant species -Possibility of identifying and developing new species.
3.	Changes in rainfall/ precipitation patterns	-Droughts may cause water use competition and high production costs. -Floods may lead to water quality deterioration, pollute the environment and high loss of species. -Destruction of production facilities	-In some regions, floods may develop suitable areas for various aquaculture practices. -Drought can promote improve management of wastewater.

2.4. Adaptation strategies:

To mitigate climate change impacts on water resources and aquaculture industry, stakeholders are exploring various adaptation strategies. These include developing efficient water management systems, such as recirculating aquaculture systems (RAS), reduce water consumption and minimize 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 (Elsheikh 2021; Malau 2021).

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 (Elsheikh 2021).

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 (Barange et al. 2018; Zolnikov 2019; Maulu et al. 2021). Table (1) summarizes the expected elements as well as negative and positive impacts of climate change that have effect on the production and sustainability of the aquaculture sector**.**

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.

3. 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 (Halwart 2020; FAO 2020)

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 (Ahmed et al. 2019). 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 (Dey et al. 2010; Ahmed et al. 2019). The Following paragraphs briefly discuss water productivity in agriculture and aquaculture, and the different types and advantages of IAAS.

3.1 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 (Fig1). In other words, it's a measure of how efficiently water resources are utilized to generate a certain level of productivity or output (Molden et al. 2007; Kumar 2021; Ibrahim 2023).

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 (Molden et al. 2010; Brauman et al. 2013).

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 (Ali and Talukder 2008 and Kilemo 2022).

3.1.1 Water productivity in agriculture

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.

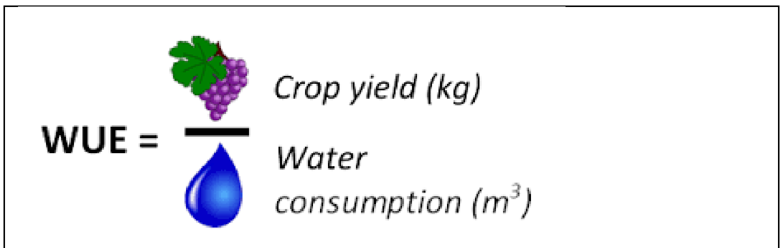

Fig (1) Relation between water use efficiency (WUE), crop yield(kg) and water consumption(m^3)
Source: https://business.esa.int/news/water-use-efficiency-for-vineyards

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 (Chapagain and Hoekstra 2011 and Ahmed 2014).

As indicated in table (2), water productivity varies among major agricultural crops. 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 Molden et al. (2010). 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 via adopting modern irrigation strategies, managing water efficiently, increase soil fertility, selecting suitable crops, improve farming systems, and increase yield per volume of water used (Ali and Talukder 2008; Molden et al. 2010; Brauman et al. 2013).

Table (2) Comparative water productivity among crops in different farming systems

	Crop	**Type of study**	**Average water productivity (Kg/m^3)**	**Reference**
Agriculture	Maize	Field exp.	0.56	Igbadun et al. (2006)
		Field exp.	1.01	Moayeri et al.(2011)
		Monitoring through remote sensing	1.59	Fapeng et al. (2013)
	Rice	Crop production and land use data	0.74	Cai et al. (2010)
		Data review	1.09	Zwart and Bastiaanssen (2004)
		experimental study	1.10	Steduto et al.(2012)
	Wheat	Crop production and land use data	0.94	Cai et al. (2010)
		Data review	1.09	Zwart and Bastiaanssen(2004)
		experimental study	1.10	Steduto et al.(2012)
Aquaculture	fish	Assessment	0.21	Verdegem et al. (2006)
		Data review	0.36	Brummett (1997)
		Assessment	0.37	Verdegem et al. (2006)
IAA	Fish-maize	Filed exp.[a]	2.31 (fish 0.22 + crop 1.91)	Abdul-Rahman et al. (2011)
	Fish-vegetables	Filed exp.[a]	8.46(fish 0.22+ crop 8.24)	Abdul-Rahman et al. (2011)
	Rice- fish	Assessment	1.21	Ahmed and Granett (2011)

				, Abdul-Rahman et al. (2011) [b]

[a] Fish stocking density 10/m^3 seems to be extensive culture
[b] The studies of Ahmed and Granett (2011), and Abdul-Rahman et al. (2011) revealed that IAA increases water value index by 11% and water productivity by over 10% without any additional consumptive use of water). Based on these results, it appears that fish and rice farming will increase water productivity compared to rice farming by at least 10% from 1.1 to 1.21 kg/m^3.

3.1.2 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 (Ahmed and Granett 2011; Abdul-Rahman et al. 2011). Whenever water is available, aquaculture can be integrated with other crop production thus potentially increasing water productivity (Ahmed et al. 2014). 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 (Ali and Talukder 2008).

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 (Verdegem et al. 2006; Verdegem and Bosma 2009; Molden, 2010).

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.

3.1.3 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 (Verdegem et al. 2006; Zajdband 2011).

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 (Table 2). Although water productivity in rice-fish farming is not well documented, IAA is reported to increase water productivity by at least 10 % (Abdul-Rahman et al. 2011). Moreover, studies showed that water productivity could be improved in non- integrated farming system through integration and diversification of crops (Ali and Talukder 2008; Ahmed and Granett 2011).

3.2 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:

3.2.1 Integrated crop-aquaculture systems.

It includes either rice, horticulture, sericulture or mushroom integrated with fish system (Ahmed et al. 2007; Fapeng 2013; Tran 2013). 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 (Liu et al. 2020). 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 (Ahmed and Granett 2011).

Fish farming in rice- fields increases the rice yield by 8-26%, as a result to the presence of fish (Dye et al. 2010). Therefore, such integrated system is better than rice monoculture in terms of high production and providing 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 are to eliminate aquaculture residues and provide organic fertilizers for agricultural crops (Phong et al. 2010; Cai et al. 2010; Tran et al. 2013) .

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 3). 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 (Ahmed et al. 2012; Long et al. 2013).

