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Climate change impacts on Egyptian aquaculture: challenges, opportunities, and research gaps

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The Egyptian aquaculture sector is subjected to several threats caused by climate change, including a considerable decline in Nile River flow, the sea level rise with the risk of inundation, salty-water intrusion, and the loss of productive farms besides increases in temperatures and decreased water supplies. Due to other urgent issues in Egypt, such as rising food and living expenses and decreased land productivity along the coast, climate change has recently risen to the top of the priority list for national decision-makers. This study aims to highlight climate change impacts on Egyptian aquaculture food systems considering the three sustainability pillars: environmental, economic, and social. We also highlighted the related challenges, opportunities, and research gaps to suggest future needs for further studies. National efforts to improve the local aquaculture sector were presented, as well as potential opportunities for climate change adaptation strategies. The results of this study are intended to assist researchers, policy, and decision-makers in developing strategies that would help in mitigating climate change impacts on the aquaculture sector, to assist sustainably expanding aquaculture food systems, and to enhance local food security. The study reveals that the most productive fish farms in the coastal lakes, mainly brackish, are vulnerable to sea level rise with expectations of salty-water intrusion and disturbance of the cultivated species and loss of aquaculture farms with the consequent environmental and socio-economic impacts. Data availability is one of the main challenges that face academics interested in the aquaculture field. Research fields such as hydrodynamics, remote sensing, geographical information systems and life cycle assessment are promising fields that can contribute to the prediction of climate change impacts on aquaculture systems which helps in developing proper mitigation strategies. Socioeconomic aspects that need to be considered include climate change impacts on living conditions and the physical well-being of small-scale aquaculture farmers, the vulnerability of small-scale farms related to their location, circumstances, disadvantages, and labor challenges. Solar energy usage expansion, development of hatcheries for fry production, expansion in integrated fish farming in reclaimed lands, water-return maximizing and usage of intensive and semi-intensive systems are all some of the strategies adapted by national authorities to mitigate the climate change impacts on local aquaculture sector. Furthermore, the involvement of investors, policy and decision makers is a must to expand the Egyptian aquaculture sector in a sustainable way. Regulations must be set to encourage investments in sustainable technologies as aquaponics, desalination and water recycling. Funds can be provided to stimulate the research and development in in this sector. A national awareness campaign among farmers to explain the potential impacts of climate change on local aquaculture farms and how to adapt is highly recommended, and enhancing collaboration and communication between local stakeholders "researchers, investments, policy makers and farmers" is a must.

KEYWORDS

environmental impacts, social impacts, economic impacts, food security, aquaculture, climate change, Africa, Egypt

1 Introduction

In recent years, climate extremes, environmental degradation and economic shocks, combined with the high cost of nutritious foods and growing inequalities, continue to threaten food security and nutrition. Over 40% of the world's population "about 3.1 billion people" cannot afford a healthy diet (Food and Agriculture Organization (FAO), 2024). Aquatic systems are a valuable provider of vital and nutritional food that can contribute to attaining food security. Therefore, the Food and Agriculture Organization (FAO) adopted the Blue Transformation Program in 2021 with a strategic framework from 2022 to 2031 to maximize the opportunities of the aquatic food systems to enhance food security, improve nutrition, reduce poverty, and support the achievement of the Sustainable Development Agenda 2030. It aims to do so by adopting new strategies on climate change, innovation, and biodiversity (Food and Agriculture Organization (FAO), 2024).

Currently, the global aquaculture production accounts for 130.9 million tons, an equivalent of USD 312.8 billion, a few countries dominate the global aquaculture market, producing more than 89.8% of the total global aquaculture, these countries include: China, Indonesia, India, Vietnam, Bangladesh, the Philippines, the Republic of Korea, Norway, Egypt, and Chile (Food and Agriculture Organization (FAO), 2024; Figure 1).

Egypt is the top aquaculture producer in Africa, the third globally in tilapia production and the sixth in global aquaculture output in 2022. The total production of Egyptian aquaculture exceeds 1.6 million metric tons and valued USD 3.5 billion (Statista, 2024; WorldFish, 2024). Furthermore, aquaculture is the largest single source of fish supply in Egypt accounting for almost 80% of the total fish production of the country (WorldFish, 2024) and becoming a major contributor to Egypt's food security and economy (Chan and Mosbah, 2024; United States Department of Agriculture (USDA), 2022). Although farming takes place in both freshwater and marine, freshwater farming is far more successful than marine aquaculture in Egypt. This is due to that the majority of marine farming still depends on the collection of seed from the wild and the main farmed species are European seabass, gilthead seabream, sole, meagre and penaeid shrimp. On the other hand, the freshwater farming in Egypt cultivates 14 different species of finfish and two species of crustacean, ten are native and six are introduced species. The native species are: Nile tilapia (*Oreochromis niloticus*), blue tilapia (*Oreochromis aureus*), North African catfish (*Clarias gariepinus*), flathead grey mullet (*Mugil cephalus*), thinlip mullet (*Liza ramada*), bluespot mullet (*Valamugil seheli*), European seabass (*Dicentrarchus labrax*), gilthead seabream (*Sparus aurata*), meagre (*Argyrosomus regius*) and penaeid shrimp. The introduced species are: common carp (*Cyprinus carpio*), grass carp (*Ctenopharyngodon idellus*), silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*), black carp (*Mylopharyngodon piceus*) and the giant river freshwater prawn (*Macrobrachium rosenbergii*) (Food and Agriculture Organization (FAO), 2025). Nile tilapia is widely favorable in Egypt and its yield accounts for 75.5% of national aquaculture production reaching 9.5 million tons in 2020, placing Egypt as the third largest worldwide producer of tilapia after China and Indonesia. The remaining 24.5% of Egyptian aquaculture production are mainly Mullets, Carps, Catfish and other (Food and Agriculture Organization (FAO), 2022).

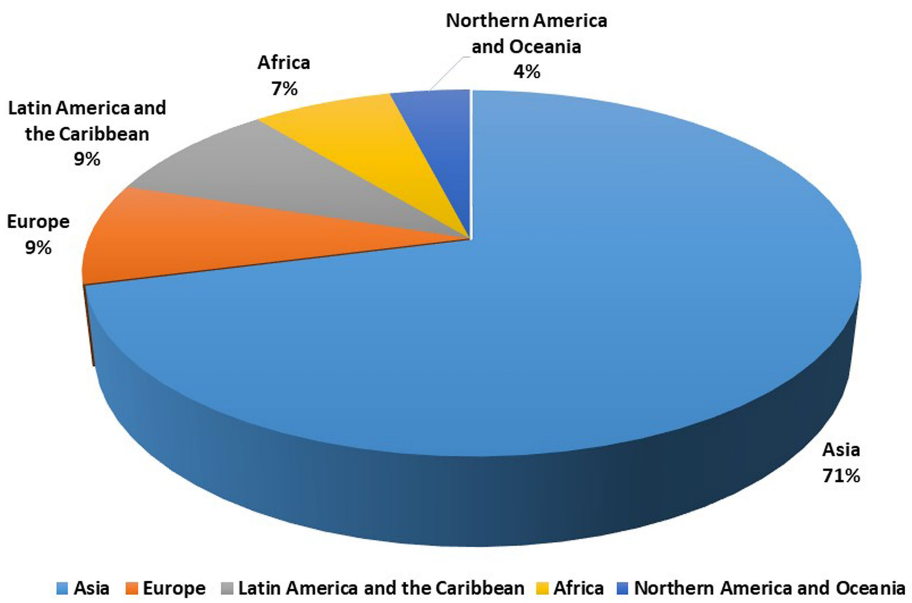

FIGURE 1
Global aquatic Production by region [Based on Food and Agriculture Organization (FAO), 2024].

Despite the high aquaculture yield, Egypt does not export its seafood due to the high rate of self-consumption (Kamal, 2021). Fish has been a longstanding traditional component of the Egyptian diet since the time of the ancient Pharaohs and recently it is the main source of animal protein for lower-income groups. Per capita, fish consumption has nearly tripled in the last three decades. At the same time, Egypt is one of the most populated countries in Africa, its total population exceeds 112 million individuals (World Population Review (WPR), 2024). The country's population is expected to increase in the upcoming years; consequently, the associated food and water requirements will also increase. The need for local sustainable food systems became a must to ensure food security of the local population.

Furthermore, Egypt is one of the most vulnerable countries to the potential impacts of climate change, especially in the aquaculture sector (Mehrim and Refaey, 2023; Food and Agriculture Organization (FAO), 2024). Although Egypt possesses long shores on the Mediterranean and Red Seas and owns many lakes in addition to River Nile crossing its land, most of the aquaculture farms in Egypt are located in the Nile Delta region and are concentrated mainly in the brackish Northern lakes (Lakes Maryut, Idku, Burullus and Manzala) (Figures 2, 3; Table 1). Presented in Figure 3 the location of Egyptian aquaculture farms, with a focus on the northern coastal lakes where most aquaculture farms are located (Food and Agriculture Organization (FAO), 2025). These aquaculture farms contributed with about 81% of fish production in 2018 (Maiyza et al., 2020; Figure 4).

