sustainability

Review

An Overview of the Implication of Climate Change on Fish Farming in Egypt

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Abstract: Aquaculture is an important component of the human diet, providing high-quality aquatic food for global or local consumption. Egypt is one of the countries most vulnerable to the potential impacts of climate change (CC), especially in the aquaculture sector. CC is one of the biggest challenges of our time and has negatively affected different water bodies. CC leads to the combination of changes in water availability, a decrease in water quality, the movement of salt water upstream due to rising sea levels, and the salinization of groundwater supplies will threaten inland freshwater aquaculture. Similarly, higher temperatures resulting from CC lead to reduce dissolved oxygen levels, increased fish metabolic rates, increased risk of disease spread, increased fish mortality, and consequently decreased fish production. CC may also indirectly affect aquaculture activities; for example, large areas of lowland aquaculture ponds can be highly vulnerable to flooding from rising sea levels. Thus, the current overview will briefly discuss the state of the aquaculture sector in Egypt, the meaning of CC, its causes, and its effects on the different elements of the aquaculture sector, and finally, we will review the appropriate ways to mitigate the adverse effects of CC on fish farming, especially in Egypt.

Keywords: climate change; aquaculture; sustainability; Egypt

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1. Introduction

Fish is one of the most widely consumed foods in the world, and it is only becoming more popular over time, as fish is considered a healthy and nutritious food by many consumers and is expected to further grow in the next decade [1]. Millions of low-income women and men rely on the fishing and aquaculture sectors for income [2,3], which contribute both directly and indirectly to their food security. Since the 1990s, capture fisheries have plateaued at about 90 million tons. At the same time, the world's human population is growing rapidly. Thus, aquaculture is shaping up into a global venture, and it is considered the fastest-growing food-producing sector in the world to feed the ever-growing population. Moreover, the global aquaculture industry, in the current or future food systems, will become the most important source of high-quality aquatic food [1]. In 2020, global aquaculture's share was 49.2% of the world's fish production, compared to 25.7% in 2000. It is predicted that aquaculture will contribute 62% of the global food supply by 2030 [4]. Regionally, aquaculture accounted for 17.9% of total fish production in Africa, which is roughly 2.70% of world aquaculture production [1]. Compared to 57.7% in 2000, inland aquaculture produced the most farmed fish (51.3 million tons, or 62.5% of the global total), mostly in freshwater [1].

In Egypt, aquaculture has been practiced since ancient times. However, it still contributes significantly to a country's GDP, employment, and food security, as well as being important to nutritional well-being, the economy, and the lives of the population [5]. Egypt produces significantly more aquaculture than the rest of Africa combined. According to the most recent annual fish production statistics from GAFRD [6], Egypt's aquaculture industry supplied nearly 80.5% of the nation's fish needs in 2019 (Figure 1). Small- and medium-sized privately owned farms produced more than 99% of this output, accounting for nearly all the output. The area being farmed increased from 42,000 ha in 1999 [7] to 123,327 ha in 2019 [6]. Egyptian aquaculture has played a critical role in increasing per capita fish consumption from 14.3 kg in 2002 to 25.4 kg per person by 2019, representing a 56.3% increase in per capita consumption over this period [6]. In addition, aquaculture plays an important role in the economy [8], where the total marketing value of the aquaculture industry in Egypt was USD 3.2 billion in 2019 [6]. In recent years, aquaculture has developed rapidly, creating many job opportunities for farm technicians and skilled laborers. Moreover, the development of new industries, financial services, and aquaculture-related activities has created employment opportunities [8,9]. Meanwhile, aquaculture expansion has reduced and stabilized the cost of fish in Egypt, making it more accessible to poorer rural populations and allowing them to consume healthy and affordable animal protein [9].

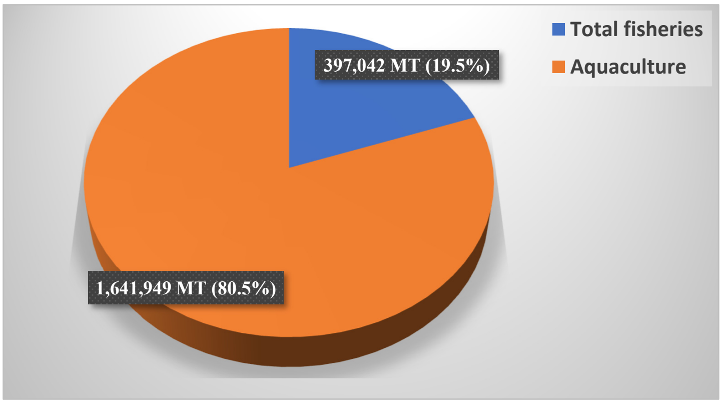

Figure 1. Annual total fisheries and aquaculture production in Egypt [6].

In Egypt, many fish culture systems include: (A) Extensive aquaculture that includes earthen pond culture, as well as restocking lakes with fry and fingerlings, adding to grass carp in the Nile River, its branches, and enclosures. (B) A semi-intensive culture system that accounts for 80% of Egypt's total output. (C) Intensive culture systems in concrete ponds, tank culture, greenhouse culture, and cage culture, all of which have grown in popularity in recent years [1]. Additionally, (D) integrated aquaculture production systems with plants (aquaponics) and animals (ducks) [10]. Fish farms are dispersed through the Nile Delta region and focused mainly on the Northern lakes (Manzala, Maruit, Boruls, and Edko; Figure 2). Historically, the extensive cultural system is the oldest system in Egypt. This system is characterized by a low input in fish density and a very poor output. Meanwhile, the semi-intensive system is more widely distributed and preferred by both small- and large-scale commercial farmers. This system plays the main role in increasingly contributing to the development of aquaculture in Egypt. The intensive culture systems depend on an increasing stocking density, which requires big capital investment and complete formulated feeds, representing 40–60% of the production costs. In the coming years, it is expected that intensive aquaculture will play a greater role in food security than semi-intensive systems in terms of production efficiency [11]. Additionally, El-Gayar [12] stated that there is a significant possibility for enhanced output in this system if the production process is intensified by increasing the stocking density of fish, aeration, the use of supplemental feeding, and improved pond management. Despite aquaculture being a significant industry, it is prohibited from using Nile water and is instead mostly reliant on groundwater and agricultural drainage systems [13], which are of poor quality. This water causes many problems, such as increased production costs for hatchers and fish farmers, declining fish production, and increases in disease outbreaks [14]. Moreover, drainage water negatively affects the quality of farmed fish due to the accumulation of pollutants and potential contamination of fish [15], reducing opportunities for fish export. Therefore, fish farmers are demanding the use of fresh water in their fish production.

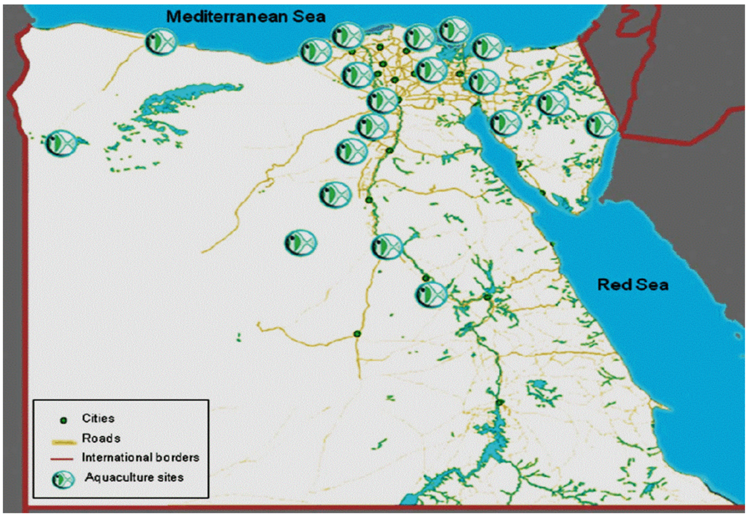

Figure 2. Distribution of the main aquaculture production sites in Egypt [9].

One of the most dynamic and defining environmental, legal, and political challenges of the twenty-first century is climate change. The production of agriculture is currently hampered by climate change worldwide, particularly in the Mediterranean region [16]. One of the most significant environmental issues that has an adverse impact on both the environment and human lives is global warming. Since 1950, the average global temperature has risen by 0.13 °C on average per decade [17]. It is expected to increase by between 0.3 and 0.7 °C in the global mean surface temperature during 2016–2035, which may be due to the emissions scenario [18]. In general, climate change has led to many environmental phenomena such as flooding, extreme heat, and water scarcity, which have had negative impacts on food security, the spread of infectious diseases, economic losses, and displacement. These impacts have led the World Health Organization to call climate change the greatest threat to global health in the 21st century. The problems of climate change are global, but Africa is likely to suffer to a greater degree compared with other regions. Scientists and policymakers in Africa need every available tool to help the continent adapt to the severity and scale of this problem [19]. For the aquaculture sector, climate change has had many negative impacts, resulting from direct or indirect impacts on the cultured organisms (fish—natural food) or the resources needed for aquaculture (water, land, seeds, feed, and energy) [20]. Changes in temperature and rainfall patterns affect water quality parameters such as pH, salinity, and oxygen, which are expected to impact reproduction, growth, survival, and pond productivity. Furthermore, climate change increases physiological stress, which leads to increased disease vulnerability, as well as higher risks and lower returns for farmers [21].