Table (3) 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	Ahmed et al. (2007)
	China		13,575	Not documented	Kangmin (2010)
	Egypt	Tilapia	350	5400	van der Heijden (2012)
	India		3,000	800	Kumar and Ayyappan (1998)
	Malawi	Tilapia	2,017	1,976	Tran et al. (2013)
	Tanzania	Tilapia- catfish	2460	2460	Mulokozi et al. (2021)
	Thailand		2,307	Not documented	Pant et al. (2004)
	Vietnam	Common carp, silver carb, kissing gourami, tilapia, and catfish	474	1,618	Phong et al. (2008)
Rice-fish* farming	Bangladesh)	*C. carpio, B. gonionotus, O. niloticus*	259	5,261	Ahmed and Garnett (2011)
	China	Cyprinus carpio	372	6,290	Hu et al. (2013)
	Ghana	Nile tilapia (Oreochromis niloticus)	201	4,410	Ofori et al. (2005)
	India	*C. catla, C. carpio, C. mrigala, L. rohita*	906	3,629	Mohanty et al. (2004)
	India	Rohu, Catla, Silver carp, Common carp, & Mrigal	1230	5800	Dey et al. (2010)
	Indonesia		0.8–625	7,800	Purba (1998)
	Nigeria		2,376	1,656	Akegbejo-Samsons (2010)
	Philippines		233	2,750	Corales et al. (2004)

	Thailand		146–363	1,630–2,651	Deomampo (1998); Halwart and Gupta (2004)
	Vietnam	carpio, B. gonionotus O. niloticus	326 C.	4,209	Berg (2002)
*Fish production from rice fields is low because they only depend on natural foods (e.g., plankton, periphyton, and benthos).					

3.2.2 Integrated livestock-fish aquaculture systems. In this system livestock, such as poultry, pigs or cattle are raised in combination with aquaculture. Livestock manure is utilized to fertilize fish ponds, providing nutrients like nitrogen (N) and phosphorus (P), stimulating plankton growth and providing natural food for the fish (box 1 and2). The fish pond water can also be used for livestock drinking water and irrigation for crops (Little and Edwards 2004).

Box (1) Case studies from Ethiopia

In a study conducted by Waktola et al. (2016) where components of the integration were fish (*O. niloticus*), livestock's (poultry and cow) and vegetables (Tomato and onion), the authors reported that:

- generally, no significant change in the physical and chemical characteristics of pond water and remained within the required level for the growth of Nile tilapia.
- higher level of nitrate and total phosphorus in the IAA ponds were recorded
- higher level of soil organic carbon and organic matter were recorded in the IAA ponds comparing to the non-IAA ponds
- higher number and bigger size of tomato fruit and onion from the IAA plots than the control plots
- The results of the expenditure and income analysis indicated that the integration of vegetable cultivation using fish pond water alone was more profitable than the conventional method of vegetable cultivation with the application of fertilizers.

Another study by Tugie et al. (2017) where components of the integration were fish (*O. niloticus, C. carpio and C. gariepinus*)), livestock's (Lohman brown chicken) and vegetables (maize and onion), the authors reported that:

- Total profit from the integrated system was 12,030 ETBirr (1 Birr=0.44 USD) while the profit farmers get from the sole maize production from the same plot of land was 1300 ETB.
- the poultry manured ponds gave significantly better growth rate in both O. *niloticus* and *C. carpio* species
- the overall farm production was 8 tons of fish/ha/year, 233eggs/hen/year, 10800 kg onion/ha/year

The authors indicated in their studies that IAA farms were significantly more efficient compared to non-IAA farms. IAA farms also had higher total factor productivity, higher farm income per hectare, and higher returns to family labor.

3.3.3 Integrated Multi-trophic Aquaculture (IMTA)

Integrated multitrophic aquaculture is a resource recycling system in which discharged nutrients from higher trophic levels become input to the lower trophic levels (Reiriz 2013; Melaku and Natarajan 2019). IMTA involves the cultivation of different species in the same aquaculture system to create a balanced ecosystem. For example, finfish are farmed alongside shellfish and seaweeds. The fish provide nutrients for the shellfish and seaweeds, while these species help in removing excess nutrients and waste from the water. This system is mainly practiced in developed countries where there is an intensive cage culture of finfishes like salmon (Handa et al. 2012).

Box (2): Case studies from South Africa and Kenya

Prinsloo and Schoonbee (1987) conducted a study in South Africa where components of the integration were 4 species of carps, pecking ducks and 3 types of vegetables (Tomato, spinach and lettuce), the authors reported that:

- Ducks grew to an average weight of 2.6 kg in 55 days
- Fish production exceeded 19.5tonnes/hectare/year with substantial yield of vegetable production
- Ten batches of Peking ducks at a density of 2500 ducks/ha of water over a period of 6 months with an average yield of 32.184 tons/ha/year
- Mean feed conversion factor (FCR) of 3.05

Another study by Muendo et al. (2011) In Kenya, the authors showed that:

- Farms with IAA systems were found to have a drop by 23-35% of nutrient consumption rates, increased agricultural production by 2--26% and an increase of the overall farm food production by 22-70%.

Generally, the author's' assessment indicated that IAAS practices have increased farm productivity, increased household incomes, improved food and nutritional security through production and consumption of fresh fish, ducks and the food crops grown around fish ponds.

3.3.4 Aquaponics

Aquaponics 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 (Atique 2022).

The basic principle of aquaponics 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 (Panigrahi 2016; Goddek 2019; Krastanova et al. 2022).