As a result of global sea level rise, wide areas of the Nile Delta coastal zone are expected to be susceptible to saltwater intrusion and inundation, with a wide range of implications. Associated climate change risks may impact aquaculture activities at the national level, influencing the social and economic aspects of local communities both directly (influencing fish stocks, production quantity, and efficiency) and indirectly (impacting fish prices and services required by fishers and fish farmers) (Soliman, 2017).

This work aims to study the current impacts of climate change on brackish aquaculture food systems in Egypt, taking into consideration the environmental, economic and social impacts, highlighting the related challenges, opportunities and research gaps, and suggesting future needs of study. The results of this study will assist policy and decision-makers in adapting strategies that will help in mitigating climate change impacts on the aquaculture sector, assist in sustainably expanding aquaculture food systems, and enhance local and global food security.

2 Study methodology: systematic searching strategy

In this study, a rapid literature review search was performed to identify the challenges, opportunities and research gaps of climate change impacts on aquaculture in Egypt, taking into consideration the three pillars of sustainability "Environmental, economic, and social aspects."

The study was conducted following the systematic literature review procedure suggested by Xiao and Watson (2019) on how to conduct systematic reviews, this approach was employed by several similar studies like Abu Samah et al. (2021) and Predragovic et al. (2024). The

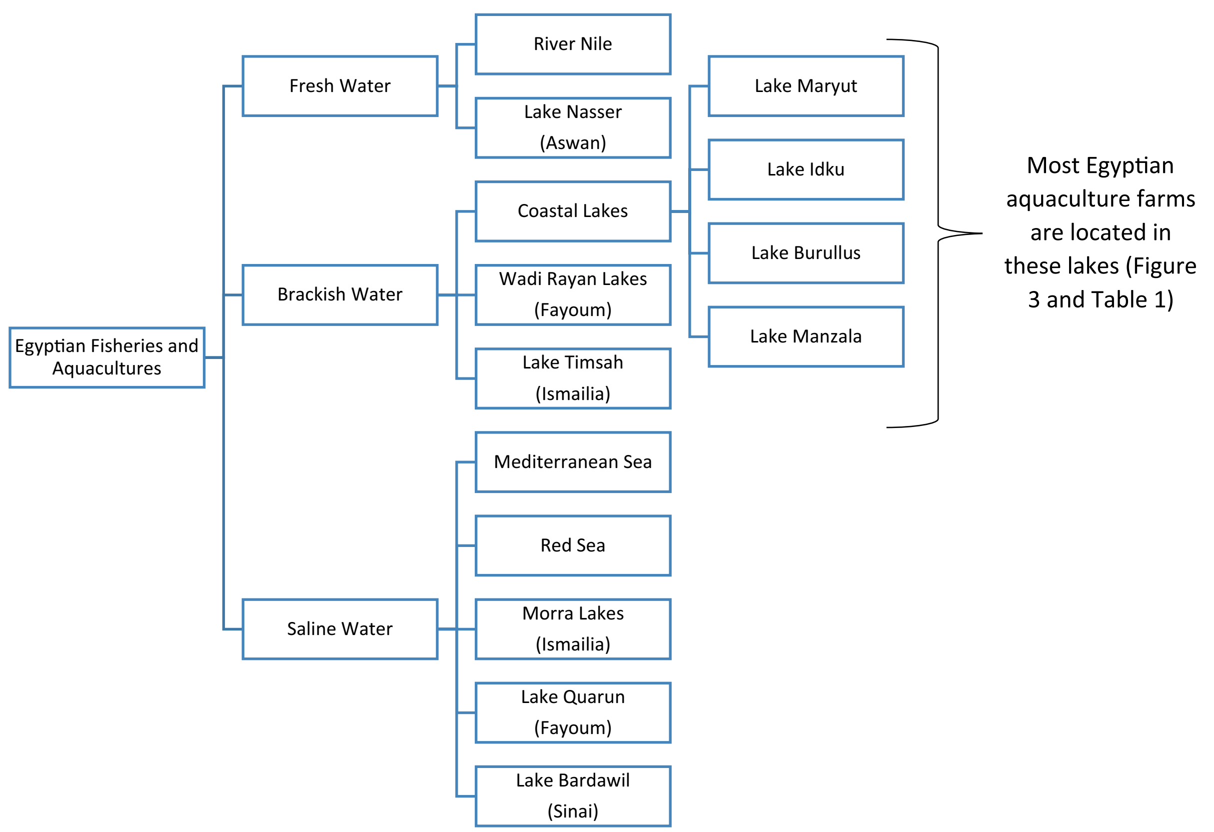

FIGURE 2
Egyptian fisheries and aquacultures.

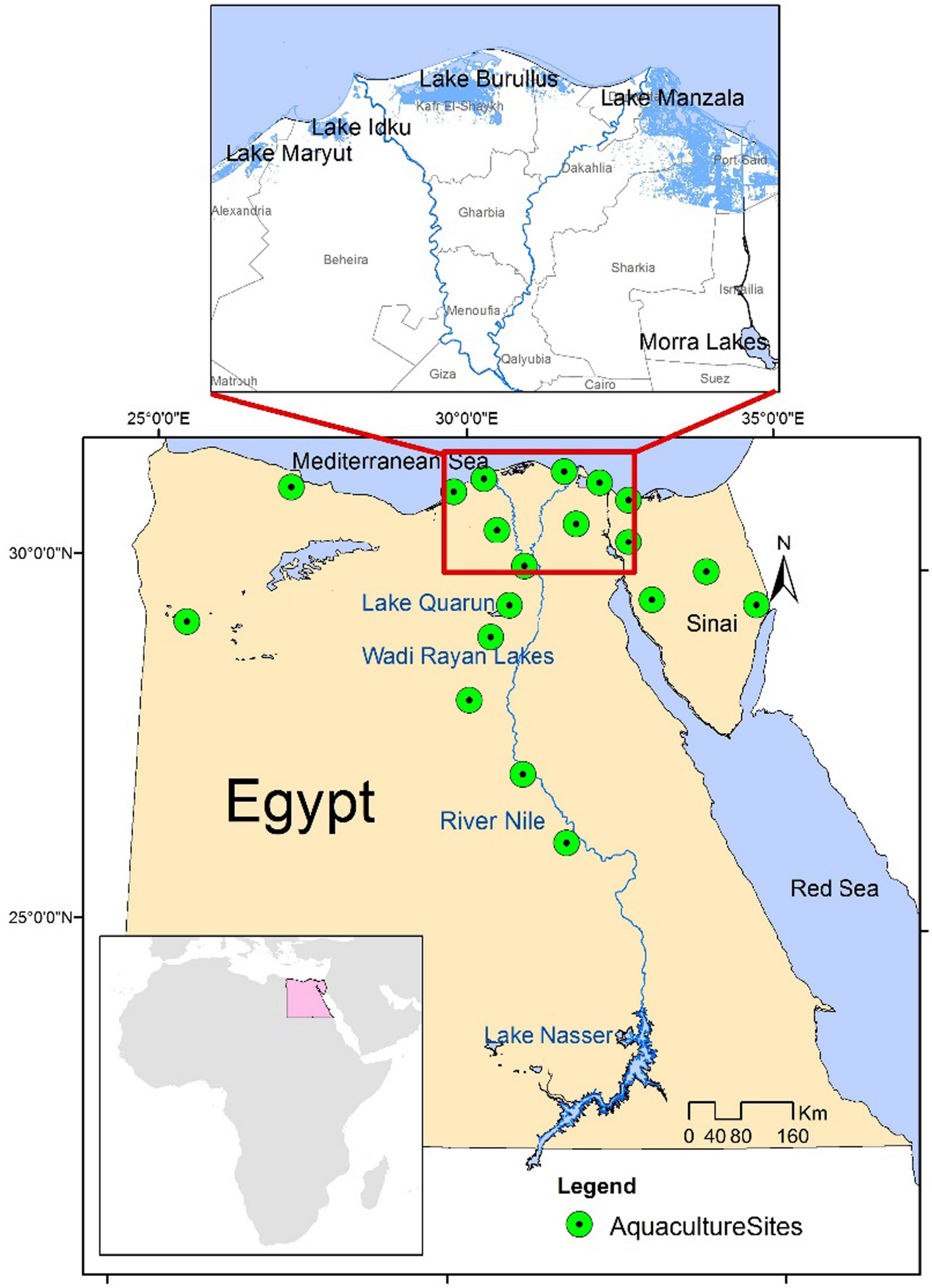

FIGURE 3
Map of Egyptian aquaculture sites.