The threat of climate change is a major concern for food security, sustainability, and the resilience of the systems on which humans rely [22]. Similar with any food system, aquaculture is affected by climate change, effects that will differ depending on the cultivated taxa (e.g., finfish, shellfish, or seaweed), the farming ecosystem (e.g., freshwater, brackish, or marine), practices (open or closed systems), and the regions [23]. Climate change impacts on aquaculture are considered as direct, e.g., changes in either water availability, temperature, or damage by extreme climatic events, or indirect, such as in the case of increased fishmeal costs as well as for other aquaculture feeds [20]. Changes in climate-related factors, mainly temperature, directly affect the biochemical reaction rates that govern the rates of cellular processes, feeding, digestive, and metabolic performance of fish [24], which in turn, affect the growth performance [25,26], physiological status [27–29], immune responses [30–32], reproduction, behavior [33–35], and disease resistance [36,37] of different fish species in the wild and in aquaculture. This, consequently, may have significant impacts on aquaculture productivity and thus may adversely affect food security in Egypt [38]. In addition, Egypt's precipitation may decrease due to climate change, with some modeling indicating an annual decline of up to 5.2% by 2030, 7.6% by 2050, and 13.2% by 2100 [39]. Therefore, it would be prudent for Egypt to identify adaptive strategies to manage climate risks in vulnerable areas [40]. Consequently, this overview classically represented the implications of climate change on the fish farming sector in Egypt.

2. The Meaning of Climate Change

Climate change is defined as significant, protracted changes in the world's climate. The world's climate is an interconnected system of the sun, earth, and oceans, as is the wind, rain, and snow, as well as forests, deserts, savannas, and human activity [41]. According to the Intergovernmental Panel on Climate Change (IPCC), climate change is defined scientifically as a change in the climate's state that can be determined by variations in the mean and/or variability of its properties that last for a considerable amount of time, typically decades or longer. The concepts given above define climate change as long-term changes in temperature and weather patterns. These changes could be caused by natural processes such as oscillations in the solar cycle. This quick increase is problematic because it is altering our climate too quickly for living things to adjust [42]. However, since the 1800s, human activity has been the primary cause of climate change, mostly as a result of the combustion of fossil fuels such as coal, oil, and gas. In addition to rising temperatures, other effects of climate change include rising sea levels, harsh weather, shifting wildlife populations and habitats, and a variety of other effects. The release of heat-trapping gases, often known as greenhouse gases (GHGs), to power our contemporary lives has clearly been the main driver of the last century's warming. We are achieving these using fossil fuels, land usage, agriculture, and other factors that contribute to climate change. Over the past 800,000 years, GHG levels have been at their highest point. This quick increase is problematic because it is altering our climate too quickly for living things to adjust [42].

3. The Cause Factors of Climate Change

The earth's climate changes as a result of a variety of human-made and natural forces. Thus, the two main causes of climate change are human and natural causes. The human causes relate to artificial factors and people's activities that change the climate on the Earth. The human (anthropogenic) factors that are causes of climate change (Figure 3), include the use of fossil fuels (transport, industries, and urbanization), air pollution, agriculture (animal digestion, manure, soil management), and land use changes (deforestation, upsetting grasslands and croplands) [17,41]; there are other human causes as well. Climate change includes both large-scale changes in weather patterns that come from human-caused global warming and shifts that result from these changes. Since the mid-20th century, people have had an unparalleled impact on the earth's climate system and have led to change on a global scale. Human actions are to blame for the current, rapid climate change, which is endangering humanity's basic existence. Global warming causes the emission of gases, of which more than 90% are carbon dioxide (CO_2) and methane (CH_4), which are the main causes of global warming. The primary source of these emissions is the burning of fossil fuels (coal, oil, and natural gas) for energy consumption, with smaller amounts coming from manufacturing, agriculture, and deforestation [43]. Most scientists accept that human causes refer to people's activities that change the atmosphere on the planet. People pollute the environment directly, which changes the climate; it is the human cause. Therefore, it is also known as the anthropogenic cause of climate change. Since the mid-1800s, scientists have known that CO_2 is one of the main GHGs of importance to Earth's energy balance. Direct measurements of CO_2 in the atmosphere and in air trapped in ice show that atmospheric CO_2 increased by more than 40% from 1800 to 2019. Measurements of different forms of carbon reveal that this increase is due to human activities. Other GHGs (notably CH_4 and nitrous oxide) are also increasing as a consequence of human activities. The observed global surface temperature rise since 1900 is consistent with detailed calculations of the impacts of the observed increase in atmospheric GHGs (and other human-induced changes) on Earth's energy balance. Human activities—especially the burning of fossil fuels since the start of the Industrial Revolution—have increased atmospheric CO_2 concentrations by more than 40%, with over half the increase occurring since 1970. Since 1900, the global average surface temperature has increased by about 1 °C. CO_2 has also increased in the atmosphere due to deforestation. It is a primary human cause of rising GHGs and climate change. In 2019, deforestation was responsible for an increase of 11% of CO_2 [44].

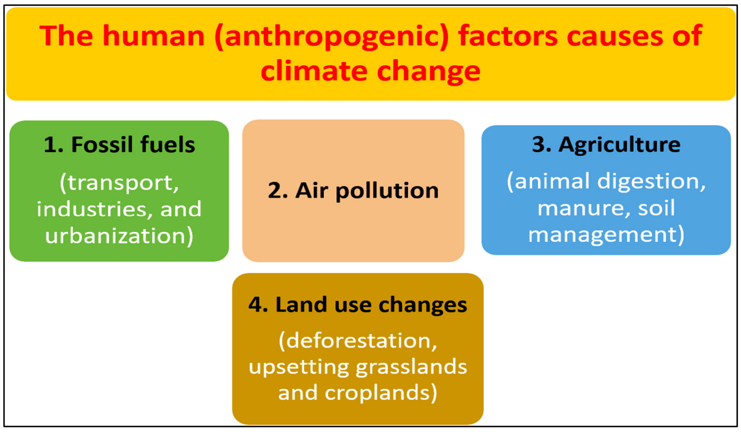

Figure 3. The human (anthropogenic) factors that are causes of climate change [17,41].

Livestock production is another primary human cause of climate change. It contributes to producing GHGs that trap heat in the atmosphere. Nowadays, people farm domestic animals for commercial purposes to produce meat, milk, leather, etc. The most common animals in livestock farms are cows and sheep. These animals generate CH_4 gas when they consume and digest foods. A report shows that cows generate around 150 billion gallons of methane gas daily. CH_4 is one of the GHGs that contributes to raising the temperature of the planet. Livestock production is responsible for producing 14.5% of GHGs. Domestic animal farming produces a large carbon footprint which causes climate change. The fluorinated and industrial gases are also human causes of climate change as people produce these gases for commercial purposes. Food waste is one of the silent human causes of climate change, which many people are unaware of. Food waste produces CH_4 gas when it decomposes in landfills. CH_4 is a powerful GHG that causes global warming and climate change on Earth. Around 6–8% of CH_4 gas is emitted from wasted food. Therefore, food waste is a significant factor of climate change [45].

The second factor of climate change is natural causes, which refer to the physical factors that contribute to the change of the atmosphere on earth. Over a period of thousands to millions of years, they have had an impact on the climate. Natural causes occur mostly automatically rather than through people's contributions [44]. These natural causes stimulate changes to the condition of the planet both instantly and slowly. For example, solar activities mean releasing various types of radiation from the sun from time to time. It includes sunspots, solar flares, and solar radiation. Sunspots emit many ultraviolet rays that hit the planet's surface and increase the temperature. In recent decades, the planet's temperature has risen by 0.1 °C due to the solar maximum. It makes the sun brighter and the planet warmer. Other natural causes, such as volcanic eruptions, axial tilt (obliquity), precession, eccentricity, continental drift, the ocean current, natural forest fires, and natural GHGs (Figure 4) also have different negative impacts on the climate of our planet: where they have led to the release of a massive amount of dust, magma, and gases that affect the environment, creating a dark ash cloud in the atmosphere; the planet consumes more solar radiation; it receives more heat from the sun, or it gets less heat when tilted away from the sun due to the planet's orbital path variation; changing the atmosphere on the planet due to the slow movement of continental drifts of the planet's plates; the sea level increasing continuously due to the ocean current melting the ice on the northern part of the planet; the release of numerous GHGs, which trap the heat in space; increasing the temperature of the planet due to natural forest fires; and natural GHGs which additionally allow solar radiation to enter the planet easily [45].

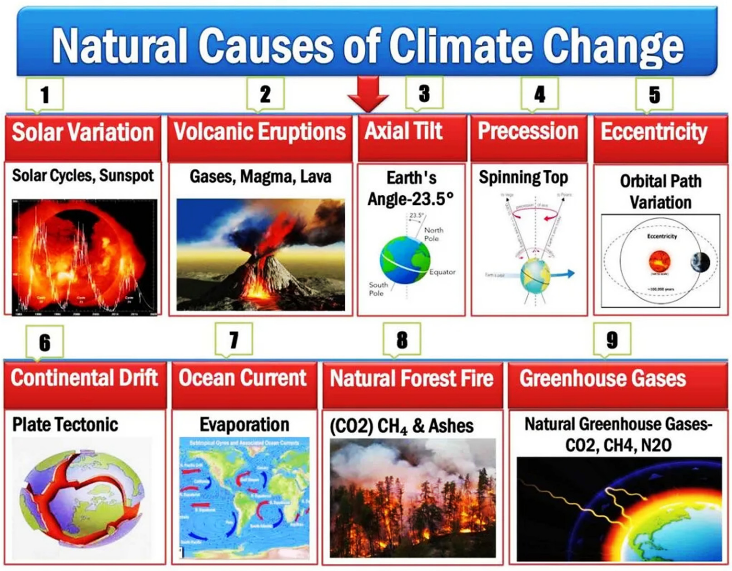

Figure 4. The natural factors that are causes of climate change [44].