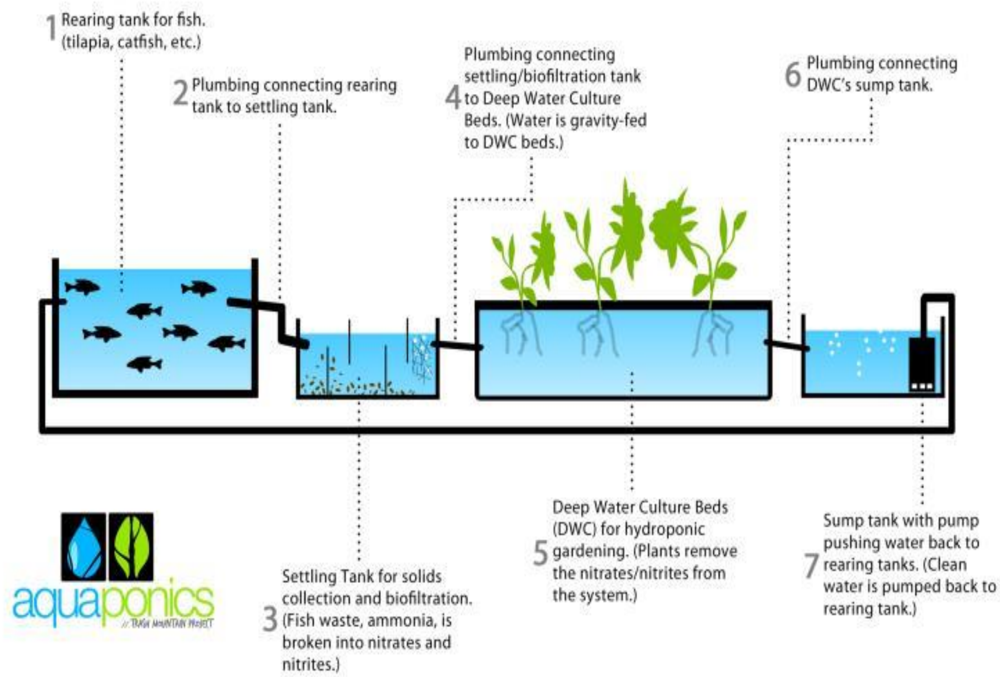

Figure 2: General setup of an aquaponics system (Panigrahi et al. 2016)

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. Aaquaponic has the advantage 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 4).

Table (4) Comparison between hydroponics, aquaculture and aquaponics

System	Advantages	Disadvantages
Hydroponics	• Produces a high crop yield in a small space.	• Using expensive fertilizers.

	• Highly water use efficient for crop production	
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.
Aquaponics	• 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.

Current studies on the aquaponic 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 availability of enough knowledge and experience of the fish, bacteria, and plant components at the individual and systems levels (Sharma et al. 2018; Goddek et al. 2019; Atique et al. 2022).

3.4.4.1 Species in aquaponics

A. **Aquaculture**

Currently, some fish species are frequently used in aquaponic system. In 2014, a study conducted in 44 countries revealed that the most prevalent fish species in aquaponic were tilapia (55%) followed by ornamental fish (koi, goldfish and tropical fish) (48%) (Love et al. 2014). Other studies reported that catfish (25%), bluegill (15%), trout (10%) and some other aquatic animals (18%) are also used (Love et al. 2015 and Villarroel et al. 2016). The most common farmed fish in aquaponics is presented in table (5).

Tilapia is popular in the aquaponics industry due to its omnivorous nature, low cost, robustness, and rapid growth rate as it has a lower feed conversion ratio (FCR) of approximately 1.0 compared to large ruminants, whose FCR is 8.8. (Rakocy et al 2004). Moreover, Tilapia can thrive in various water conditions and a wide range of water temperatures (15-30 °C) and free ammonia (NH_3) concentrations (0.2 − 3.0 mg/L) for short period, making them adaptable to different climates and locations (Popma and Masser 1999).

Table (5) Most common farmed fish in aquaponics.

Scientific name	Common name	Most commonly farmed fish (ranked)	References
Oreochromis niloticus	Nile tilapia	First place	Love et al. (2014, 2015), Villarroel et al. (2016)
	Ornamental fish	Second place	Love et al. (2014, 2015)
Silurus glanis	European catfish	Third place	Love et al. (2014, 2015)

B. Vegetation (Plants)

Many types of plants can grow in an aquaponics system; However, the choice depends on the stocking density of the fish and the concentration of nutrients available in the aqueous solution. Nitrate requirements for plants vary during their growth phases depending on the surface area of the roots and the type of plant. For example, leafy vegetables require higher amounts of nitrate than fruit vegetables (Li et al. 2019).

The most favored and prominent plants in the aquaponic systems are herbs and spices for cooking purposes (e.g. basil, coriander, chives, parsley, purslane and mint), leafy vegetables (e.g. lettuce, spinach, chard, Chinese cabbage and watercress) and medicinal plants (e.g. aloe vera, chamomile, feverfew, lavender, ginger, and sage). These plants grow well in water with high nitrogen concentration, have a short-term growing period, do not require high nutrient contents and there is substantially a high consumer demand (Bailey and Ferrarezi 2017). Moreover, in well stocked and established aquaponic systems, the vegetables with higher nutritional requirements such as tomatoes, peppers and cucumber can perform well (Licamele 2009).

Love et al. (2014 and 2015), Villarroel et al. (2016) and Danner et al. (2019) have outlined the most commonly grown plant species in aquaponics (Table 6). Experimental data generally showed a higher yield of crops in aquaponics than in hydroponics or conventional agriculture (Buzby 2016; Johnson 2017).

Table (6) Most commonly grown crops in aquaponics.

Scientific name	Common name	Crop	Most commonly grown crops (ranked)	References
Ocimum basilicum	Basil	Herb	First place	Love et al. (2014, 2015)
Lactuca sativa	Lettuce	Leaf vegetable	Second place	Villarroel et al. (2016)
Solanum lycopersicum	Tomato	Fruit vegetable	Second place Third place	Love et al. (2014), Villarroel et al. (2016)
	Salad greens	Leaf vegetable	Second place Third place	Love et al. (2014, 2015)
	Herbs	Leaf vegetable	Third place First place	Love et al. (2015) Villarroel et al. (2016)

3.4.4.2 Water quality in aquaponics

In aquaponic systems, a large production of plants and fish could be attained if there is a prominent balance between dissolved nutrients and quality of water. Thus, proper monitoring and management of certain water quality variables are essential in order to have a functional system and obtain high performance in raising fish and plants. it is also necessary to have enough background on the effects of these parameters and how they interact.