TABLE 1 Water quality of coastal lakes in 2012 (ESOE, 2015).

Lake name	Temperature (°C)	Salinity (g/L)	pH	Dissolved oxygen (mg/L)	Total nitrogen (mg/L)	Total phosphorus (mg/L)
Lake Maryut	22.17–23.4	1.63–5.89	7.82–8.37	3.75–8	2.8–18.5	57.9–2184.7
Lake Idku	21.85–22.88	1.01–3.81	8.08–8.68	3.4–11.5	3.62–5.82	485.8–1055.86
Lake Burullus	22.45–24.03	0.9–13.93	7.9–8.89	2.6–13.96	2.77–7.51	247.14–1059.03
Lake Manzala	20.8–24.1	1.75–22.6	7.85–8.6	1.9–13.03	3.36–8.26	63.61–881.96

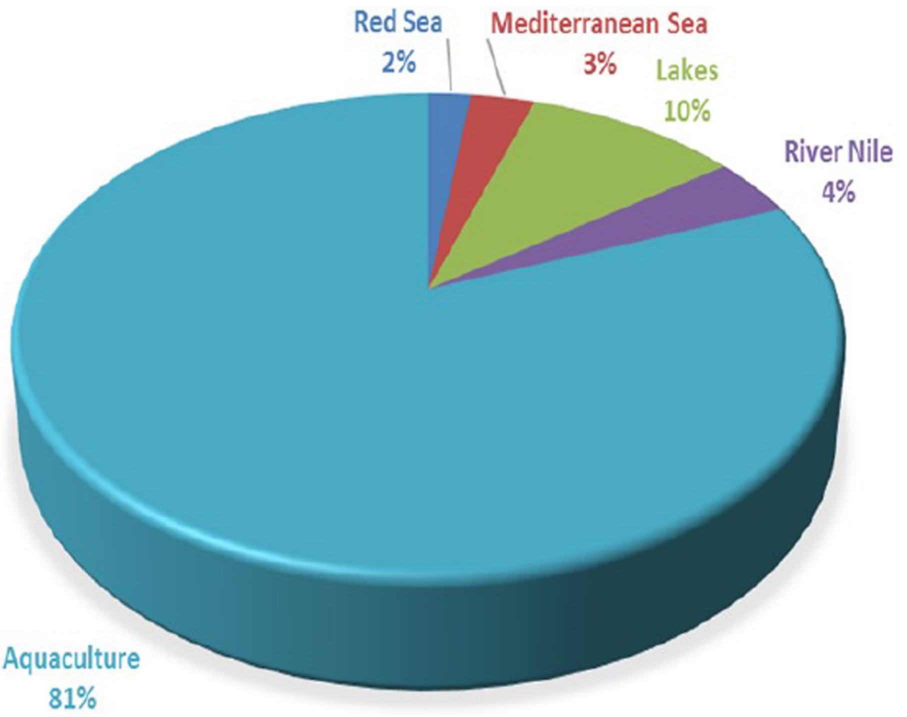

FIGURE 4
Contribution of Egyptian fisheries and aquaculture in fish production in 2018 (Maiyza et al., 2020).

framework for the systematic searching strategy for this approach, which is used in this study, is presented in Figure 5, it includes the following steps:

i Scoping.
ii Literature search and evaluation (identification, screening, and selection).
iii Data extraction, analysis, and results.

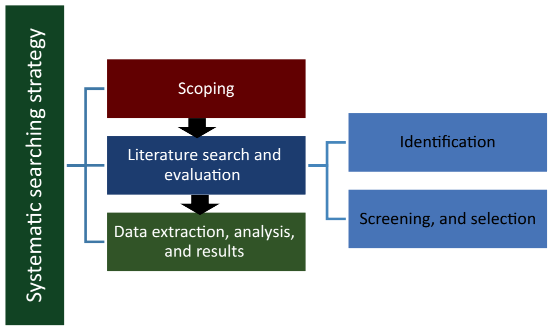

FIGURE 5
Framework for Systematic Searching Strategy.

2.1 Scoping

This review aims to assess the climate change impacts on aquaculture which is one of the main sources of protein in Egypt. The review identifies the challenges and opportunities related to this important food production system and also identifies the research gaps, and future need for studies to expand it in a sustainable way. The main issues addressed by this review are:

- To what extent climate change impacts on aquaculture food systems in Egypt have been covered by research work?
- Which aspects have been investigated?
- How have environmental, economic, and social aspects been studied?
- What are the challenges related to studying climate change impacts on aquaculture food systems in Egypt?
- What are the knowledge gaps and further need for research?

National Egyptian efforts to improve the local aquaculture sector were also considered, and a number of potential opportunities for climate change adaptation strategies were suggested and discussed.

2.2 Literature search and evaluation

The search was conducted in different databases (Science Direct, Web of Science, Scopus, and relevant academic journals) to identify reports and academic peer-reviewed studies on the environmental, economic, and social impacts of climate change on the Egyptian aquaculture sector. Since the article aims to assess climate change impacts on Egyptian aquaculture, special focus was given to literature related to aquaculture production in Africa, and particularly in Egypt.

2.2.1 Identification

Identification of available literature was done using the following keywords and synonyms: climate change OR/AND environmental OR socio-economic OR economic OR social OR life cycle assessment AND impact AND assessment AND aquaculture AND/OR Africa AND/OR

Egypt. The search was restricted to articles published in English. Identification enriches the main keywords used and is important as in order to increase the possibility of obtaining more related articles for the review [Shaffril et al., 2021, Abu Samah et al. (2021)].

2.2.2 Screening and selection

The criteria selected for the screening process consisted of the literature type, language, and year of publication. According to the systematic reviews procedure developed by Xiao and Watson (2019) and followed in this study to avoid outdated information this study focused on the articles published in the period from 2014 to 2024. In total, 115 articles were found related to the scope of the study, they were reviewed and studied (Supplementary Table S1).

2.3 Data extraction and analysis

The data extracted from the 115 articles was assessed and analyzed. Topic wise it was found that 77% of the articles were related to the environmental impacts of the aquaculture sector in Egypt, 18% were concerning the local economic impact, and only 4% were found for local social impacts. Presented in Figure 6a, an overview of publications considered in the study based on topic.

From the geographical perspective, the authors considered it important to take into consideration the articles that relate climate change impacts on Egyptian aquaculture at national level and as part of the aquaculture sector at both global and African levels. It was found that out of the selected 115 articles: 33% addressed the environmental impacts on the aquaculture sector in Egypt as part of the global aquaculture sector, while only 11% considered that as part of the African aquaculture sector. Presented in Figure 6b, an overview of publications considered in the study for Egyptian aquaculture at national, global and African levels.

3 Results and discussion

3.1 Pillars of sustainable aquaculture systems

Despite the great potential of the aquaculture sector in Egypt, several challenges constrain the sector's sustainable growth (Chan and Mosbah, 2024; Mehrim and Refaey, 2023; Soliman and Yacout, 2016a; Soliman and Yacout, 2016b). Presented in Figure 7, a summary of the pillars of sustainable aquaculture systems. In order to ensure the sustainable development of the aquaculture systems, the following points need to be considered:

3.2 Environmental impacts

3.2.1 Climate change

Egypt is facing several threats due to climate change (Smith et al., 2014; Soliman, 2017), including a considerable decline in River Nile's flow and the consequent decrease in freshwater supply, an increase in temperatures and the sea level rise with the risk of the loss of productive agricultural lands mainly those on the Mediterranean coast in the Nile Delta. As the most productive aquaculture farms are located in the coastal lakes on the Mediterranean, they are also exposed to the risk of sea level rise and salty water intrusion as a potential impact of climate change. Figure 8 summarizes climate change impacts on aquaculture and related challenges in Egypt. Further details are presented in the following sections:

3.2.2 Fish seed and fish feed

Expansion in Egyptian aquaculture has been accompanied by increased demand for both fish seed and fish feed (El-Sayed, 2014; Soliman, 2017). According to the United States Department of Agriculture (USDA) (2022), the Egyptian fish feed industry estimates that aquaculture feed demand reached 1.3 MMT in 2020 and is expected to grow to 1.9 MMT in 2025. The local aquaculture feed industry consists of 105 privately-owned feed mills, which provide 95% of fish feed. Feed production has shifted from conventionally pelleted feed (10%) to high-quality extruded feed (90%). About 85% of marine fish feed is formulated locally and contains 25% crude protein. The most common fish feed formulations contain 35–40% soybean meal, which is mainly imported from the United States, Ukraine, Argentina, Uruguay, and Brazil (United States Department of Agriculture (USDA), 2022).