4. Effects of Climate Change on the Fish Farming Sector in Egypt

In general, there are two effects of climate change on the planet, the direct and indirect impacts. The direct impacts include increasing the maximum temperature levels and reducing the minimum temperature levels. The prolonged maximum temperature melts the ice in the northern part of the earth and increases the sea level. Additionally, it raises the ocean's temperature and brings a humid atmosphere. The higher temperature of the ocean evaporates water into vapor and creates heavy rains. On the other side, the indirect impacts of climate change create a water crisis, and the groundwater level is decreasing daily. In many developing countries, people suffer from water crises. These countries experience droughts and floods every year, subsequently increasing hunger and diseases among poor people. Climate change is directly responsible for the loss of diversity and the ecosystem crisis. The contamination of CO_2 and HCO_3 concentrations in the water creates acid rain which is bad for people's health. Furthermore, climate change is also responsible for floods, erosion, landslides, and salinization. The sea level is increasing day by day due to global warming [41].The Egyptian fish farming industry uses several crucial inputs, including land, freshwater, feed, and energy, all of which have substantial environmental effects. At the same time, the supply of these inputs is constrained and is probably going to get even more so in the future [46]. Egypt is mostly reliant on the Nile River, which provides the nation with an annual water volume of about 55.5 km^3, accounting for 93% of its conventional water resources. There is a discrepancy between water demand and supply, which is filled by reusing drainage water, wastewater, and shallow groundwater. Additionally, the uncertainty of climate change implications is a difficulty for Egypt's water resources system. Climate change could have a direct impact on the quantity of water in Egypt, leading to indirect effects on Mediterranean saltwater intrusion into groundwater, exposing the agriculture to vulnerability [47]. Moreover, Chen et al. [48] reported that the Egyptian Nile Delta has been suffering from complex environmental hazards especially caused by climate change, which have led to adverse impacts on national food security. The development of aquaculture in Egypt during the next period will largely depend on finding solutions to the key issues facing this industry, including conflicts over the use of resources (water and land), energy consumption, price changes for the primary raw materials used in the fish feed industry, and getting high-quality fish fry from a reliable source [49]. Egypt is one of the nations that are thought to be most susceptible to climate change impacts. These effects will have serious repercussions on all sectors of the country [50] including the aquaculture industry. Aquaculture could be impacted by climate change through adjustments to fish stocks, species, reduced aquaculture land, production volumes and efficiency, water quality, and fish pricing. The growth of sustainable aquaculture is likewise threatened by the effects of climate change, which require the implementation of mitigation and adaptation strategies. These measures will combine socioeconomic and technical strategies.

Due to Egypt's huge and expanding population and reliance on the Nile River, the effects of climate change on water resources is seen as a major concern. Egypt has already exceeded the threshold of water scarcity. Numerous international studies have been conducted in this area, including one by Hammond [51], who predicted that the management of water resources in the Nile River would grow more difficult as a result of socioeconomic and climatic changes. Schilling et al. [52] presented a comparison of the social impacts of climate change and their relation to the vulnerability of Algeria, Egypt, Libya, Morocco, and Tunisia. According to the findings, all nations are vulnerable to severe temperature increases and a high risk of drought due to climate change. Climate change and rapid population expansion in North Africa are very likely to exacerbate the region's already precarious water supply situation. Egypt is thus subject to several serious threats due to climate change. These concerns, which include a considerable decline in Nile River flow, sea level rise (SLR), and greater temperatures which result in decreased water supplies and loss of land, might have a negative impact on Egypt's economy, ecosystems, and people's health. Egypt already confronts significant water management issues due to the uncertain changes in availability brought on by climate change, as well as the more certain demographic trends and potential abstraction by upstream riparian countries. A decrease in the Nile's flow brought on by climate change might exacerbate the problem. 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 [53].

Egypt produces 93% of its fish needs from different sources [6]. Furthermore, a lot of social classes rely on freshwater fish as a primary source of animal protein. Increased temperatures will work on fish migrating to the north and to deeper waters, as well as fish farms, which will face competition over the redistribution of water usage and the productivity of some varieties of fish. Fish farms and small waterways are more vulnerable than fish in the sea and large water bodies. Thus, the rising air and water temperatures will affect an increased growth rate of fish and their vulnerability in fish farms. These changes will be related to a higher need for nutrition and increased competition between different fish species and other organisms in the fish pond, thus raising the biological oxygen demand (BOD). Additionally, in terms of the hydrological aspect, the Mediterranean Sea level rise—whether it is 50 cm or one meter—will have a significant impact on the rates and locations of egg hatching. Egypt is considered one of the top five countries expected to be vulnerable to the impacts of SLR [54], wherein in terms of aquaculture production, it is the largest African country and the tenth worldwide, with approximately 1.64 million tons/year [1]. In addition, the likelihood of increased water salinity in the northern Delta will negatively affect the productivity of freshwater fish and increase the productivity of saltwater fish [55]. The impacts of climate change on aquaculture are more complex than those on terrestrial agriculture due to the greater diversity of fish species produced and the systems used [56]. The extensive areas of aquaculture ponds that exist in the lowlands can be highly vulnerable to flooding from rising sea levels. Furthermore, the movement of saline water further upstream in rivers caused by rising sea levels, and the salinization of groundwater supplies, will threaten inland freshwater aquaculture [17]. Changes in rainfall will cause a spectrum of changes in water availability and will reduce water quality. Similarly, rising temperatures from climate change events reduce dissolved oxygen levels and increase fish metabolic rates, consequently leading to an increase in the mortality rate of fish, decreased production of fish, and/or increased feed requirements, as well as increased risk and spread of disease [57].

Currently, the expanding aquaculture production hubs in Asia and Africa, particularly Egypt, are quite concerned about climate change. The dry and wet seasons have changed due to climate change. It is increasingly recognized that economic, social, and ecological systems are dynamic, interacting, and interdependent. In this way, the linkages between aquaculture and climate change are reciprocal—aquaculture influences and contributes to climate change. All areas of development, including aquaculture, will be significantly impacted by climate change in Egypt [50]. The Egyptian aquaculture may be impacted by climate change through changes in the amount of available land for fish farming, fish species, water quality, production volumes and efficiency, and fish pricing. Additionally, the growth of sustainable aquaculture is being threatened by the effects of climate change, necessitating the targeted application of mitigation measures. These initiatives will combine socioeconomic and technological strategies [58]. Aquaculture relies on resource inputs (water, land, seed, feed, and energy) that are connected to various feed, processing, transport, and other sectors of society. Aquaculture ecosystems produce products of economic value. In addition, uncontaminated wastewater and fish waste are produced from fish farms, which can be important inputs to environmentally designed aquaculture and terrestrial farming systems [58]. Thus, the following subsections will provide a quick overview of the main impacts of climate change on aquaculture inputs, including water, land, feed, seed, and energy.

4.1. Water

According to the FAO [57], Egypt is one of the African countries that is expected to be most vulnerable to the impacts of SLR [57]. Increased sea levels lead to coastal groundwater becoming more saline, especially in low-lying areas, which is reflected in the decrease in fresh water available for aquaculture [59]. Many studies have addressed the sensitivity of the Nile River waters to climate change. The sensitivity of different Nile basins to uniform changes in rainfall have been documented [60]. The sensitivity of Nile water flows and consequently species diversity are also affected by the change in temperature, which causes corresponding changes in evaporation and evapotranspiration [61,62]. An increase of 4% in evapotranspiration would result in a reduction of Blue Nile and Lake Victoria flows by 8% and 11%, respectively. In addition, Khordagui [63] expected that the Nile water would be reduced by 20% over the next 50 years. Meanwhile, the increasing temperatures will cause a rise in the evaporation process in natural ecosystems, which will lead to an increased water demand [17]. Recently, Radwan and Ellah [64] revealed that Egypt is one of the countries negatively affected by climate change within its borders, and, outside its borders, within the whole of the Nile River. The river is expected to be severely reduced. From the other side, aquaculture activities in desert areas depend on groundwater. Twenty commercial aquaculture farms operating in Egypt's desert regions total 893 hectares in size and produce roughly 13,000 tons annually [65]. According to El-Guindy [66], brackish and marine water may be very important for the development of aquaculture in the Egyptian desert in the long run.