The ranges of the most important water quality parameters that affect the health and productivity of aquaponics systems are shown in Table (7). These parameters should be carefully monitored particularly key water quality parameters such as pH, temperature and total ammonia nitrogen (TAN) to avoid sudden changes in their values and losses in productivity. (Odema et al. 2017; Ibrahim et al. 2023).

Table (7) Water quality ranges for aquaponics systems

Parameters	range	Parameters	range

pH	6.5 – 7.0	**Total Ammonia-Nitrogen (TAN)= NH_3+ NH_4-N**	<2 mg/L
Water Temperature (T)	17 °C – 30 °C	**Nitrites (NO_2)**	< 1 mg/L
Dissolved Oxygen (DO)	>4 mg/L	**Nitrates (NO_3)**	50 mg/L – 100 mg/L
Electrical conductivity (EC)	1100 – 2000 µS/cm	**Flow**	1 – 2 L/min
Total dissolved solids (TDS)	< 1000 mg/L	**Air Temp.**	18 °C – 30 °C
Salinity	0 -2 ppt	**Relative humidity**	60% - 80%
Water hardness	50 – 150 mg/L as $CaCO_3$	**Carbon dioxide (CO_2)**	340 ppm – 1300 ppm
Alkalinity	50 – 150 mg/L as $CaCO_3$	**Light Intensity**	600 PPFD – 900 PPFD (PPFD is the Photosynthetic Photon Flux Density)

4. 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 (Shaalan 2017; Adeleke et al. 2020 ; Wally and Akingbe, 2022). In Egypt, the aquaculture is practiced in almost all different production systems that have been described in previous paragraphs. (Soliman and Yacout 2016; Shaalan 2017).

Egypt's total fish production increased by 17.64 % from 1.7 million metric tons (MMT) in 2016 to 2.0 MMT in 2020 (Figure 2). 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 (GAFRD 2022; Wally and Akingbe, 2022).

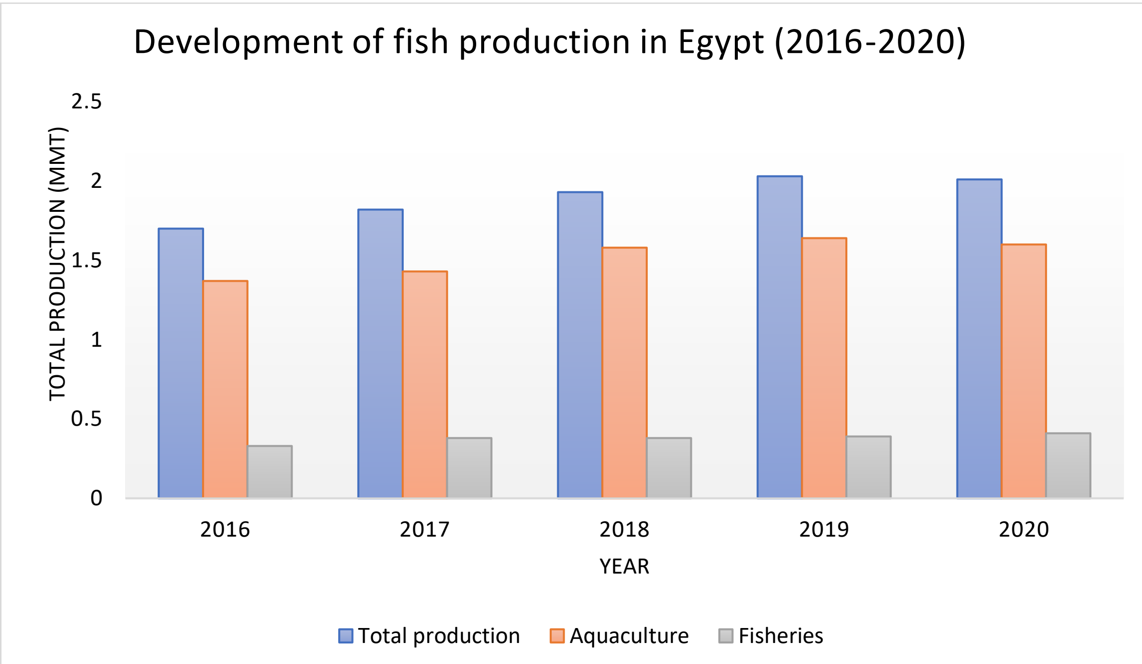

Figure (2) Development of Fish Production in Egypt (2016-2020)
Source: GAFRD (2020)

IAA systems in Egypt

According to Ibrahim et al. (2023), 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 (Corner et al. 2020).

Moreover, brackish groundwater with salt concentration of 25g/L is also used in IAAS as Salicornia crops (a halophytic vegetables 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 (Corner et al. 2020; van der Heijden et al.2012).

Furthermore, aquaponics is a relatively new technique in Egypt for growing aquatic species and soilless plants in a single integrated system. Commercial aquaponics 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 (table 4). In Egypt, some trials (Box 3) have been initiated by national institutions and the private sector to highlight that aquaponics could be an ally or alternative to traditional agriculture and land reclamation (Goda et al. 2015; El-Essawy et al. 2019; Corner et al. 2020). 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.

Box (3) Case studies on aquaponics in Egypt

The study conducted by Goda et al. (2015), aimed to highlight some of the technical, biological, social, and economic features of aquaponic systems in Egypt as a method of integrated aquaculture agriculture system (IAAS). Two systems using renewable energy were studied: 1) Integrated Multi-Trophic Aquaculture, IMTA– Nutrient Film Technique (NFT) System and 2) IMTA– Floating Raft System (FRS) in comparison with traditional soil culture system.

The study included different fish species (e.g., tilapia, catfish, mullets, prawn and clams) and plants (broccoli, cucumber, tomato, eggplant and pepper). The results revealed that IMTA–FRS and IMTA–NFT systems were able to bear costs and attain excess economic capacity of 53% and 47% respectively. Moreover, the results confirmed the potentiality of these two systems to tolerate the burden of increased costs of production and bear the risks of lower fish and vegetables prices.