As for fish seed, the recent expansion of Egypt's aquaculture industry has been accompanied by the development of a large number of tilapia hatcheries, all producing sex-reversed all-male fry and fingerlings (Nasr-Allah et al., 2014). It is predicted that climate change will affect the availability of seed from the wild. Therefore, more effort should be made to increase seed production in hatcheries and genetically improve seed selection to adapt to new environmental conditions (Soliman, 2017). Incorporation of modern technology to secure marine species seeds and develop more hatcheries is recommended (Abdel-Hady et al., 2024).

Furthermore, Local users and stakeholders, like traders, crushers, and fish feed producers, demand sustainability and quality of the supply. The availability of local quality fish feeds and seeds is one of the main challenges impacting the expansion of the local aquaculture industry in a sustainable way (Chan and Mosbah, 2024; United States Department of Agriculture (USDA), 2022; Mazumder et al., 2015; Mur, 2014).

3.2.3 Water resources and efficient water use

The availability of water resources is becoming one of the most significant economic and social issues of the century (Abd Ellah, 2020). Egypt is situated in an arid to semi-arid geographical zone. River Nile is the main source of water, providing about 95% of the water supply to Egypt (Adeleke et al., 2018). Limited Egyptian water resources influence the quantity and quality of water available for fish farming (Soliman and Yacout, 2016a; Soliman and Yacout, 2016b; United States Department of Agriculture (USDA), 2022; Chan and Mosbah, 2024). The use of Nile water for aquaculture is prohibited; instead, fish farms are mostly dependent on Egyptian lakes for their waters (mainly brackish) or else in some other cases farmers depend on poor-quality groundwater and agricultural drainage systems. Poor-quality water causes declining fish production, and increases disease outbreaks (Mur, 2014). Water withdrawal for fish framing from lakes can put pressure on the lake ecosystem as in in case of Wadi Rayan lakes in Fayoum province (Abd Ellah, 2016). Therefore, it is important to give more attention

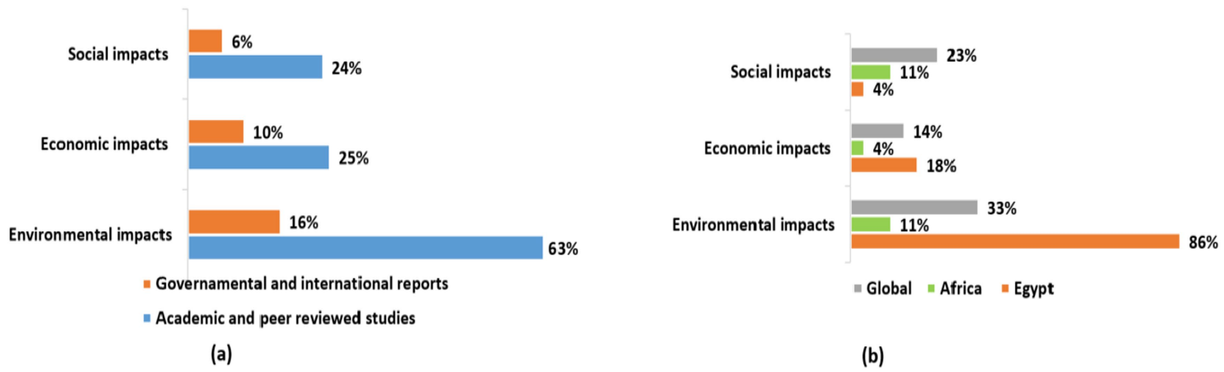

FIGURE 6
An overview of publications considered in the study based on **(a)** Topic and **(b)** Geographic location.

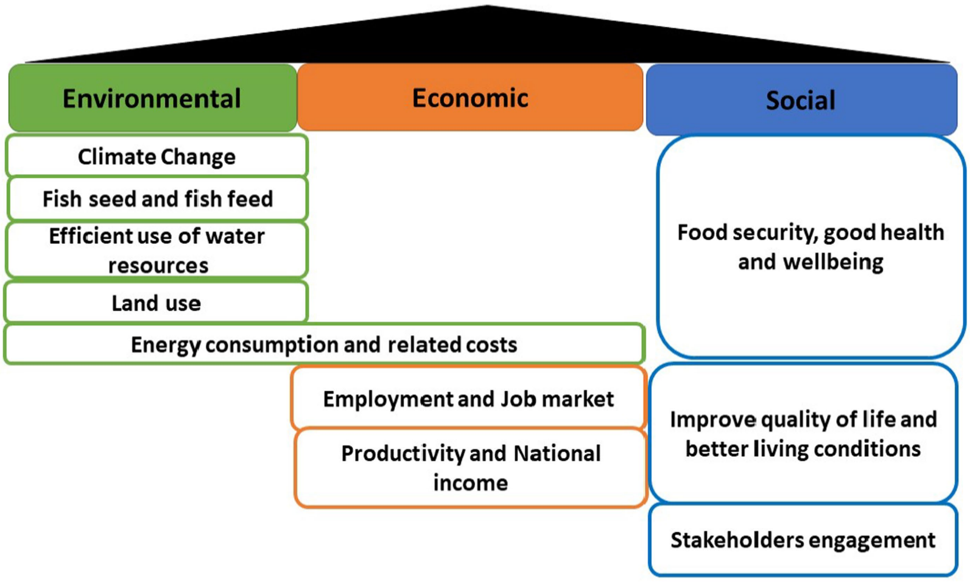

FIGURE 7
Pillars of sustainable aquaculture systems.

to how the expansion of aquaculture farming in Egypt would affect natural fisheries and water withdrawals.

Furthermore, climate change impacts can cause changes in water availability, a decrease in water quality, salty-water intrusion as a result of rising sea levels, and salinization of groundwater supplies which can threaten inland freshwater aquaculture. Aquaculture activities in desert areas depend on groundwater, there are 20 commercial aquaculture farms operating in Egypt's desert regions with a total of 893 hectares, which produce roughly 13,000 tons of Tilapia annually (Mehrim and Refaey, 2023; Mostafa et al., 2021). At the same time, high temperatures caused by climate change can lead to reduced dissolved oxygen levels, increased salinity, greater maturity at a younger age, increased fish metabolic rates, increased risk of disease spread, increased fish mortality, changes in the fish sex ratio, disturbance in spawning season and, consequently, decreased fish production (Mehrim and Refaey, 2023; Islam et al., 2022; Shalby et al., 2020; Khallaf et al., 2020; Chen et al., 2021; Gado and El-Agha, 2021; Maulu et al., 2021; Hasan, 2019; Soliman, 2017).

3.2.4 Scarcity of land

In recent years, the majority of existing Egyptian fish farms have expanded rapidly at the expense of wetlands and coastal sand dunes in the Nile Delta region, these farms are centered around the Delta Lakes Burullus (31%), Manzala (44%) and Idku (15%), as well as the area situated between Gamasa and Damietta (10%) (Figure 2). They reached a total production of 200,000 MT in 2020 (Ali and El-Magd, 2016; United States Department of Agriculture (USDA), 2022).

The Nile Delta region is highly vulnerable to marine erosion, and previous studies record a retreat in the shoreline (Iskander, 2021), reaching about 21 m/year in some areas (White and El-Asmar, 1999), caused by the lack of sediment after the construction of the High Dam in Aswan in the 1960s (Abd Ellah, 2020). Land erosion is also expected to accelerate, leading to the loss of large areas of lowland aquaculture ponds due to their vulnerability to flooding from rising sea levels (Mehrim and Refaey, 2023; Soliman, 2017; Ali and El-Magd, 2016; Smith et al., 2014) with a subsequent impact on the Delta fish farms as

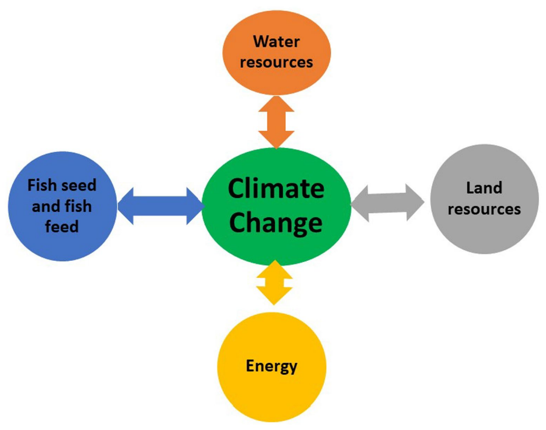

FIGURE 8
Climate change impacts on aquaculture and related challenges.

a result of the low-altitude of the Nile Delta (Adeleke et al., 2018). Negative consequences can occur for fish production as one third of Egypt's fish catches take place in the Mediterranean lakes (Sušnik et al., 2014). Therefore, climate change impacts Egyptian aquaculture through changes in the amount of available land for fish farming and the increased salinity of the water available for fish farming. Adaptation strategies to overcome these impacts are suggested in section 6.