Adaptation options for Egypt's water resources meanwhile are closely intertwined with Egypt's development choices and pathways. Any changes in water supply due to climate change over the medium term will occur alongside the certainty of increased demographic pressures (the national population is growing by one million every nine months) as well as the potential increases in Nile water abstractions by the upstream riparian countries. Adapting to climate change will have close resonance with adapting to water scarcity and is likely to require the implementation of water demand management strategies, which may require capacity building and awareness raising across institutions and society. Adaptation measures on the supply-side include ways to improve rain harvesting techniques, increasing extraction of groundwater, water recycling, desalination, and improving water transportation [67]. Fish ponds can obtain water from various water sources depending on the availability, location, and law. In Egypt, the following water sources and percentages were identified: lake (13%), river (6%), agricultural drainage water (78%), and mixed drainage and Nile (45%). It was observed that most of the fish farmers relied on agricultural drainage water. The result is not far-fetched from the fact that aquaculture is the last user of water in Egypt because it makes use of reused water, according to the water policy in Egypt [68]. Apparently, Egypt represents a good example of a green aquaculture because 78% of the fish farmers depend solely on agricultural drainage water. In Egypt, recent research showed that the use of aquaculture drainage water for agriculture is preferred to the existing practice of agriculture drainage water for aquaculture. The use of aquaculture drainage water is best practice due to its numerous advantages. Aquaculture drainage water contains a lot more nutrients for the crops than the agricultural drainage water, which might at the same time not be good for the cultured fish. Efforts should be geared to convince the government in Egypt to pay more attention to the reuse of aquaculture drainage water for effective and maximum utilization of water in the country. Eighty percent (80%) of the fish farmers in Egypt state that the source/s of water to their farms/ponds is/are challenging, while only 20% believe the source/s of water is/are good and not challenging [68]. In Egypt, the problem that was highlighted and emphasized mainly on water sources was pollution. In Egypt, 57% of the respondents have taken precautionary measures with regards to reducing the effect of pollution on the water source that enters their farms by checking the water qualities, filtering the water when pumping, and treatment of the water and pond, but 43% are yet to take any precautionary measures. The reason might be due to the fact that they are constrained to the available water source to be used for aquaculture in the country [68].

4.2. Land

The Egyptian Nile Delta is considered an area vulnerable to SLR. The overturning of coastal defenses and increased flooding, harm to urban areas, the retreat of barrier dunes, increased coastal erosion, increased soil and lagoon water salinity, and lower agricultural and fishery products are all possible effects of SLR on the delta [69]. In addition, Yates and Strzepek [70] stated that a large portion of arable land located in the Nile Delta is particularly sensitive to increased sea levels and precipitation, and to temperature change in Egypt. Due to floods, SLR causes land to be lost, which reduces the area that can be used for aquaculture. It also affects estuary systems, species abundance, the distribution of fish stocks, and freshwater fisheries, as well as the availability of freshwater and aquaculture seeds. With rising sea levels, seawater intrusion into freshwater aquifers is becoming a bigger issue [71]. In many regions, salinization of the soil and groundwater due to SLR would result in optimal conditions for aquaculture [72]. Low-lying areas will be flooded. One hypothesis is that as freshwater supply declines, aquaculture will become more diverse due to a shift to species found in brackish waters. The expanded regions might be appropriate for the brackish water cultivation of valuable species such as shrimp and mud crab. A significant portion of the area used for current agricultural activities, primarily rice farming, has become unsustainable in these places as a result of SLR, which causes the salinization of the water to increase. These areas can still be used for aquaculture, thereby providing much-needed alternative livelihoods and food production [73]. Starting new culture systems in salinity-intense locations is thus aquaculture's largest challenge. Planning procedures must be implemented quickly in order to tackle this issue [73]. A greater significance of the integrated agricultural system is therefore assumed in these conditions of SLR, as well as its detrimental effects on agricultural activities and aquaculture for the adequate management of agricultural resources in order to reduce environmental degradation, improve agricultural productivity, improve the quality of life of poor farmers, and maintain sustainability [58]. Farmers are drawn to integrated systems in particular because they produce three different crops thanks to the use of water sources enriched with organic fish waste from intensive aquaculture ponds as fertilizer for terrestrial crops and water for raising sheep and goats, which results in the production of three different crops from the same amount of water [65]. El-Keram (a trading investment company in Egypt) is an ideal model which has applied this integrated system since 1990 [66].

4.3. Feed

Aquaculture relies heavily on capture fisheries for fishmeal. Fish output could be dramatically impacted by climate change, which would limit the availability of fishmeal and fish oil. In 2003, the aquaculture industry consumed 2.94 million tons of fishmeal, equivalent to 14.95 to 18.69 million tons of trash fish, feed fish, and low-value fish [74]. Climate change has the potential to have a negative influence on world fishmeal output, as seen by periodic shortages related to weather oscillations such as the El Nino phenomenon. Aquaculture industry expansion is boosting the demand for global sources of wild fishmeal to provide protein and oil elements for aquafeeds. Approximately 30% of the world's fish harvest (29.5 million tons) is used to produce fishmeal and fish oil for use in agriculture, aquaculture, and industry. Depending on the species, they can account for more than 50% of the meal. As a result, there is an urgent need for plant-based alternatives to fishmeal [59]. Recently, Egypt is seeking to change from low-intensity fish farming systems such as extensive and semi-intensive cultures to an intensive system that relies mainly on manufactured feed. This strategy increases the demand for commercial fish feed [75]. Furthermore, between 50% and 99% of feed ingredients used in aquafeed production in Egypt are imported [76,77]. The prices of components and processed feeds have significantly increased as a result of rising feed raw material costs globally and the Egyptian pound's deteriorating exchange rate against major currencies [78]. Similarly, feed accounts for 70–95% (on average, 85%) of all farm operating expenses. Fishmeal's partial or entire replacement with alternative protein sources has become more important as a result of its growing price, decreasing availability, erratic supply, and poor quality [79]. As a result, there is ongoing interest in finding and developing ingredients as substitutes for the expensive fishmeal feed [80] as well as in reducing its usage. Furthermore, climate change could also reduce the agricultural production of soy, corn, and other ingredients that today's fish feeds rely upon; hence, the industry has to search for new and sustainable resources to produce cultured fish, such as algae, in the future. The industry is in need of innovative solutions to solve this urgent challenge. Thus, several attempts on the different types of protein sources that have the ability of partially and/or totally replacing fishmeal in aquaculture feeds without affecting the performance of growth rates of fish are being extensively studied [81]. Particularly, many studies have been conducted to assess the partial or complete substitution of fishmeal in feed diets for tilapia with less expensive, as well as locally available, plant and animal protein sources [82–85]. Technology may lower the risks of higher prices and overfishing. It can provide substitutes to the use of captured fish derived inputs. Fishmeal and fish oil substitution in aquafeeds with nutritionally equivalent feedstuffs will diminish the reliance of different kinds of aquaculture on wild stocks. This substitution may also minimize pressure on the prices of feed inputs that result from capture fisheries.

4.4. Seeds

The climate change-related effects of variations in water temperature can affect the neuroendocrine control of reproduction in fish by acting at multiple levels of the brain–pituitary–gonad axis [86]. Consequently, this climate change is likely affecting sexual maturation, reproductive behavior, gametogenesis, spawning, and reproductive output. All the cited climate change-related factors seem to affect steroidogenesis. It is also important to note that the effects of climate change are not limited to breeders and gametes, but they also have direct consequences on their progeny, in particular at the level of growth. For instance, thermal embryonic history, potentially impacted by global warming, will influence the growth and fitness of larvae and juveniles [87]. Mechanothermal nociceptors responding to extreme heat (above 20 °C), but not to cold, have been found in the head trigeminal nerve of rainbow trout, and their properties are closely linked to the behavior of rainbow trout in natural and high-temperature stream pools [88,89]. Increased water temperature appears to represent the most detrimental factor of climate change, with the gonads as one the organs more damaged by high temperatures [90]. A high temperature regime also affects oocyte osmoregulation and causes a reduction in their phospholipids and free fatty acids content [91]. In fish, elevated temperatures may have irreversible effects during sensitive periods of early development, affecting larval growth, the incidence of malformations, and sex determination/differentiation, provoking functional masculinization [92,93]. Therefore, elevated temperatures might modulate the sex differentiation process and induce masculinization through its action on gonadal steroid synthesis and/or release during early developmental stages by acting at different levels of the developing reproductive axis (e.g., gonad and brain). Generally, temperature is the variable that influences fish seed production the most, followed by rainfall, humidity, and solar radiation intensity [94,95]. Unfavorable temperatures impair growth by changing the metabolic and developmental processes of fish [96,97], ultimately affecting seed production [20,98]. Rearing temperature considerably affects egg production, hatching rate, and larval growth rate [99,100]. Further climate change-related effects, such as hypoxia [101,102], acidification [103,104], and salinity [105,106] are likely to strongly affect the quality and amount of fish gamete and the viability of the offspring.

The Egyptian fish seed sector started in the 1980s when the General Fisheries Authority decided to establish 14 freshwater hatcheries to produce carp seed for stocking public and private fish farms, as well as to support the integration of aquaculture into rice fields and the stocking of natural reservoirs and lakes [107]. Private freshwater hatcheries started producing Nile tilapia fry in the early 1990s to satisfy growing demand from private fish farms, and to stock their own farms. The number of private hatcheries had increased from 7 by 1996 to some 86 licensed plus around 600 unlicensed hatcheries in 2020 [108]. According to the latest annual fish statistics in Egypt presented by GAFRD in 2020 [108], the annual production of fish fry from the fish hatcheries and wild fry collection centers developed from 538 million units in 2011 to 721 million unit in 2020. There are 15 governmental freshwater fish hatcheries; their total production of fingerlings are 55.9 l million units in 2020, while there were two governmental marine water fish hatcheries that produced 534.3 million units of fingerlings in 2020 [108]. Meanwhile, there were 86 licensed private hatcheries in 2020, which produced 64.8 million units of fry and fingerlings of tilapia fish in freshwater fish. In marine water, the private fish hatcheries produced 18.9 million units of fingerlings in 2020 [108]. Particularly, in Egypt, numerous tilapia hatcheries have sprouted up along with the development of the aquaculture sector, all of which produce fingerlings and male fingerlings with their sex reversed [109]. The seasonality of the climate is one of the major issues facing Egyptian aquaculture. The primary farmed species, Nile tilapia, develops and reproduces best in the summer (when temperatures range from 25 to 30 °C), whereas winter temperatures fall below the ideal range for growth and reproduction to satisfy the increased demand for seed by fish farmers at the beginning of the season [110]. A growing number of tilapia hatcheries in Egypt are bringing forward and prolonging their spawning season by heating the water in their systems [111]. The most popular method is solar heating, which involves enclosing breeding tanks or ponds in greenhouse tunnels. However, this can be supplemented by heating with a boiler or by utilizing groundwater that is warmer than surface water. As a result, the hatchery is able to satisfy the early-season high demand for seeds [109]. On the other hand, a major beneficial effect of the process is the generation of seeds and larvae for aquaculture for the creation of new or additional fishing resources for fisheries and livelihoods. Under the risks posed by climate change, restocking can offer significant potential to enhance fisheries or preserve and improve endangered species [49]. All the aforementioned climate change factors, in general, might have an immediate or long-term impact on aquaculture. As stated, these effects cannot always be traced to just one aspect of climate change; in most situations, a variety of elements combine to cause the effects [112].