Another study was conducted by El-Essawy et al. (2019). The study discussed the possibility of applying the aquaponic system as an alternative to traditional agriculture in Egypt. A comparative pilot study examined two aquaponic systems (deep water culture system and integrated aquaculture agriculture system, IAAS). The crop quality (e.g., vitamins, heavy metals, and pesticides residues) of the two systems was compared between each other, as well as to that of the commercially organic crops available in the market.

Results indicated that both systems produced safe high-quality organic food. The economic feasibility analysis indicated that IAAS produced more crops with a wider variety of almost 20% less capital expenditure and operational expenditure costs. Fish production in both systems was similar, yet slightly higher in Deep Water Culture. Although, on the short term, aquaponics entails relatively high capital and operational expenditure costs compared to traditional agriculture; however, it is more profitable on the long term, saving up to 85% of the water wasted due to traditional farming techniques.

Conclusion

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 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.

- Aquaponics 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. Aquaponics 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 country strategy. These encompass the efficient use and better management practices of blue and green water.

References

Abdul-Rahman S, Saoud IP, Owaied MK, Holail H, Farajalla N, Haidar M, Ghanawi J, (2011) Improving Water Use Efficiency in Semi-Arid Regions through Integrated Aquaculture/Agriculture. J Appl. Aquacult., 23, 3, 212–230.

Adeleke B, Andersson DR, Moodley G, Simon Taylor S (2020) Aquaculture in Africa: A Comparative Review of Egypt, Nigeria, and Uganda Vis-À Vis South Africa, Reviews in Fisheries Science & Aquaculture. https://doi.org/10.1080/23308249.2020.1795615

Ahmed N, Thompson S, Glaser M (2019) Global aquaculture productivity, environmental sustainability, and climate change adaptability. Environ. Manag., 63, 159–172.

Ahmed N, Ward JD, Saint CP (2014) Can integrated aquaculture-agriculture (IAA) produce "more crop per drop"? Food Sec. 6:767–779. The final publication is available at link.springer.com".

Ahmed N, Muir JF, Garnett ST (2012) Bangladesh needs a "blue-green revolution" to achieve a green economy. Ambio, 41, 211–215.

Ahmed N, Granett ST (2011) Integrated rice-fish farming in Bangladesh: Meeting the challenges of food security. Food. Secur. 3, 81-92**.** DOI 10.1007/s12571-011-0113-8

Ahmed N, Wahab MA, Thilsted SH (2007) Integrated aquaculture-agriculture systems in Bangladesh: Potential for sustainable livelihoods and nutritional security of the rural poor. Aquacult. Asia. 12:15–23.

Akegbejo-Samsons Y (2010) Rice-fish production strategies in the coastal floodplains of Ondo State, Nigeria. Bamako: Second Africa Rice Congress. https://api.semanticscholar.org/CorpusID:55610328

Ali MH, Talukder MSU (2008) Increasing Water Productivity in Crop Production—A Synthesis. Agricultural Water Management, 95, 1201-1213.

Atique F, Lindholm LP, Pirhonen J (2022) Is Aquaponics Beneficial in Terms of Fish and Plant Growth and Water Quality in Comparison to Separate Recirculating Aquaculture and Hydroponic Systems? Water, 14, 1447. https://doi.org/10.3390/w14091447

Bailey DS, Ferrarezi RS (2017) Valuation of vegetable crops produced in the UVI commercial aquaponic system. *Aquac*. Reports 7(c): 77-82.

DOI: 10.1016/j.aqrep.2017.06.002

Barange M, Bahri T, Beveridge MCM, Cochrane AL, Funge-Smith S, Paulain F (2018) Impacts of Climate Change on Fisheries and Aquaculture, Synthesis of Current Knowledge, Adaptation and Mitigation Options. FAO Technical paper 627, Rome, Italy.
Berg H (2002) Rice monoculture and integrated rice-fish farming in the Mekong delta, Vietnam – economic and ecological considerations. Ecological Economics, 41: 95–107.

Brauman KA, Siebert S, Foley JA (2013) Improvements in crop water productivity increase water sustainability and food security—a global analysis. Environ. Res. Lett. 8 (2): 1-7. http://doi10.1088/1748-9326/8/2/024030

Brummett RE (1997) Farming fish to save water. Bioscience. 47, 402.

Buzby K, Waterland N, Semmens K, Lin LS (2016) Evaluating aquaponic crops in a freshwater flow-through fish culture system. Aquaculture.460:15–24. DOI: 10.1016/j.aquaculture.2016.03.046

Cai X, Sharma BR, Matin MA, Sharma D, Gunasinghe S (2010) An Assessment of Crop Water Productivity in the Indus and Ganges River Basins: Current Status and Scope for Improvement; Int Water Management Institute, Rep Project CGIAR Challenge Program Water Food: Colombo, Sri Lanka.

Chapagain AK, Hoekstra AY (2011) "The blue, green and grey water footprint of rice from production and consumption perspectives," Ecological Economics, Elsevier. 70(4): 749-758.

Corales RG, Juliano LM, Capistrano AOV, Tobias HS, Dasalla NV, Canete SD, Casimero, MC, Sebastian LS (2004) Palayamanan: a rice-based farming systems model for small-scale farmers. Philippine Journal of Crop Science, 29: 21–27.

Corner R, Fersoy H, Crespi V, (Eds) (2020) Integrated agri-aquaculture in desert and arid Lands: Learning from case studies from Algeria, Egypt and Oman. Fish. Aquacult. Circular No. 1195. Cairo, FAO.

Dabbadie L, Aguilar-Manjarrez J J, Beveridge MCM, Bueno PB, Ross L G, Soto D (2018) Chapter 20: Effects of Climate Change on Aquaculture: Drivers, Impacts and Policies. FAO, Rome,Italy.