3.2.5 Energy consumption

Several studies pointed out that one of the major issues related to the sustainability of Egyptian aquaculture is energy consumption (Soliman, 2017; Soliman and Yacout, 2016b; Yacout et al., 2016). The aquaculture sector in Egypt depends mainly on fossil fuels for the operation of different processes like water pumping, pond aeration, feed raw material production, feed manufacturing, hatchery, grow-out fish cultivation, and transportation. Fuel costs have risen dramatically in recent years, directly impacting production costs. Expansion in aquaculture sector is associated with energy consumption which has a direct economic impact besides its environmental impacts due to the release of emissions during energy production. To ensure sustainable aquaculture production, improving the efficiency of energy usage in this sector is becoming a must (Soliman, 2017; Yacout et al., 2016; Eltholth et al., 2015).

3.3 Economic impacts

Egyptian Aquaculture is one of the main economic sectors with great potentials not only to provide nutritious food but also to contribute to the national economy (Nasr-Allah et al., 2020). Ali et al. (2020) stated that "Despite the increase in the amount of fish production in Egypt from about 1.45 million tons in 2013 to about 1.82% million tons in 2017, with an increase of 25.0%, the price of fish has increased from about 2 USD/kg in 2013 to about 3/kg in 2017, and reached 2.53 USD/kg in 2023," this increase can be attributed to the increase costs of energy, and feed which directly impacts the local consumer (Statista, 2023). The economic impacts of the aquaculture sector at the national level and the related climate change impacts considered in this study are as follows.

3.3.1 Employment and job market

Aquaculture has an important role in the economy and job market. According to the latest report by Food and Agriculture Organization (FAO) (2024), about 61.8 million people were employed in the primary production sector worldwide, mostly in small-scale operations. Women represent 40% of all those engaged in the aquatic value chain; 24% of fishers and fish farmers were women, with 62% women in the post-harvest sector.

In Egypt, national production provides 93% of local fish needs from different sources (GAFRD, 2019; Soliman and Yacout, 2016a). The rapid development in the aquaculture sector has created over 580,000 job opportunities in the form of direct permanent jobs for farm technicians and skilled labors. Additionally, other employment opportunities have been created in the form of seasonal work during harvesting and other periods of intensive activity, as well as indirect employment in the fish processing, transport, retailing, boat, and net manufacturing sectors (Nasr-Allah et al., 2020; Shaalan et al., 2018; Wally, 2016; WorldFish, 2024). Furthermore, new industries and financial services supporting the aquaculture sector also provide other employment opportunities (Food and Agriculture Organization (FAO), 2020, 2024). The aquaculture value chain provides substantial employment-generating opportunities, including for women and young people.

Nasr-Allah et al. (2020) estimated the substantial employment generation across the aquaculture value chain in Egypt; their study focused on the five governorates responsible for approximately 80% of aquaculture production in Egypt (Kafr El-Sheikh, Sharkia, Beheira, Damietta and Fayoum) (GAFRD, 2018). They reported that for every 100 tons of fish production, approximately 20 fulltime jobs are created. Currently, most of the jobs along the aquaculture value chain in Egypt are performed by men over 30 years of age, with few jobs for women or younger people (Nasr-Allah et al., 2020). The sustainable expansion of this sector will provide more job opportunities for the different categories (men, women and young people) along the entire value chain of aquaculture production.

3.3.2 Productivity and national income

Egypt is one of the countries where aquaculture can generate important socioeconomic benefits (Nasr-Allah et al., 2019). In 2015, fish production contributed about 3.2 billion USD to the Egyptian national Gross Domestic Product (GDP) (GAFRD, 2018). In 2016, this contribution increased, reaching about 3.6 billion USD to Egypt's GDP (GAFRD, 2018). Fish share in total export value increased from 0.04 to 0.16% between 2005 and 2017 and import share increased from 0.75 to 1.00% in the same period. The export value of aquatic products grew 23% a year during 2000–2017 to nearly 40 million USD in 2017; the growth rate was much higher than the 5.9% in Africa and the 6.3% globally (Food and Agriculture Organization (FAO), 2019). According to United Nations World Population Prospects (United Nations World Population (UNWP), 2019), Egypt's population is expected to reach 160 million in 2050, making expansion of local aquaculture systems in a sustainable way a must to meet local demand.

Climate change is expected to have profound economic consequences for Egypt in general (Smith et al., 2014) and for the aquaculture sector in particular as the most productive farms are on the Mediterranean and vulnerable to sea level rise and salty-water intrusion besides increased temperature lowers water supplies and disturbs fish production. Consequently, increased unemployment, higher food prices, and increased risk of malnutrition are all expected.

3.4 Social impacts

Beyond local challenges of pollution and urbanization, climate change is adding more urgency to Nile Delta fish farmers. The adaptation to climate change can constitute a range of interventions across all societal levels, from individuals and communities, to regional and national levels (Ajilogba and Walker, 2021; Ferrando, 2023). The following can be considered in the case of sustainability of the Aquaculture sector in Egypt.

3.4.1 Food security, good health, and well-being

Fish is an important source of dietary protein in Egypt, fish consumption has been increasing recently because of population increase and is being consumed by a large portion of the population. Expansion in low-cost domestic fish production, improvements in distribution networks, and increased importation of inexpensive canned products have made fish more accessible to different societal levels (Soliman, 2017; Wally, 2016). Furthermore, fish consumption exceeded local production by 325,000 MT in 2022, which was compensated by imports. Per capita consumption of fish grew from 16.67 kg/year in 2012 to 20.26 kg/year in 2020 (excluding imports) (United States Department of Agriculture (USDA), 2022). Changes in water temperature, salinity and fish feed availability due to climate change can affect growth and mortality rates reducing fish production which in turn will impact the income of local farmers and their livelihood (Ziska et al., 2016). Schilling et al. (2020) and Smith et al. (2014) expressed their concerns that climate change and rapid population expansion in Egypt are very likely to exacerbate the country's existing water supply situation, reduce agriculture production, and increase food prices. This will have an impact on the national food security, Egypt's economy, ecosystems, and people's health in the form of malnutrition.

3.4.2 Improved quality of life and better living conditions

The expansion of local aquaculture systems will provide a great opportunity for job employment for men, women, and young people, not only in the aquaculture industry but also in associated industries and services like logistics, transportation, financial services, etc. (Food and Agriculture Organization (FAO), 2020, 2024). This will create improved quality of life and better living conditions for families involved in the local services and employment related directly and indirectly to the aquaculture industry.

3.4.3 Stakeholders engagement

Recently, the Food and Agriculture Organization (FAO) (2024) highlighted how efforts to achieve the Sustainable Development Goal (SDG) targets related to fisheries and aquaculture must be accelerated. The international community must take action to support the implementation of the Blue Transformation Roadmap and achieve sustainable aquaculture growth. Local stakeholders' engagement at different levels is crucial for sustainable expansion of the aquaculture system and to achieve the related SDGs. As suggested by Chan and Mosbah (2024), the engagement of local stakeholders is a must to develop the aquaculture sector in Egypt. Mur (2014) conducted a series of five local workshops in Egypt with 70 public and private sector stakeholders involved in the country's aquaculture development, the stakeholders included seven different groups active along the local aquaculture value chain, including farmers, women retailers, input suppliers, and national and local policymakers.

The participants identified the following ten issues which constrain the growth of the aquaculture sector in their respective governorates:

1. Farmers are not represented in policy and decision-making,
2. Poor image of farmers among government agencies,
3. Fish diseases,
4. High production costs,
5. Low-quality feed,
6. Difficulty obtaining a license for fish farming,
7. Limited ability to own land,
8. Deterioration of water quality available for use in fish farms,
9. Insufficient water quantity and restricted rights to use water, and
10. A lack of well-equipped fish markets/formal selling space.

At the same time, stakeholders' engagement is very important for the sustainable expansion of this industry and in addressing climate change impacts on local aquaculture systems. Further attention is needed in this aspect, more details and suggestions are presented in the following section.

4 Research gaps, opportunities, and future need for studies for sustainable food systems

It is expected that local fish demand will increase within the coming years due to the increasing population and economic growth, this will require a sustainable increase in fish production, which can be done by using modern feed improvement technologies, high-quality feed, efficient use of water circulation systems and farm management practices (Food and Agriculture Organization (FAO), 2024; United States Department of Agriculture (USDA), 2022). Furthermore, for sustainable development of local aquaculture, there are some requirements to be considered such as the availability of data needed for research work, the modern applications facilitating the study work, energy usage and water resources besides the socioeconomic aspects. Summarized in Table 2 the identified research gaps in this study, potential opportunities for future studies and improvement action for development of sustainable Egyptian aquaculture systems.

4.1 Data collection and availability

Data availability for conducting different studies is one of the main challenges that face stakeholders, especially academics and researchers interested in the aquaculture field. For example, Yacout et al., 2016, who conducted a life cycle assessment (LCA) to assess the environmental impacts of Nile tilapia in Egyptian aquaculture

TABLE 2 Summary of research gaps, potential opportunities for future studies, and improvement action for development of sustainable aquaculture systems.