5. The Threats of Climate Change on Food Security in Egypt

The weather in Egypt is often dry, hot, and desert. The coastal region has winter rainfall, but summers are hot and dry [113]. Climate characteristics have changed during the past few decades, and this has been seen and documented. According to recent research by Yin et al. [114], the mean maximum and minimum air temperatures have risen by +0.34 °C; each decimate characteristic has changed during the past few decades, and this has been seen and documented. The average air temperature and atmospheric pressure are also rising, by 0.017 °C and 0.026 hectopascals (hPa), respectively, every decade and year. According to the IPCC in 2008, climate change would have a significant impact on industries that depend on water. Agriculture, forestry, and fisheries are the three primary industries that are impacted by climate change [115]. Climate change has an influence on each of their manufacturing processes, although the effects will differ depending on the location. Because of the decline in output in tropical regions and the potential for adaptation issues, emerging nations such as Egypt may have difficulty adapting because of their poor economic capabilities [57]. SLR is also a critical concern in the climate change discussion [115]. The study by Conway et al. [116] confirmed that SLR had an adverse impact on water security and an increase water scarcity in Egypt. Furthermore, Bizikova et al. [117] suggested that climate change would lead to high market prices for food and thus, food will not be available to the poorest people leading to a food utilization problem of getting insufficient nutrients from the food consumed. In addition, according to the FAO report in 2008, the effects of climate change are expected to have a high impact on global food systems and food security [57]. Climate change poses a serious threat to Egypt's agricultural sector, increasing desertification rates, increasing water scarcity, threatening biodiversity, and affecting crop productivity and leading to food deficits and low levels of investment agriculture.

Due to its low-cost, high-quality protein, micronutrients, and omega-3 polyunsaturated fatty acid content, fish plays a significant role in food security [118]. Food security, according to the World Food Summit (WFS), is the condition in which all individuals always have physical or financial access to an adequate supply of wholesome foods that satisfy their dietary requirements and food choices for an active and healthy life [119]. However, the FAO study has introduced a novel idea by explaining that socioeconomic conditions and food access, rather than agroclimatic variables and food availability, determine food security [57]. When all members of society have the natural, social, and economic ability to get enough food that is safe, nourishing, and satisfies their dietary needs and preferences in order to live an active and healthy life, then there is a state of food security. Food availability, food stability, food intake, and access to food are therefore the four key components of food security. The expected impacts of climate change are posing a growing danger to food security, particularly to the availability of dietary protein. Due to aquaculture's substantial contribution to global food security, nutrition, and livelihoods, its effects on the industry have been thoroughly investigated and assessed on both a regional and worldwide level [19]. Fresh fish consumption is a historic and important part of the Egyptian diet, particularly in coastal towns and the northern Delta, and is a significant source of animal protein for the majority of the population. Fish imports of certain varieties, such as mackerel, tuna, herring, sardines, salmon, and frozen shrimp, make up for the 325,000 MT yearly difference between local consumption and production of fish. The yearly growth of imports reflects the influence of growing affluence on the consumer demand for fish species that are not grown in Egypt. Population growth (102 million projected by 2021) and economic expansion are also factors contributing to an increase in fish consumption. Consumption of fish per person increased from 16.67 kg per year in 2012 to 20.26 kg per year in 2020 (imports excluded [1]). Due to the Mediterranean Sea's rising level, climate change directly affects food security in Egypt by posing several dangers to the Nile Delta.

As a result, agricultural regions will have more salt and groundwater. Additionally, the north's freshwater lakes will become more salinized, which will result in the loss of some of the region's most productive farmland and a decline in fish output and other plants and animals. Fish, which is Egypt's main supply of animal protein and a crucial and reasonably priced source of nourishment for the underprivileged, will vary in species and composition. Numerous residents of these areas have been forced to leave because of waterlogging, poor fertility, and a lack of other employment [120]. Egypt is currently putting into action a number of massive projects in the agricultural sector to address climate risks, including the construction of 100,000 greenhouses that can supply year-round vegetables at affordable prices to curb price increases and introduce high-quality agricultural products. Egypt has put in place a horizontal extension project for the reclamation and cultivation of 1.5 million acres, along with programs for agricultural industrialization [113].

Finally, because of the possibility of infrastructure damage or degradation, food systems, particularly those in poor nations, face a significant danger from the anticipated effects of climate change. Transporting food and supplies may be a challenge for local suppliers in this situation [121,122]. Therefore, all of these factors must be taken into account in all nations' adaptation efforts to climate change [122]. The hazards of climate change affect every element of the food system in Egypt. With the bulk of the population residing in the Delta and along the coast, agriculture is essential to Egypt's GDP and food production. Geographical distribution has a greater effect on the food chain since the delta and coastal regions are both at risk of drowning in the next decades. As a result, climate change has an impact on and is sensitive to Egypt's food system. Global food systems and food security are significantly and directly impacted by climate change as well. The FAO highlighted possible effects on the following elements: food system assets, activities, food availability and accessibility, livelihoods, and policies and regulations [57]. The anticipated consequences of climate change are posing a growing danger to food security, especially to the availability of dietary protein. Due to aquaculture's substantial contribution to global food security, nutrition, and livelihoods, its effects on the industry have been thoroughly investigated and assessed on both a regional and worldwide level [19].

6. Effect of Climate Change on the Sustainability of the Fish Farm Sector in Egypt

Sustainable development focuses on the management and conservation of natural resources and the orientation of technological and institutional changes in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations [123]. As a concept, sustainable aquaculture is the practice of aquaculture that emphasizes environmental, economic, and social sustainability to enhance capacity building and utilize land for the aquaculture industry successfully. Similarly, sustainability can refer to the management of financial, technological, institutional, natural, and social resources to assure a consistent supply of human needs, not just for today but also for future generations [124], which refers to the management of institutional, environmental, financial, technological, and social resources to guarantee a steady supply of human needs for both the present and future generations [125]. Aquaculture may compete with other food-producing sectors for the same resources or be impacted by pollution from those sectors [46]. The sustainability of aquaculture has been debated for decades. Potential issues include habitat destruction, the use of marine ingredients in feeds, freshwater usage, using wild juveniles for farm stocking, influencing wild gene pools through farm escapees, and the excessive loss of stock through disease and associated overuse of antibiotics, which are environmentally non-degrading, technically appropriate, economically viable, and socially acceptable. Although the aquaculture industry is expanding in Egypt, the fish culture sector is also facing some problems, such as environmental degradation, water scarcity, limited availability of land for aquaculture, high input costs, etc. Thus, sustainability in the aquaculture sector is more needed nowadays. Concerns about nutrition and sustainability are significantly related; feed consumption, species choice, and the adaptability of production systems to climate change are crucial for both [126]. Environmental, economic, and social sustainability indicators may be used to evaluate the sustainability of aquaculture systems. The effective use of natural resources and pollution are examples of environmental sustainability indicators, pollution prevention, and biodiversity conservation [125]. In Africa, Egypt is regarded as one of the top nations for aquaculture. Additionally, Egypt has a mixed economic system that combines a range of individual freedoms with centralized financial planning and governmental supervision [127]. Egypt is a classic example of a developing nation that is seriously at risk from climate change and has severe challenges to its capacity to maintain its economic, social, and environmental sustainability. As a result, the competitiveness of Egypt is under tremendous fundamental strain. Increasing dangers to national security can also be used to characterize these tensions. They are propelled by an expanding population, increasing demand, and the limitations imposed by a limited resource base. If not handled swiftly and forcefully, they could escalate into true crisis situations. The whole aquaculture value chain is sensitive to the effects of climate change, despite certain elements of this being unclear [128,129]. Aquaculture is not an exception to the fact that the viability of food production systems is progressively being threatened by climate change [1,42]. According to the IPCC [42], climate change consequences and solutions are directly related to sustainable development, which strikes a balance between environmental preservation, economic success, and social well-being. This implies that aquaculture output cannot be sustainable without addressing the consequences of climate change.