Danner R, Mankasingh U, Anamthawat-Jonsson K, Thorarinsdottir R (2019) Designing aquaponic production systems towards integration into greenhouse farming. Water. 11(10):2123. DOI:10.3390/w11102123

Deomampo NR (1998) Farming systems, marketing and trade for sustainable aquaculture, p. 201-217. Annex IV-5 of ADB/NACA, 1998. Aquaculture sustainability and the environment. Report on a regional study and workshop on aquaculture sustainability and the environment. Bangkok, Thailand. Asian Development Bank and Network of Aquaculture Centers in Asia-Pacific, 492 p.

De Silva SS (2013) Climate change impacts: challenges for aquaculture. In Proceedings of the Global Conference on Aquaculture 2010. Farming the waters for people and food (pp. 75110). FAO/NACA.

Dey MM, Paraguas FJ, Kambewa P, Diemuth E, Pemsl DE (2010) The impact of integrated aquaculture-agriculture on small-scale farms in Southern Malawi. Agricultural Economics 41(1):67-79. http://doi:10.1111/j.1574-0862.2009.00426.x

El-Essawy H, Nasr P, Sewilam H (2019) Aquaponics: a sustainable alternative to conventional agriculture in Egypt – a pilot scale investigation. Environ. Sci. Pollut. Res. 26, 15872–15883. DOI: 10.1007/s11356-019-04970-0

Elsheikh W (2021) Effects of Climate Change on Aquaculture Production. Eurasian Journal of Food Science and Technology. 5(2):167-173.

FAO (2020) Food and Agriculture Organization. The State of World Fisheries and Aquaculture 2020. In Brief. Sustainability in Action. Rome, Italy.

FAO (2013) Food and Agriculture Organization. FAO statistical yearbook 2013. World food and agriculture. Rome, Italy.

FAO (2009) Food and Agriculture Organization. Climate change implications for fisheries and aquaculture, Overview of current scientific knowledge (eds.). Rome, Italy.

Fapeng L, Chesheng Z, Zongxue X, Shanshan J, Jun X (2013) Remote sensing monitoring on regional crop water productivity in the Haihe River Basin. J. Geog. Sci. 23, 1080–1090

GAFRD (2020) General Authority for Fish Resources Development. Fish Statistics Year Book-2020, 30th Edition. Ministry of Agriculture and Land Reclamation, Cairo, Egypt.

Goda AM, MA, Mohamed S, Hassaan MS, Sharawy Z (2015) Bio Economic Features for Aquaponic Systems in Egypt. Turkish Journal of Fisheries and Aquatic Sciences 15: 525-532. DOI: 10.4194/1303-2712-v15_2_40

Goddek S, Joyce A, Kotzen B, Burnell GM (Eds.) (2019) Aquaponics Food Production Systems, Combined Aquaculture and Hydroponic Production Technologies for the Future. Springer International Publishing: Cham, Switzerland. https://doi.org/10.1007/978-3-030-15943-6

Godfray HCJ, Beddington JR, Crute IR (2010) Food security: the challenge of feeding 9 billion people. *Sci*. 327, 812–818.

Guyondet T, Comeau LA, Bacher C, Grant J, Rosland R, Sonier R (2018) Climate change influences carrying capacity in a coastal embayment dedicated to shellfish aquaculture. Estuar. Coasts 38, 1593–1618. DOI: 10.1007/s12237-014-9899-x

Halwart M (2020) Fish farming high on the global food system agenda in 2020. FAO Aquaculture Newsletter. Rome, Italy. 61: II–III

Halwart M, Gupta M (2004) Culture of Fish in Rice Fields. Rome: FAO; Penang: WorldFish. https://www.researchgate.net/publication/23550931_Culture_of_Fish_in_Rice_Fields

Handa A, Min H, Wang X, Broch OJ, Reitan KI, Reinertsen H (2012) Incorporation of fish feed and growth of blue mussels (*Mytilus edulis*) in close proximity to salmon (*Salmo salar*) aquaculture: Implications for integrated multi-trophic aquaculture in Norwegian coastal waters. Aquaculture, 356.

Handisyde N,Telfer T C, Ross LG (2017) Vulnerability of aquaculture related livelihoods to changing climate at the global scale. Fish. 18: 466–488. DOI: 10.1111/faf.12186

Hanjra MA, Qureshi ME (2010) Global water crisis and future food security in an era of climate change. Food Policy 35:365–377

Hu L, Ren W, Tang J, Li N, Zhang J, Chen X (2013) The productivity of traditional rice-fish co-culture can be increased without increasing nitrogen loss to the environment. Agriculture, Ecosyst. Environ. 177, 28–34.

Ibrahim LA, Abu-Hashim M, Shaghaleh H, Elsadek E, Hamad AAA, Alhaj Hamoud YA (2023) Comprehensive Review of the Multiple Uses of Water in Aquaculture-Integrated Agriculture Based on International and National Experiences. Water 15, 367. https://doi.org/10.3390/w15020367

Igbadun HE, Mahoo HF, Tarimo AKPR, Salim BA, (2006) Crop water productivity of an irrigated maize crop in Mkoji subcatchment of the Great Ruaha River Basin, Tanzania. *Agric. Water Manag*., 85, 141–150.

Johnson G, Buzby K, Semmens, K, Holaskova, Waterland NL (2017) Evaluation of lettuce between spring water, hydroponic, and flow-through aquaponic systems. Int. J. Veg. Sci. 23(1):456–470. DOI:10.1080/19315260.2017.1319888

Kangmin L (2010) Extending integrated fish farming technologies to mariculture in China. Biotechnology Vol. IX, Encyclopedia of Life Support Systems. http://www.eolss.net/sample-chapters/c17/e6-58-08-10.pdf

Kibria G, Haroon YAK, Dayanthi, N. (2017) Climate change impacts on tropical and temperate fisheries, aquaculture, and seafood security and implications–a review. Livestock Res. Rural Dev. 29:22.