Research area	Related sustainability impact	Need for study description	Potential opportunities for future studies and Improvement action	References
Climate change	Environmental impact	To reduce the climate impacts of different aquaculture systems and related processes, environmental systems analysis are required	Life cycle assessment (LCA) can be employed using local data	Dickson and Henriksson (2016) and Yacout et al. (2016)
		Prediction of short- and long-term effects of climate change on local aquaculture areas, including predictions related to weather patterns, floods, droughts, and human migration patterns	Geographic information systems (GIS), remote sensing and hydrodynamic modeling applications for local case study farms/area	Ashry (2015), Rutenberg et al. (2021), and Khalil et al. (2025)
Fish feed	Environmental impact	Reduce environmental impacts of aquaculture systems to make it more sustainable	Develop feed formula using new ingredient ratios with lower impact on the environment	Yacout et al. (2016)
		Reduce environmental impacts of aquaculture systems to make it more sustainable	Using novel raw materials for fish feed production with lower environmental impacts	Iribarren et al. (2012) and Hatch (2024)
Fish seed and productivity	Environmental impact	It is predicted that climate change will affect the availability of seed from the wild	Develop genetically improved seed that can adapt to new environmental conditions	Soliman (2017)
		There is a need to secure marine species seeds and develop more hatcheries	Investigate the potential of incorporation of modern technology to secure marine species seeds and develop more hatcheries	Abdel-Hady et al. (2024)
Efficient energy consumption	Environmental, economic and social impacts	Reduce environmental impacts of aquaculture systems, reduce cost of aquaculture production and improve livehood of aquaculture farms	Explore potential use of different energy sources in different production processes	Yacout et al., 2016, Soliman and Yacout (2016b), and Eltholth et al. (2015)
Usage of renewable energy	Environmental, economic and social impacts	Reduce environmental impacts of aquaculture systems, and create new job opportunities	Study the potential of using solar, wind and tide energy for aquaculture production	Bharathi et al. (2019) and Yacout et al. (2016)
Water resources and efficient water use	Environmental impact	Reduce environmental impacts of aquaculture systems to make it more sustainable	Explore potential use of efficient water management technologies like aquaponics, desalination and Integrated water resource management (IWRM)	Soliman and Yacout (2016a, 2016b), United States Department of Agriculture (USDA) (2022), and Chan and Mosbah (2024)
		Development of efficient water use for sustainable aquaculture systems	study how the expansion of aquaculture farming in Egypt would impact water withdrawals	Soliman and Yacout (2016a, 2016b), United States Department of Agriculture (USDA) (2022), and Chan and Mosbah (2024)
Scarcity of land	Environmental, economic and social impacts	Climate change will impact Egyptian aquaculture through changes in the amount of available land for fish farming	Predict the potential impacts of climate change on the availability of land for fish farming and related environmental and socioeconomic aspects	Mehrim and Refaey (2023), Soliman (2017), Ali and El-Magd (2016), and Smith et al. (2014)
Productivity and national income	Economic and social impacts	Improve socioeconomic aspects for sustainable development of aquaculture farming	Study the characteristics, performance, and trade-offs of tilapia farming systems	Rossignoli et al. (2023)
	Environmental, economic and social impacts	Sustainable development of local aquaculture systems	Identify the potential use of low-value fish/trash fish	Ajilogba and Walker (2021) and Food and Agriculture Organization (FAO) (2016)

(Continued)

TABLE 2 (Continued)

Research area	Related sustainability impact	Need for study description	Potential opportunities for future studies and Improvement action	References
Quality of life and better living conditions	Social impacts	Improve quality of life and better living conditions of local aquaculture farmers	Investigated the availability and implementation of labor rights in local communities	Rossignoli et al. (2023)
		Improved quality of life and better living conditions, good health and well-being of local aquaculture farmers	Explore vulnerability of small-scale farms related to their location, circumstances, and disadvantages	Ajilogba and Walker (2021) and Food and Agriculture Organization (FAO) (2016)
	Environmental, economic and social impacts	Sustainable development of local aquaculture systems	Study climate change impacts on living conditions and the physical well-being of small-scale aquaculture farmers	Ajilogba and Walker (2021) and Food and Agriculture Organization (FAO) (2016)

systems, reported that the available data in the LCA database may not exactly represent the quantity being studied due to the geographical/regional location of the case study as no available database represented that regional location in Egypt at that time. Ashry (2015) suggested that using spatial technologies like Geographic information systems (GIS), remote sensing and hydrodynamic modeling applications can generate necessary information for research, policy analysis, planning, and monitoring that will assist in sustainable aquaculture development. These tools can be used to identify preferable site locations, aquaculture facility mapping, market proximity analysis and associated roadway infrastructure, epizootic mitigation, meteorological event and flood early warning, environmental pollution monitoring, and aquatic ecosystem impacts. However, this can only happen with proper available data based on ground realities and in-hand information, which represents a challenge in many cases.

Furthermore, the development of sustainable aquaculture systems requires benchmarking data about actual sustainability performance to support policy and investment decisions made by policy and decision-makers; otherwise, the results will be poorly developed and implemented interventions which ignore potential sustainability trade-offs (Rossignoli et al., 2023). The Food and Agriculture Organization (FAO) (2024) has invested significant resources to strengthen capacity and improve data collection, analytical tools, and methodologies for managing fisheries and aquaculture effectively. However, more attention and investments are required in providing local data for the proper development and expansion of sustainable aquaculture.

4.2 Modern applications for studying climate change impacts

Modern applications make use of the advances in computer science and the availability and accessibility of international databases. LCA, hydrodynamic modeling, remote sensing, GIS and artificial intelligence (AI) are all examples of modern applications that can be used to facilitate the study of complex environmental issues such as the impacts of climate change on the aquaculture sector. These applications can be used separately or in integrated approaches depending on the aim of the study and the applied methodology.

4.2.1 Life cycle assessment (LCA)

LCA is a helpful tool in studying sustainable aquaculture such as assessing the environmental impacts of different aquaculture production systems and the selection of fish feed formula that is nutritive and eco-friendly.

Aquaculture industry depends on several inputs and outputs (Yacout et al., 2016; Soliman, 2017), namely:

(a) Resources like water, energy, land, seed, and feed
(b) Related processes like fish feed production, water pumping, air aeration, and transportation
(c) Wastewater, fish waste, air emissions from energy production, and solid waste from different production processes.

The related outputs can negatively influence the environment and present challenges for the expansion of this industry. Climate change, variability, and extreme weather events are threats to the sustainability of aquaculture development in marine, brackish, and freshwater environments (Chan and Mosbah, 2024). Few studies took into consideration a system analysis perspective using life cycle assessment (LCA) tools to assess the environmental impacts of different aquaculture production systems in Egypt including climate change impacts. Yacout et al. (2016) used LCA to study the environmental impacts of the two most common Nile tilapia production systems (semi-intensive and intensive production) and compared them. The production of tilapia is practiced in different production systems, including intensive and semi-intensive systems (Yacout et al., 2016). Four impact categories were taken into consideration: Global Warming Potential (GWP) as an indicator of climate change (CC), Acidification Potential (AP), Eutrophication Potential (EP), and Cumulative Energy Demand (CED). Their results indicated that the production of tilapia in intensive farming has less impact on GWP, AP, and CED, while its impact on EP is higher than in semi-intensive farming. The major contributors to different impact indicators in both systems were fish meal production and energy consumption. They suggested that an overall improvement in environmental performance for tilapia production systems can be achieved by: (1) using novel feed formulations that have better environmental performance, and (2) using proper energy management practices to reduce energy consumption. To develop sustainable aquaculture systems and assess related technologies and services, there is a need to consider the entire systems perspective, considering the different environmental impacts including climate change; LCA proved to be an efficient tool to do this (Dickson and Henriksson, 2016; Yacout et al., 2016).

LCA has been used to study the environmental impacts of feed production for Nile tilapia in aquaculture systems in Egypt which is composed of fish meal and oil, soybeans, wheat, rice bran, and yellow corn (Yacout et al., 2016). LCA results indicated that energy consumption and fish meal production were the main factors affecting the different environmental impacts (acidification, eutrophication, and climate change), changing the feed formula to new ingredient ratios that also contain proper protein, lipids and phosphorus with lower impact on the environment is recommended (Yacout et al., 2016). Although Eid et al. (2020) mentioned that, in Egypt, the usage of meagre feeding with trash fish showed the best growth performance and economic evaluation compared to the use of artificial feed under current conditions, Iribarren et al. (2012) and Hatch (2024) suggested to add less fish meal in fish feed formula in order to have better environmental impacts in acidification and climate change. Instead, the use of soybeans, soy protein, wheat grains, corn fermented protein, fermented soybean meal, barley protein concentrate, insect meal, Methanotrophic bacteria, Mycelium, grass protein concentrate, canola protein concentrate, and mixed nut meal are all suggested as alternatives to replace fishmeal (Iribarren et al., 2012; Hatch, 2024). These alternatives meet the nutritional requirements and volume threshold, and are cost-competitive with commercialized counterparts. LCA confirmed that ingredients from plant sources and agricultural processes have the lowest environmental impact from an economic allocation perspective (Hatch, 2024).