Although many constraints are facing fish farmers in Egypt, including climate change, there is a rapid expansion in aquaculture. Egypt has increased its aquaculture production significantly to become the first major producer in Africa, although the share of Africa is still low at about 2.7% of world aquaculture production [1]. Fish aquaculture farms are considered as the main source of Egyptian fish production, which represents about 79.2% [108]. Fish production represented 16.25% of the total Egyptian agricultural GDP [108]. Aquaculture is an effective solution to reduce the gap between fish production and demand in Egypt. Despite the economic importance of aquaculture, some fish farmers have abandoned it due to some challenges that make the project unprofitable. In Egypt, parts of the vast Nile Delta are dotted with man-made, open-air ponds stocked with tilapia, perch, and other fish. In Egypt, aquaculture has become increasingly popular in recent years, as breeding and technological improvements make each pond more productive and profitable. Fish farming produces more protein and revenue per acre than crop farming, and with a lower water and carbon emission footprint per kilo of product. One kilogram of farmed fish requires about 1000 L of water to produce, while the same weight of rice or wheat can require two to four times the volume of water [130]. Moreover, fish farmers are not really a consumer of water; they are a user of water. While in agriculture, water is only used once, fish farmers are able to use it several times. However, water scarcity and rising supply costs—the problems that loom over the Delta at large—are threatening to capsize the fish farming industry in Egypt. With a rapidly growing population, an unstable global supply chain for food imports, rising temperatures, and limited land and water resources, Egypt could still find a promising path to food security and economic growth in pisciculture, but only if it can be undertaken by a smarter sustainability process [131]. Aquaculture plays a crucial role in Egypt's economic development, contributing substantially to achieving the Sustainable Development Goals. However, contexts are increasingly changing and are characterized by shifts in dietary needs, more integrated value chains, globalization, population dynamics, and climate change. An enhanced understanding of aquaculture's performance under these rapidly changing contexts is necessary. Yet, the ability to generate the required knowledge is often constrained by a lack of accurate data about the integrated on-farm performance of aquaculture systems. In efforts to address this gap, in Egypt, farmers practicing tilapia monoculture stocked smaller fingerlings than their polyculture counterparts, reaching the same harvest weight and obtaining a 20% higher yield than under polyculture. Tilapia monoculture was 42% more profitable and 18% more cost-effective than polyculture systems. There were no significant differences in productivity, profitability, and cost-effectiveness across different farm sizes. There is also a notable increase in the adoption of modern extruded feed. However, there is a growing trend in incidences of abnormal fish mortality. Farmers' perceptions of climate change and its impacts on tilapia aquaculture are very low. Similarly, farmers' awareness of fish food safety certification is very low and only a few are interested in participating in such schemes if established [130]. Thus, the need for continued efforts and investments to promote aquaculture in Egypt is necessary. Specifically, the results on the cost-effectiveness of tilapia culture present evidence about the scalability of tilapia in Egypt. At the same time, interventions to promote the wide-scale adoption of aquaculture and the best management practices might help to reverse the trends in abnormal fish mortality in the immediate and medium term. In the long term, breeding for resilience traits will be crucial. There is also a need for increased access to climate information services to improve farmers' perceptions of climate change and its impacts in order to facilitate timely adaptation.

7. The Mitigation of Negative Impacts of Climate Change on Fish Culture

The fastest-growing industry in Egypt is aquaculture, which is also the country's primary source of fish and animal protein. Fish farming in Egypt has gradually transitioned from extensive to semi-intensive to intensive, with rapid development in the use of modern technologies, such as the use of a recirculating aquaculture system (RAS), fish–plant integrated system (such as aquaponics), fish–animal integrated system, and biofloc technology (BFT), as well as enhanced farm management techniques. The demand for resources used in aquaculture, including fish food, seeds, water, energy, and land, has risen as a result of this strategy [108]. In addition, climate change is considered one such constraint as it may have negative implications on the productivity of aquaculture. For alleviating these severe effects of climate change on the fish farming sector not only in Egypt, but also all over the world, there are two ways: the first is mitigation action, and the second is adaptation action. Regarding mitigation action, we can mitigate climate change, which involves reducing the concentration of gases from the winter effect; there is a sea reduction in leaks or an increase in sinks. Aquaculture can produce wholesome food with a small carbon footprint by concentrating on herbivorous species. Growing aquatic plants aids in the removal of trash from contaminated waters, while raising shellfish such as oysters and mussels is not only profitable but also contributes to the cleaning of coastal waters. In contrast to the potential declines in agricultural yields in many parts of the world, the climatic environment provides new opportunities for aquaculture in the medium term; that is, farming more species [58]. In addition, Egypt has developed various policies and measures to internalize renewable energy, energy efficiency, and reduce GHG emissions, as endorsed by the UNFCCC. Technology transfer needs to mitigate the effects of climate change in the medium term to include environmentally friendly technologies to protect the Mediterranean coast in general and the low-lying coastal areas of the Nile Delta in particular. Technical and financial support is urgently needed to establish research programs with teams from existing universities and research institutes [132]. Consequently, the second strategy to cope with climate change is a possible adaptation option, to improve the resilience of Egyptian aquaculture to the impacts of climate change which is imperative for the future development and sustainability of the sector. Whilst Egypt considers all possible adaptation options and regards adaptation as a key part of its climate change policy [133], farmers need to adapt in order to protect their everyday operations, cope with harsh weather, and ensure their revenue [134]. As a result, adaptation measures are taken in Egypt to either mitigate or capitalize on the real and anticipated effects of climate change, either by raising or decreasing a system's resilience. To lessen the ecosystem's overall susceptibility to climate change, this may entail reprioritizing present activities and setting new goals and objectives. In addition, adaptation action can take place in legal, regulatory, institutional, or decision-making processes, as well as in on-site conservation activities. For example, measures to restore or protect wetlands and riparian zones can help to moderate or lower river temperatures, alleviate flooding and the erosive effects of extreme rainfall or rapid snowmelt, improve habitat quality, and allow species to migrate. Thus, the early implementation of strategic adaptation measures can reduce severe impacts and avoid the need for more costly measures in the future. The actions aim to: eliminate other threats and reduce non-climate stressors that exacerbate the effects of climate change; establish, expand, or adapt protected areas, habitat buffer zones, and corridors; and improve monitoring and facilitate management under uncertainty, including scenario-based planning and adaptive management.

Role of Modern Aquaculture (Integrated) Systems to Mitigate the of Impacts of the Climate Change

Global food demand will increase by 70–100% by 2050 [135], and the key role of the agricultural sector in food security [136], one of the greatest issues of the 21st century, is to find a way to produce more food using fewer resources and minimizing environmental impacts [137]. Among the systems currently used by the agricultural sector, aquaculture seems to be the most suitable and convenient for counteracting shortages in food production [138]. In the integrated fish culture system, the main beneficiary is fish, which utilize animal and agricultural wastes directly or indirectly as food. As integrated farming involves the recycling of wastes, it has been considered an economic and efficient means of environmental management. Moreover, diversifying food systems and integrated agriculture production systems can be important climate change adaptation measures [139]. In this respect, modern aquaculture systems reuse the same volume of water [140,141], where the rate of water reuse ranges between 80 and 99%, therefore reducing water requirements and the environmental impact of aquaculture [142]. The unification of a RAS and aquaponics improves sustainability and ensures food sufficiency, providing various significant economic and social benefits [143].

A. Recirculation aquaculture system (RAS)

The RAS is considered a promising intensive fish culture system. RAS is designed to raise large quantities of fish in relatively small volumes of water by treating the water to remove toxic waste products and then reusing it [144]. RAS is a technology where water is recycled and reused after mechanical and biological filtration and removal of suspended matter and metabolites. This method is used for the high-density culture of various species of fish, utilizing minimum land area and water. RASs have become more numerous and equally sophisticated as land-based aquaculture production has increased. The complexity of the system gives rise to a good deal of health management issues, whereby the water quality of the production system directly impacts the health of the fish. Additionally, the challenges of using RAS in a seawater environment pose unique issues of water chemistry, fish production biology, and health. Fish health management in RAS depends largely upon the quality of the intake water for controlling the known obligate fish pathogens [145]. RAS technology is based on the use of mechanical and biological filters and the method can be used for any species grown in aquaculture as shown in Figure 5. New water is added to the tanks only to make up for splash out, evaporation, and that used to flush out waste materials. The reconditioned water circulates through the system and not more than 10% of the total water volume of the system is replaced daily. In order to compete economically and to efficiently use the substantial capital investment in the recirculation system, the fish farmer needs to grow as many fish as possible in the inbuilt capacity [144]. The management of recirculating systems relies heavily on the quantity and quality of feed and the type of filtration. RASs have low direct land and water requirements and enable high stocking densities but do require large energy inputs and thus have high production costs and waste disposal challenges [146]. RAS technologies are typically beneficial when advantages in fish performance outweigh the increased costs. Grow-out operations in RAS are progressively focused on species with a high market value. In addition, RAS is an invaluable alternative for preventing water pollution by diminishing both the volume and the eutrophication potential of the effluents [147]. The development of a commercial-scale RAS has been stimulated primarily by an interest in producing high-value warm water fish and eels. RASs overcome the constraints imposed by temperate climates and other environmental factors by providing a controlled, predictable, and biosecure environment for the cultured species [148]. Thus, RAS is an eco-friendly, water efficient, highly productive intensive farming system, which is not associated with adverse environmental impacts, such as habitat destruction, water pollution and eutrophication, biotic depletion, ecological effects on biodiversity due to captive fish and exotic species escape, disease outbreaks, or parasite transmission. Moreover, RASs operate in an indoor, controlled environment, and thus, are only minimally affected by climatic factors, including rainfall variation, flood, drought, global warming, cyclones, salinity fluctuation, ocean acidification, and sea level rise. However, energy consumption and GHG emissions are the two most stringent limiting factors for RASs. Despite these potentials and promises, RASs have not yet been widely practiced, particularly in developing countries, due to their complex and costly system designs. Further research with technological innovations is needed to establish low-cost, energy-efficient RASs for intensifying seafood production, reducing GHG emissions, and adaptation to climate change [149].