Kilemo DB (2022) The Review of Water Use Efficiency and Water Productivity Metrics and Their Role in Sustainable Water Resources Management. Open Access Library Journal, 9: e7075. https://doi.org/10.4236/oalib.1107075

Krastanova M, Sirakov I, Ivanov S, Yarkov D, Orozova, P (2022): Aquaponic systems: biological and technological parameters. Biotechnology and Biotechnological Equipment 36(1):305-316. http://doi:10.1080/13102818.2022.2074892

Kumar Mk (2021) Conceptual issues in water use efficiency and water productivity (chapter 3). In: Current Directions in Water Scarcity Research. Volume 3, Pages 49-63. Elsevier. https://doi.org/10.1016/B978-0-323-91277-8.00005-8

Kumar K, Ayyappan S (1998) Current practices in integrated aquaculture from India. Working paper no.5. Bhubaneswar: Central Institute of Freshwater Aquaculture. India. https://www.scribd.com/document/160656465/Integrated-Fish-Farming-Current-Practices#

Li C, Zhang B, Luo P, Shi H, Li L, Gao Y, Lee CT, Zhang Z, Wu W (2019) Performance of a pilot-scale aquaponics system using hydroponics and immobilized biofilm treatment for water quality control. J. Clean. Prod. 208: 274–284. https://doi.org/10.1016/j.jclepro.2018.10.170

Licamele JD (2009) Biomass production and nutrient dynamics in an aquaponics system (Ph.D. thesis). Tucson, University of Arizona(AZ), USA. http://hdl.handle.net/10150/193835

Little DC, Edwards P (2004) Integrated livestock-fish farming systems. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. https://www.researchgate.net/publication/259999240

Liu D, Tang R, Xie J, Tian J, Shi R, Zhang K (2020) Valuation of ecosystem services of rice-fish coculture systems in Ruyuan County. China. Ecosyst. Ser. 41, 101054.

Long P, Huang H, Liao X, Fu Z, Zheng H, Chen A, Chen C (2013) Mechanism and capacities of reducing ecological cost through rice-duck cultivation. Journal of the Science of Food and Agriculture, 93, 2881–2891.

Love DC, Fry JP, Li X, Hill ES, Genello L, Semmens K, Thompson RE (2015) Commercial aquaponics production and profitability: findings from an international survey. Aquaculture. 435:67-74. https://doi.org/10.1016/j.aquaculture.2014.09.023

Love DC, Fry JP, Genello L, Elizabeth S, Hill ES, Frederick JA, Li X, Semmens K (2014) An international survey of aquaponics practitioners. In PLoS One. 9(7): e102662-10. https://doi.org/10.1371/journal.pone.0102662

Maulu S, Hasimuna OJ, Haambiya LH, Monde C, Musuka CG, Makorwa TH, Munganga BP, Phiri KJ, Nsekanabo JD (2021) Climate Change Effects on Aquaculture Production: Sustainability, Implications, Mitigation, and Adaptations. Front. Sustain. Food Syst.5:609097. DOI:10.3389/fsufs.2021.609097

Melaku S, Natarajan P (2019) Status of integrated aquaculture - Agriculture systems in Africa. International Journal of Fisheries and Aquatic Studies. 7(4):263-269.

Moayeri M, Siadat H, Pazira E, Abbasi F, Kaveh F, Oweis TY (2011) Assessment of maize water productivity in southern parts of the Karkheh river basin, Iran. *World Appl Sci J*, 13, 1586–1594.

Mohanty RK, Verma HN, Brahmanand PS (2004) Performance evaluation of rice-fish integration system in rainfed medium and ecosystem. Aquacult., 23, 125–135.

Molden, DJ, Oweis TJ, Steduto P, Bindraban PS (2010) Improving Agricultural Water Productivity: Between Optimism and Caution. Agricultural Water Management 97(4):528-535. https://doi.10.1016/j.agwat.2009.03.023

Molden JD, Oweis T, Steduto P, Kijne J (2007) Pathways to increase agricultural water productivity. In book: Water For Food Water For Life" A comprehensive assessment of water management in Agriculture. Publisher: EARTHSCAN, UK. https://www.researchgate.net/publication/266382480

Muendo PN0, Stoorvogel JJ, Verdegem MCJ, Mora-Vallejo A, Verreth JAJ (2011) Ideotyping integrated aquaculture systems to balance soil nutrients. Journal of Agriculture and Rural Development in the Tropics and Subtropics112:157-168.

Mulokozi D (2021) Integrated Agriculture and Aquaculture Systems (IAA) for Enhanced Food Production and Income Diversification in Tanzania, Ph.D. Thesis, Department of Physical Geography, Stockholm University, Stockholm, Sweden. https://stockholmuniversity.zoom.us/j/68951088257

Ngoan LD (2018) Effects of climate change in aquaculture: case study in Thua Thien Hue Province, Vietnam. Biomed. J. Sci. Tech. Res. 10:2018. DOI: 10.26717/BJSTR.2018.10.001892

Odema M, Adly I, Wahba A, Ragai H (2017) Smart Aquaponics System for Industrial Internet of Things (IoT). Advances in Intelligent Systems and Computing, Proc. Int. Conf. Adv. Intell. Syst. Infor. 639: 844-854.

Ofori J, Abban EK, Otoo E, Wakatsuki T (2005) Rice-fish culture: an option for smallholder Sawah rice farmers of the West African lowlands. Ecol. Eng. 24: 235–241.

Pant J, Demaine H, Edwards P (2004) Assessment of the aquaculture subsystem in integrated agriculture-aquaculture systems in Northeast Thailand. Aquaculture Research. 35:289–298. DOI:10.1111/j.1365-2109.2004.01014.x

Panigrahi GK, Panda S, Padhi SN (2016): Aquaponics: An innovative approach of symbiotic farming. International Journal of Bioassays 5(09):4808 http://doi:10.21746/ijbio.2016.09.005

Phong LT, van Dam AA, Udo HMJ, van Mensvoort MEF, Tri LQ, Steenstra FA, van der Zijpp AJ (2010) An agroecological evaluation of aquaculture integration into farming systems of the Mekong Delta. Agri. Ecosys. Environ., 138: 232–241.

Phong LT, Udo HMJ, van Mensvoort MEF, Tri LQ, Bosma RH, Nhan DK van der Zijpp AJ (2008) Integrated agriculture aquaculture systems in the Mekong Delta, Vietnam: an analysis of recent trends. Asian J Agric. Dev., 4: 51–66.