The development of sustainable feeds using emerging ingredients is a promising field of research. LCA is recommended for further analysis of the environmental performance of novel raw materials for fish feed production in order to develop fish feed that is nutritious, eco-friendly and sustainable (Yacout et al., 2016; Iribarren et al., 2012; Hatch, 2024).

4.2.2 Hydrodynamic modeling

Hydrodynamics is the study of water motion and hydrodynamic modeling is the development of mathematical model that simulates the water motion in a given waterbody. Hydrodynamics (or water motion) depends on different driving forces such as wind, density currents and discharges. Water motion determines the distribution of dissolved oxygen and nutrients among many other aspects in the waterbody.

Coupled hydrodynamic modeling with climate change modeling enables more reliable prediction of the impact of climate change on natural fisheries as well as aquaculture. In this way, temperature, salinity, dissolved oxygen, nutrients, and other aspects can be simulated for the year 2,100, for instance, and the simulation output is then used to predict the expected fish growth/mortality, reproduction behavior, dominant fish species, and many other items, depending on the available knowledge about fish biology and tolerance. Shalby et al. (2020) developed a hydrodynamic model for Lake Burulus and used it to predict the impact of climate change on the lake. The results showed that the lake is expected to become warmer and more saline with a remarkable decrease in dissolved oxygen. This knowledge would help to decide which fish species could be cultivated in the lake to adapt to changes and to keep the lake productive in a sustainable way.

4.2.3 Remote sensing and GIS

Remote sensing is the study of an area or a phenomenon without being in a physical contact with the area or the phenomenon being investigated by the use of sensors. These sensors can be mounted on drones, airplanes and/or satellites. The s gathered by the sensors are then recorded on digital images which are processed later to extract useful information from them. Geographical information systems (GIS) is a tool specialized in the analysis of spatial data.

Remote sensing studies are valuable when studying the over-year changes in landscape such as changes in Egyptian northern lakes, the expansion of fish farms and the erosion of the Mediterranean coastal zone of Egypt, including the Nile Delta coastal zone. Studies confirmed a loss of coastal lands through erosion that is expected to be accelerated by sea level rise and hydrodynamic changes caused by climate change (Iskander, 2021; Ali et al., 2020). Moreover, remote sensing and geographical information systems (GIS) can be used to predict areas most likely to be subjected to inundation and salt intrusion due to climate change (El-Quilish et al., 2023). This would help in planning for new investments and/or expansion of existing ones in fish farms, for example. This is a promising field of research that can contribute to predict climate change impacts on aquaculture systems and developing proper mitigation strategies.

4.2.4 Artificial intelligence (AI)

Currently, AI is being employed as a tool in many sectors, including environmental modeling. Using AI can assist in making better predictions on the short- and long-term effects of climate change, including predictions related to weather patterns, floods and droughts, and human migration patterns (Rutenberg et al., 2021). Rutenberg et al. (2021) studied the opportunities and impacts of using AI on climate change adaptation in Africa, they suggested that there are three important factors for the application of AI tools on climate change adaptation in the African context: the availability of sufficiently large datasets, the suitability of the algorithms, and the creativity of developers, entrepreneurs, and others in applying AI in the creation of new products, services, and solutions. Furthermore, human labor is required to label data, as AI algorithms require accurately labeled data to learn and increase the accuracy of predictions.

Egypt has the potential to use AI to develop models for climate change that will assist policy and decision-makers in developing proper adaptation strategies. The country has the necessary human resources, including large numbers of unemployed or underemployed youth who have sufficient computer skills for data collection and labeling. It is up to researchers and developers to create suitable algorithms for local conditions.

4.3 Efficient energy consumption and usage of renewable energy

Numerous studies have reported that the fuel and energy sources are some of the main production constraints in the aquaculture sector. The fuel and energy sources are required for different operation activities like pond aeration. Both fuel shortages and high prices have impacted aquaculture farming activities, and alternative sources of energy, such as electricity and/or solar energy, were suggested to be explored (Yacout et al., 2016; Soliman and Yacout, 2016b; Eltholth et al., 2015).

The use of renewable energy in sustainable aquaculture has been considered as an outstanding innovation (Bharathi et al., 2019). Solar energy, wind energy and tide energy are alternatives to conventional power sources to generate electricity needed for lightening, aeration, water circulation and automatic feeding in fish farms. Also, solar energy can be used in water heating to control water temperature. Solar energy is a privilege for Egypt as Egypt enjoys an abundance of solar radiation, it receives an average of 3,050 h of sunlight per year (Global Solar Atlas, 2024). Furthermore, The Egyptian government's strategy is to boost the share of power generated by renewable energy resources to 42% by 2035, with solar energy accounting for 25% of the total electricity generated by renewable energy resources (IRENA, 2018; Moharram et al., 2022). This presents an opportunity to use solar energy in different aquaculture practices, in order to do that studies can be conducted in this field to identify preferable options to be employed for sustainable aquaculture systems at the local level.

4.4 Water resources and efficient water use

It is important to investigate new methods and develop technologies for efficient water use for sustainable aquaculture systems, such as:

4.4.1 Aquaponics technology

Aquaponics is a technology that combines fish and crop production using aquaculture and hydroponics (a method of soilless planting); it is a promising strategy to mitigate the impacts of climate change on aquaculture (Vasdravanidis et al., 2022). El Essawy et al. (2019) and El Essawy (2017) studied the potential for using aquaponics as a sustainable alternative to new land reclamation and conventional agriculture in Egypt. They studied two pilot-scale aquaponics systems (Deepwater Culture system and Integrated Aqua-Vegaculture) and compared them to conventional agriculture. Both systems were designed for testing and application in Egyptian conditions as an efficient alternative to traditional agriculture. They used the minimum water and energy requirements in both systems and found that both systems were effective and produced high-quality safe organic food. Fish production in both system is convenient and slightly higher in Deepwater Culture. Moreover, the Integrated Aqua-Vegaculture has been proven to yield more crops with wider variety when compared with conventional agriculture with about 20% less capital and operational expenditure costs according to the economic feasibility analysis. Although aquaponics requires relatively high capital and operational expenditure costs compared with conventional agriculture in the short term, it is more profitable in the long term as it saves up to 85% of the water wasted in conventional farming techniques. Besides its environmental and economic virtues, the use of aquaponics introduces new entrepreneurship and new opportunities in Egypt especially when increasing public awareness to promote their use (El Essawy et al., 2019). It will be interesting to study the possibility of reducing the capital costs of these systems more by reusing the wastewater and using reused materials in its development. It is also very important to communicate these results and raise awareness about the technological advantages among the public, local farmers, entrepreneurs and investors.

4.4.2 Desalination technology

Sadiddin and Elbehri (2016) suggest the possibility of improving the water supply in Egypt by recycling wastewater and using desalination technology. They declared that there is great potential in reusing wastewater, although this requires public awareness and proper investments from both the public and private sectors. Desalination is a potential option, as in the short run it can be done on brackish groundwater since it is much cheaper than desalinating seawater and, in many cases, can be economically viable for salt-tolerant cropping. Seawater desalination is a long-term option since it is less cost-effective but is especially useful in coastal areas. It is important to investigate how to develop the technology in a cost efficient way and promote the technology advantages among local farmers and investors.

4.4.3 Integrated water resource management (IWRM)

IWRM is another promising option for efficient water use in Egypt. IWRM in Egypt aims to maximize the desired economic benefit of using water, land management, and other related resources for society's welfare without creating a threat to vital economic systems stability. This can be done by improving local irrigation efficiency techniques, since only a third of irrigated areas apply modern irrigation techniques (drip and sprinkler schemes) (Food and Agriculture Organization (FAO), 2023; Ayad et al., 2021; Sadiddin and Elbehri, 2016). National efforts are required to check the efficiency of local irrigation systems and improve them.

4.5 Socioeconomic aspects

Few studies have been conducted focusing on the socioeconomic aspects related to Egyptian aquaculture. Sadiddin and Elbehri (2016) studied the potential impacts of climate change and related socio-economic factors by analyzing the land use, crop intensification, and economic productivity of water in a few countries in the Middle East and North Africa (MENA) region, including Egypt. They identified high vulnerability levels in Egypt's Delta, mainly due to water scarcity and poor adaptive capacity. They proposed several adaptation solutions ranging from measures to improve technical efficiency to measures that encourage economically efficient allocation through the use of market forces. Sadiddin and Elbehri (2016) also suggest that information on the impact of climate change and related socio-economic factors on fishery and aquaculture in Egypt is limited. There is a research gap in this area, making it important to consider the following for further research.