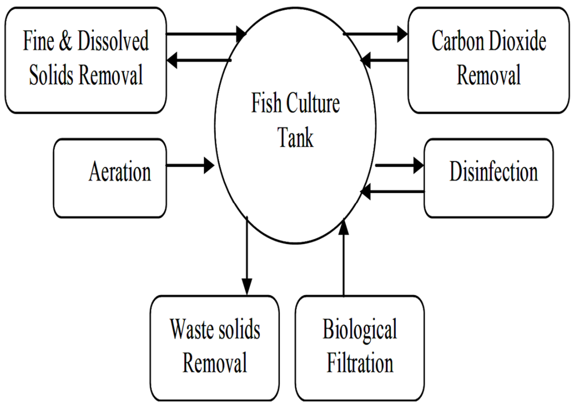

Figure 5. Recirculating aquaculture system components [144].

B. Aquaponics system

The integrated fish–plant system is named an aquaponics system, where aquaponics is a symbiotic integration of two mature disciplines: aquaculture and hydroponics. It is a hybrid food technology system that helps mitigate climate change through the combination of fish tanks and crops. The name "aquaponics" derives from a mixture of two words; aqua from aquaculture, which is the farming of aquatic organisms, and ponics from hydroponics, which uses water instead of soil to grow plants [150,151]. Many different food products can be grown using a combination of plant and fish farming in an aquaponics system. Reusing water after mechanical and biological filtration and recirculation provides local healthy food that can support the local economy [152]. Plant roots and rhizobacteria take nutrients from fish manure in the water and absorb them as fertilizers to hydroponically grow plants. In return, hydroponics acts as a biofilter stripping off ammonia, nitrates, nitrites, and phosphorus. Then, the water can be recirculated, fresh and clean, into the fish tanks in a closed cycle as shown in Figure 6. Aquaponics is a sustainable production system with two methods of cultivation, plants and fish. It combines traditional aquaculture, which is the breeding of aquatic animals such as fish, crayfish, and shrimp, with hydroponics, where plants are grown in water in a symbiotic environment. It combines conventional aquaculture, or the tank-rearing of aquatic animals, with hydroponics, the growing of crops in nutrient-rich water [153]. Clearing land for crops, artificial fertilizers, insecticides, herbicides, and larger livestock herds accounts for almost one-quarter of anthropogenic GHG emissions. Meanwhile, the aquaponic technique produces crops and raises fish without relying on toxic chemical pesticides, synthetic fertilizers, genetically modified seeds, or practices that degrade soil, water, or other natural resources. More specifically, aquaponics is a hybrid food technology system that has the potential to remove the negative environmental impact of current farming techniques [154]. This system is a valuable alternative to both traditional agriculture, fishing, and fish farming. Its advantages include water conservation, sustainability, and the eliminated need for soil [155]. In addition, aquaponics achieves the automatic and digital monitoring of aquaculture systems by controlling and mitigating abiotic factors. Generally, aquaponics systems achieve savings by requiring less water quality monitoring, less physical land, and the sharing of equipment such as pumps and heaters [151]. The operational cost savings for commercial use would also be evident through the elimination of insect and weed control. Moreover, aquaponics can be a strong alternative system to conventional agriculture and land reclamation in Egypt. Although the cost of aquaponics can be seen as expensive, especially for small farmers and startups, the profit per acre can reach 30 times more than the profit from land reclamation or conventional agriculture [156]. In developing countries or places that are frequently and heavily affected by climate change issues such as Egypt, the use of aquaponics delivers a source of food that is unaffected by climate change. Utilizing aquaponics systems could mitigate climate change and significantly add to increased food security to the benefit of people [157].

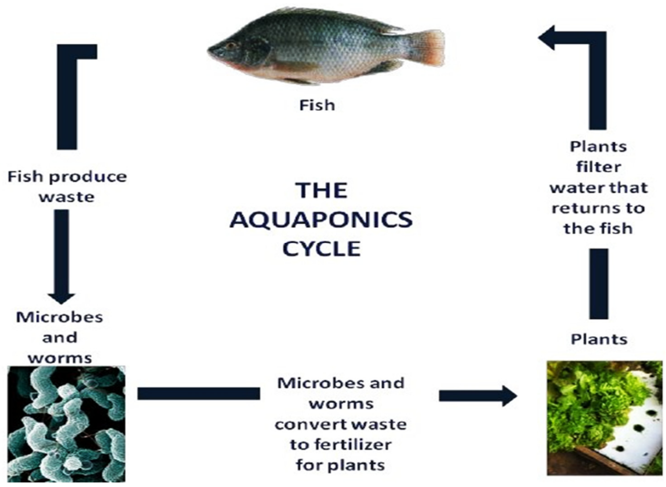

Figure 6. The aquaponics system cycle [158].

C. Biofloc technology (BFT)

Successful fish farming is entirely dependent on the physicochemical and biological qualities of water. Consequently, water quality control is required for optimum pond management [159]. Some studies suggest that the ratio between nitrogen (N) and carbon (C) in the water during the period of aquaculture should be controlled by implementing successful BFT [160]. Thus, BFT is an integrated system as shown in Figure 7, and the quality of this system, which depends on the biotic composition of biofloc and the quantity of suspended solids, is checked with Imhoff cones. For checking the biotic composition of biofloc, water collected from the system is reserved in Imhoff cones for precipitation. In this respect, BFT is a newly emerging frugal technology for fish cultivation in which nitrogenous wastes generated from fish/shellfish and unconsumed feed can be converted to protein-rich feed in the form of biofloc [161]. It was developed to improve ecological control over aquatic animal production or to treat wastewater, but now it has gained importance as an approach in aquaculture [162]. This operates the system on the principle of increasing carbon-to-nitrogen ratios, through the addition of an exogenous carbon source that consequently stimulates natural heterotrophic bacterial growth in the system, which converts them into microbial protein [163,164]. It is realized that fishmeal being used in aquaculture production systems as a protein source for the formulation of fish and shrimp feed can be significantly replaced by biofloc meal [165]. In addition, the sustainable approach of such a system is based on the growth of micro-organisms in the culture medium, the least amount or zero water exchange, high dissolved oxygen level, and a high C:N ratio; thus, it can be considered an environmentally friendly strategy and an important tool against the drastic effects of climate change [166,167]. Therefore, BFT has been widely used to maximize tilapia production for its ability to support high-density cultivation, to improve water quality, and, simultaneously, recycle feed and protein production in the same culture unit [168,169]. Moreover, Kuhn et al. [170] reported that microbial floc meal in tilapia diets significantly increase weight gain. Biofloc consumption by fish could contribute about 50% of the dietary protein requirements of Nile tilapia [171].

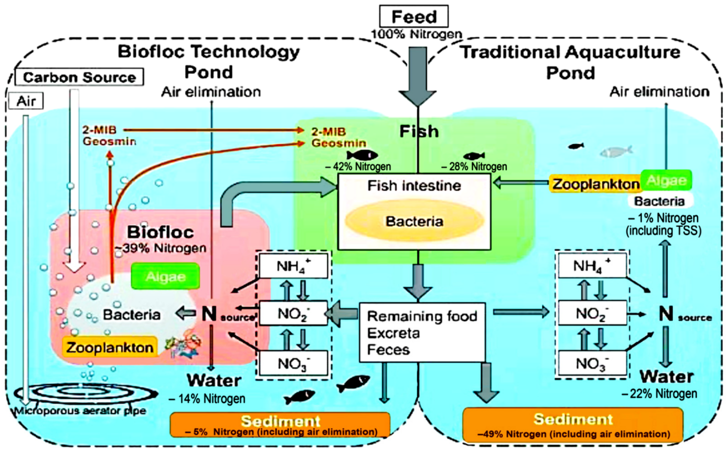

Figure 7. Role of microbial communities in biofloc technology (BFT) to improved water quality and fish yield in freshwater indoor and outdoor pond aquaculture [172].

D. Integrated multi-trophic aquaculture (IMTA)

To avoid or alleviate the negative effects posed by aquafarming, integrated multi-trophic aquaculture (IMTA) is proposed as a potential bio-mitigation approach. IMTA aims to achieve the sustainable development of aquaculture and improve the productivity of intensive monoculture through reusing waste as food resources. In this integrated system, the targeted species are co-cultivated with others that have dissimilar feeding habits in different trophic levels [173]. Various species of nutrient absorber, suspended feeder, deposit feeder, and other organic extractive organisms could be considered as the candidates to be co-cultured with targeted species (finfish, e.g., red sea bream *Pagrus major*, Atlantic salmon *Salmo salar*) in an IMTA system. Waste released from fish farms could offer food sources for inorganic and organic nutrient extractive species. For instance (Figure 8), as particulate organic waste (e.g., fish fecal matter, waste fish feed) mainly sinks down to the sea bottom, deposit feeders (e.g., Japanese sea cucumber *Apostichopus japonicus*, giant California sea cucumber *Parastichopus californicus*) will ingest it as food, consequently mitigating the problem of hypoxic bottom water due to increased oxygen consumption during the bacterial decomposition of excessive organic matter. As another form of aquaculture waste, dissolved nutrients (e.g., phosphorus, nitrogen) cause eutrophication, which increases the risk of harmful algal blooms. Planting nutrient absorbers (e.g., seaweeds *Gracilaria chilensis*, *Laminaria japonica*, *Ulva ohnoi*) could minimize this risk through their competition with phytoplankton for resources and harvesting macroalgae periodically will speed up the removal of dissolved nutrients [174]. Meanwhile, the supplement, suspension feeders, and other organic extractive species are capable of further filtering the phytoplankton, as well as the dispersed small particle organic materials from both fish food and feces in the water column. From an environmental point of view, these modern fish farming systems represent a novel technology that improves production efficiency, while mitigating environmental impacts (pollution load, including GHGs emissions), diversifying fish production, animal welfare in aquaculture systems, climate change studies, soil depletion, technologies that mitigate the emergence of animal diseases or parasites, and reducing the use of antibiotics, chemical fertilizers, new feed ingredients, and carbon footprint [175,176].