Popma T, Masser M (1999) Tilapia: life history and biology. Southern Regional Aquaculture Center. SRAC Publication No. 283: United States Department of Agriculture. USA.

Prinsloo JF, Schoonbee HJ (1987) Investigations into the feasibility of duck-fish-vegetable integrated agriculture-aquaculture system for developing areas in South Africa. Water SA. 13(2):109-118.

Purba S (1998) The economics of rice fish production systems in North Sumatra, Indonesia: an empirical and model analysis. Farming Systems and Resource Economics in the Tropics, Vol. 31. Wissenschafverlag Vauk Kiel KG.

Rakocy J, Shultz RC, Bailey D, Eric S (2004) Aquaponic production of tilapia and basil: comparing a batch and staggered cropping system. Acta Hortic. 648:63–69. https://api.semanticscholar.org/CorpusID:45134183

Reiriz MJF, Robinson SMC, Cranford PJ, Labarta U (2013) Absorption efficiency of mussels *Mytilus edulis* and *Mytilus galloprovincialis* cultured under Integrated Multi-Trophic Aquaculture conditions in the Bay of Fundy (Canada) and Ria Ares-Betanzos (Spain). Aquaculture. 388:182-192.

Rutkayova J, Vácha F, Maršálek M, Beneš K, Civišová H, Horká P (2017) Fish stock losses due to extreme floods–findings from pondbased aquaculture in the Czech Republic. J. Flood Risk Manage. 11: 351–359. DOI: 10.1111/jfr3.12332

Sae-Lim P, Kause A, H.Mulder A, Olesen I (2017) Breeding and genetics symposium: climate change and selective breeding in aquaculture. J. Anim. Sci. 95, 1801–1812. DOI: 10.2527/jas2016.1066

Seggel, A, De Young C, Soto D (2016) Climate Change Implications for Fisheries and Aquaculture: Summary of the Findings of the Intergovernmental Panel on Climate Change Fifth Assessment Report. FAO Fisheries and Aquaculture Circular No. 1122. Rome, Italy.

Shaalan M, El-Mahdy M, Saleh M, El-Matbouli M (2017) Aquaculture in Egypt: Insights on the Current Trends and Future Perspectives for Sustainable Development, Reviews in Fisheries Science & Aquaculture. http://dx.doi.org/10.1080/23308249.2017.1358696

Sharma N., Acharya S, Kumar K, Singh N, Chaurasia OP (2018) Hydroponics as an advanced technique for vegetable production: An overview. J. Soil Water Conserv. 17: 364–371.

Soliman FN, Yacout AD (2016) Aquaculture in Egypt: Status, constraints and potentials. Aquaculture international 24(5). Springer. DOI:10.1007/s10499-016-9989-9

Steduto P, Hsiao TC, Fereres E, Raes D (2012) Crop yield response to water. FAO irrigation and drainage paper 66. Rome: Food and Agriculture Organization of the United Nations.

Sukanya S, **Sabu J (2023)** Climate change impacts on water resources: An overview. In Visualization Techniques for Climate Change with Machine Learning and Artificial Intelligence, chapter 4 (pp.55-76). Elsevier. DOI:10.1016/B978-0-323-99714-0.00008-X

Tran N, Crissman C, Chijere A, Chee HM, Jiau TS, Valdivia RO (2013). Ex-ante assessment of integrated aquaculture agriculture adoption and impact in Southern Malawi. WorldFish. Penang: Work. Pap. AAS-2013-03 CGIAR Res. Program Aquat. Agric. Sys. Malaysia. https://www.researchgate.net/publication/257965404_Exante_assessment_of_integrated_aquaculture-agriculture_adoption_and_impact_in_Southern_Malawi

Troell M, Eide A, Isaksen J, Hermansen Ø, Crépin AS (2017) Seafood from a changing Arctic. Ambio 46, S368–S386.

Tugie D, Abebe A, Endebu M (2017) Potential of integrated fish-poultry-vegetable farming system in mitigating nutritional insecurity at small scale farmer’s level in East

Wollega, Oromia, Ethiopia. International Journal of Fisheries and Aquatic Studies. 5(4):377-382.

United Nations (2020): UN World Water Development Report: Water and Climate Change. https://www.unwater.org/water-facts/water-and-climate-change

United Nations (2019) World Population Prospects, Report ST/ESA/SER.A/423 Department of Economic and Social Affairs, Population Division, New York: United Nations UN.

United Nations (2017) World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Population Division, United Nations, New York, NY

Van Der Heijden PGM (2012) Water use at integrated aquaculture agriculture farms. Experiences with limited water resources in Egypt. Global Aquaculture Advocate.4:28-31.

Verdegem MCJ, Bosma RH (2009) Water withdrawal for brackish and inland aquaculture, and options to produce more fish in ponds with present water use. Water Policy, 11, 52–68.

Verdegem MCJ, Bosma RH, Verreth JAJ (2006) Reducing water use for animal production through aquaculture. Water Resou Dev, 22, 101–113.

Villarroel M, Junge R, Komives T, König B, Plaza I, Bittsánszky A, Joly A (2016) Survey of aquaponics in Europe. Water. 8(10):468 https://www.researchgate.net/publication/309336645

Waktola BA, Devi LP, Sreenivasa V, Lakew A (2016) A Study on the Profitability of Fish and Horti-crop Integrated Farming at Nono District, West Shoa Zone, Ethiopia. Greener Journal of Agricultural Sciences. 6(2):041-048.

Wally A, Akingbe OO (2022) An Overview of the Aquaculture Industry in Egypt Country". Report Number: EG2022-0003. USDA.

Zolnikov T, Ramirez-Ortiz D, Raymond J, Chambers D, Brears RC, Cook D (2019): A scoping review on global climate change vulnerability, adaptation, and resiliency. Spotlight on Climate Change Research. DOI:10.35831/sorccr/26072019trz

Zwart SJ, Bastiaanssen WGM (2004) Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. Agric Water Manag. 69, 115–133.