To develop sustainable aquaculture systems, it is important to consider socioeconomic aspects, promoting and adopting socio-technical innovations and approaches that can deliver multiple benefits across multiple socio-economic and environmental dimensions (Klerkx and Begemann, 2020); assist in national economic growth (Costello et al., 2020; Gentry et al., 2017); support job creation;

improve quality of life; and provide better living conditions (Béné et al., 2016; Haque and Dey, 2016; Nasr-Allah et al., 2020).

Rossignoli et al. (2023) stated that regarding the Egyptian aquaculture, there is a general lack of robust information about the characteristics, performance, and trade-offs of tilapia farming systems in the country that can inform policy decisions and investors on the requirements for achieving sustainable intensification, and thus how to enhance sustainability. Local data collection and further research is required in this area. Points that need to be investigated are related to labor rights in local communities, the potential use of low-value fish/trash fish, overfishing, unregulated, unreported, and illegal fishing, and labor challenges, as well as climate change impacts on living conditions and the physical well-being of small-scale aquaculture farmers, the vulnerability of small-scale farms related to their location, circumstances, and disadvantages (Ajilogba and Walker, 2021; Food and Agriculture Organization (FAO), 2016); these can be done to develop mitigation and adaptation strategies.

In agreement with Chan and Mosbah (2024), the engagement of local stakeholders to develop the aquaculture sector in Egypt is a must. It is suggested that by employing foresight modeling, different stakeholders like researchers, analyzers, businesses, and decision-makers in the sector can evaluate and analyze the factors affecting the fish demand and supply and their complicated interactions in a systematic way. Factors such as climate change impacts, market dynamics, resource limitations and technological development and their interaction are all used in this analytical approach to define potential risks and opportunities and also to provide evidence-based knowledge that helps in the development of policies, investment strategies and technological innovations to deal with current limitation and capitalize on emerging trends. In order to employ foresight modeling for Egyptian aquaculture systems efficiently, it is required to: (i) collect local data to develop the needed datasets, (ii) training local researchers to develop the foresight models, evaluate and analyze them, then (iii) ensure results communication to the policy and decision-makers.

Next, the involvement of small producers and farmers is a must to ensure the sustainable development of local aquaculture. Mur (2014) identified that among the constraints of Egyptian aquaculture growth are the negative view of farmers among government agencies and the non-representation of farmers in policy and decision-making. To author's knowledge stakeholders engagement in the value chain of Egyptian aquaculture production is not well documented with recent data, there is a gap in the related literature that needs to be addressed with proper studies.

At the same time, climate change technology transfer and policy analytics are high success factors that strengthen the collaboration between private and public sectors in developing countries to promote climate technology transfer (COP25, 2019; Matheri et al., 2021). National policymakers and investors have important roles in the development of sustainable aquaculture systems. Policymakers need to develop national policies that encourage the transfer of environmentally sound technologies that assist in adapting to climate change. Also, to set policies that attract new investors to invest in the sector and in new technologies. As for the private sector and investors, they need to be more involved in the development of aquaculture systems by investing in new sustainable technologies, training local experts and fund local research that assists in developing the sector and their investments.

5 National efforts to improve local aquaculture sector

The increasing importance and positive impacts of aquaculture at the national level have encouraged both government agencies and non-governmental organizations to implement different interventions and projects in the sector to enhance the rapid expansion of this industry and support related activities like local feed mills and hatcheries (Nasr-Allah et al., 2020; Shaalan et al., 2018). According to the United States Department of Agriculture (USDA) (2022), the Egyptian Ministry of Agriculture and Land Reclamation set a plan to develop Egypt's fisheries and aquaculture and increase fish production to 3 MMT by 2025. This will be done by:

i Developing inland fisheries (mainly lakes of Manzala, Burullus, Maryut, and Bardawil). Production in these fisheries amounted to 200,000 MT in 2020.
ii Expanding fish farming via mega-national projects such as Birkat Ghalioun in Kafr El Sheikh, Al-Diba Triangle, Al Fayrouz project in East Al Tafrea, the Suez Canal Company fish farming project and the National Project for Developing East Port Said.
iii Developing hatcheries for fry production, with special emphasis on marine fry and the expansion of shrimp cultivation.
iv Expanding integrated aquaculture fish farming in reclaimed lands.
v Increasing fish production by converting the traditional system and semi-intensive farms to the intensive aquaculture system.
vi Maximizing water return using efficient technologies such as In-Pond Raceway (IPR). IPR creates water circulation within the raceway units located in earthen ponds alongside the removal of organic wastes, the system contributes to higher fish yields in a sustainable way that ensures higher fish growth rate, survival, and an efficient feed conversion ratio.

These are great efforts conducted by the government, it is important to keep funding national projects that assist the sustainable expansion of this sector. Policy and decision-makers can set policies to encourage the investment in this sector, and use of sustainable technologies for fish feed and seed development. They can encourage small farmers and set incentives for efficient water consumption and use of renewable energy. Funding research projects to develop cost-efficient production of desalinated water and aquaponic production will encourage researchers to develop the related technologies in these areas. Conducting a national awareness campaign among farmers to explain the potential impacts of climate change on local aquaculture farms and how to adapt is highly recommended. Enhancing the collaboration and communication between the local stakeholders "researchers, investments, policy makers and farmers" is a must.

6 Conclusion

Climate change has recently risen to the top of the priority list for Egyptian national decision-makers due to rising food and living expenses, decreased land productivity along the coast, and water scarcity (Al-Mailam et al., 2023; IEA, 2023). As the Food and Agriculture Organization (FAO) (2024) puts it, "aquatic food systems represent a viable and effective solution that offers greater opportunities to improve global food security and nutrition." To ensure the development and sustainable expansion of Egyptian aquaculture systems, it is important to consider the impacts of climate change on local aquaculture systems, the related challenges, and how to mitigate them. The main sustainability pillars for the development of local aquaculture systems and related climate change impacts considered in this study were related to environmental, economic, and social impacts.

In this study, a number of research gaps for developing sustainable Egyptian aquaculture systems were identified along with potential opportunities for future studies and improvement action. It was found that to reduce the environmental impacts of aquaculture systems it is important to take into consideration the environmental systems perspective of current and new technologies employing LCA methodology using local data. GIS, remote sensing and hydrodynamic modeling applications can be used for predicting the impacts of both climate change and extreme weather conditions on local aquaculture farms. Feed formulas can be developed using new ingredient ratios and novel raw materials with lower impact on the environment and genetically improved seed can be developed for adapting to new environmental conditions.

Energy production and efficient water are two major factors in developing sustainable aquaculture systems. It is possible to reduce the environmental impacts of aquaculture systems, reduce cost of aquaculture production and improve live hood of aquaculture farms by exploring potential use of different energy sources in different production processes such as solar and wind energy. As for efficient water use, it is recommended to explore the potential use of efficient water management technologies such as Integrated Water Resource Management (IWRM), aquaponics and desalination technology. National efforts are required to check the efficiency of local irrigation systems and improve them and study how the expansion of aquaculture farming in Egypt would impact water withdrawals.

Considering the socioeconomic aspects for development of local aquaculture systems is a must, however, few studies investigated the socioeconomic aspects of local Egyptian fish farms. Engagement in the value chain of Egyptian aquaculture production is not well documented with recent data, there is a gap in the related literature that needs to be addressed with proper studies. Also, there is a need to study the characteristics, performance, and trade-offs of tilapia farming systems, identify potential use of low-value fish/trash fish.

It is expected that climate change will impact Egyptian aquaculture through changes in the amount of available land for fish farming, this is an important issues that needs to be addressed by predicting the potential impacts of climate change on availability of land for fish farming and identify the related environmental and socioeconomic impacts.

Stakeholders and local community engagement at different levels is an important factor for the successful development of climate change adaptation strategies for Egyptian aquaculture systems. Farmers need to be aware of climate change impacts to be able to take the necessary measures. Researcher need to study climate change impacts on living conditions and the physical well-being of small-scale aquaculture farmers, explore vulnerability of small-scale farms related to their location, circumstances, and disadvantages. Governmental authorities need to investigate the availability and implementation of labor rights in local communities. Policy and decision makers need to set regulations that encourage technology transfer that assist in adapting to climate change and attracts investments in it. Investors should be more involved in the expansion of the sector by funding research that assists in mitigating climate change impacts and invest in sustainable technology. The sustainable expansion of this sector has the potential to provide a lot of employment and job opportunities directly and indirectly, providing better living conditions and increasing national income.

Author contributions

DY: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing. HK: Conceptualization, Resources, Writing – original draft, Writing – review & editing. MY: Writing – original draft, Writing – review & editing.

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The authors declare that no Gen AI was used in the creation of this manuscript.

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Supplementary material

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