These systems also prevent the release of aquaculture waste that pollutes water bodies (eutrophication), allowing greater control of the water and production, which makes food safer against possible residues [151,177]. These integrated systems not only reduce waste but also increase productivity by using by-products from crops, livestock, fish systems, and other waste as inputs for different subsystems. This also reduces farmers' dependence on agro-industrial products such as commercial inorganic fertilizers and formulated pelleted feed.

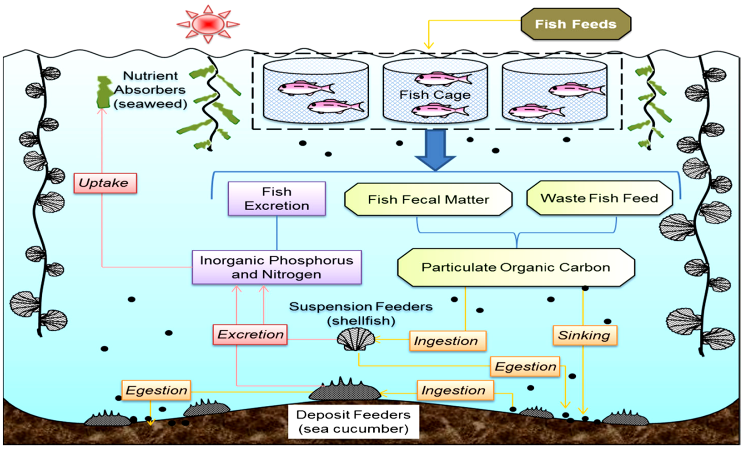

Figure 8. Conceptual diagram of the integrated multi-trophic aquaculture system (IMTA). Boxes represent state variables and/or interaction processes. Arrows denote the carbon cycle (brown color) and nutrient cycle (pink color), respectively [178].

By applying the concept of circularity, integrated agricultural systems can thus minimize energy and materials use, reduce environmental impacts, and create new business opportunities, as well as achieve more sustainability in the aquaculture sector [179]. Furthermore, traditional integrated agriculture–aquaculture (IAA) systems are semi-intensive, with limited feed and nutrient inputs and minimal use of electricity. This means that the GHG emissions from traditional IAA are negligible. Furthermore, in livestock–fish systems, where the manure of farm animals such as chickens is converted into nutrients for fish, methane and nitrous oxide emissions produced by decomposing animal waste are avoided. The Intergovernmental Panel on Climate Change (IPCC) has found that IAA systems can play an important role in making food systems more resilient while reducing GHG emissions [139]. By providing more protein for household diets, they may also reduce the demand for other kinds of meat production, including less sustainable forms of aquaculture. Ahmed et al. [180] estimated that converting 25% of the world's aquaculture area (4.5 million ha, of a total of 18 million) to agriculturally eutrophic impoundment and IAA would increase carbon storage by 95.4 million tons per year, which will consequently lead to mitigating the negative effects of climate change on this imperative sector. Particularly, in Egypt, IAA provides a proven method to increase production efficiency. An example is the tilapia farms, where integrated systems for horticulture and aquaculture focus on water use, especially in a region considered the most water-scarce in the world. With looming water wars if this crisis is not handled correctly, the efficient use of water such as these tilapia farms is much needed. One type of system is aquaponics, in which fish and plants are grown together and the nutrient-rich water resulting from fish waste is used as a fertilizer for the plants, instead of leaving the system. This is a perfect example of how interconnected interactions within an ecosystem, including humans, can serve to better address sustainability concerns. Adopting integrated aquaculture as a strategy not only increases output productivity and efficiency in a sustainable manner, it also plays a major role in reducing the sector's vulnerability and increasing its resilience to climate change, as well as offering a resilient solution to increased food security [181]. IMTA is a system that feeds species with species that remove organic substances and extractive species that are inorganic, which use aquaculture waste for their development. Therefore, one of the key strategies currently being used is encouraging IMTA, a novel process of growing finfish alongside shellfish such as oysters and marine plants such as seaweeds. Interestingly, we are seeing more applications of this system in many forms, which are environmentally friendly [182]. Thus, IMTA is considered to be more sustainable than conventional monoculture systems because it may combine several species. A few examples include the recent announcement by the South Asian Association for Regional Cooperation (SAARC) countries of introducing IMTA as a means to reduce the impacts of climate change on the sector, trials in Europe focusing on culturing lobsters alongside salmon, a vision to have a rainforest in the ocean, or better yet, an effort to carbon capture more CO_2 than is produced by the Netherlands each year [183,184].

8. Conclusions

Climate change is the major global challenge today, and the world is becoming more vulnerable to this change. Climate change is expected to exacerbate in occurrence and intensity in the future, which results in negative impacts on social, economic, and environmental aspects. Specifically, Egypt's large population makes it one of the countries most affected by the negative effects of climate change. Egypt is particularly vulnerable to the impacts of climate variability and change, particularly with respect to water security, agriculture, fish culture and livestock, increasingly adverse conditions to public health, human settlements, and energy demand and supply. In addition, climate change could have significant adverse economic impacts in Egypt. The country is heavily dependent on the Nile River (which accounts for 96% of the water resources available), which may decrease in flow [185,186]. The negative effects of climate change adversely impact not only the agriculture sector in general, or the fish culture sector in particular, but also human health. Egypt has recently created a number of national programs in the fields of climate protection and adaptation to climate change. Out of a total budget of USD 324 billion, Egypt's mitigation and adaptation projects will cost around USD 211 and USD 113 billion, respectively, in addition to energy efficiency initiatives, wind energy initiatives, and environmentally friendly transportation initiatives. Other initiatives, such as biogas projects, landfills, and recycling facilities, try to use trash as fuel and promote complete waste management. As part of an integrated model for climate change mitigation and adaptation initiatives, they also include wastewater treatment facilities, sewer lining projects, seawater desalination, and water rationalization. This also includes the implementation of natural gas supply projects, waste management, sewage treatment plants, and afforestation.

Even though aquaculture plays an essential role in the Egyptian food system, accounting for approximately 80% of total fish production [108], climate change already affects aquaculture and the impacts are likely to increase in all aspects of this vital sector. In order to reduce the possible dangers of climate change on fish productivity, it is crucial that the Egyptian government and policymakers develop sound policies. Consequently, the Egyptian government is also investing in establishing huge sea aquaculture systems in coastal governorates to compensate for the lower yield from the open sea due to climate change. The Berka Ghalion aquaculture complex in Kafr El-Sheikh includes a fish hatchery, 454 fish ponds, 655 shrimps ponds, and 156 nursery ponds. The complex covers 4000 acres, including a fodder factory and fish packaging factory offering 5000 job opportunities. The government is also taking huge strides in the rehabilitation of Egyptian coastal lakes to protect fisheries, especially the production of fish seed and the maximization of the use of its natural lakes in the production of fish wealth. This also provides the restoration of ecosystem services, thus combating climate change and loss of biodiversity. In addition, the Ministry of Water Resources and Irrigation is introducing large investments through the Shore Protection Authority (SPA), in cooperation with the UNDP with funding from the Green Climate Fund (GCF) in upscaling an ecosystem-based approach, following an ecosystem-based approach for the protection of low-lying lands in the Nile Delta. Finally, we can summarize the possible solutions for adaptations against the negative effects of climate change on aquaculture in Egypt to achieve the sustainability of this imperative sector in the following points:

a. Greater public awareness, especially among all related stakeholders to the fish farming sector in Egypt, must be raised about the problems of climate change and its negative effects on the fish sector;
b. Using environmentally friendly aquaculture techniques such as RAS, aquaponics, BFT, or cage farming systems;
c. Using groundwater and effluent discharge in order to overcome the present and future anticipated limitations of fresh water and brackish water;
d. Researchers should start to evaluate the economic feasibility and optimum usage of novel proteins as fishmeal substitutes. Furthermore, the improvement of local raw materials to be used in fish feed formulation is also highly recommended;
e. The creation of new fish strains with increased salinity tolerance or increased temperature tolerance to cope with alterations by climate change;
f. The easier solution is to diversify the production to a heat-tolerant fish species or gradually increase the production of fish species such as the African catfish, which is more resistant to higher temperatures, has a larger thermal window, and better responds to thermal stress;
g. Increasing the production of fish seeds in hatcheries, as well as the genetic selection of seeds that adapt to new environmental conditions;
h. Reducing energy use through energy conservation and introducing possible renewable energy approaches.

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