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# Decades of Efforts in Cage Fish Farming in the Caspian Sea: Challenges and Prospects

**Saeid Esameilpour-Poodeh[1,*], Leilei Zou[2], Rasoul Ghorbani[1,*], Daisuke Kitazawa[3]**

[1]Department of Fisheries Sciences, Faculty of Environmental and Fisheries Sciences, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran.
[2]Research Institute of Marine Policy and Low, Shanghai Ocean University, Shanghai, China.
[3]Institute of Industrial Science, University of Tokyo, Chiba, Japan.
[#]These authors share the first authorship.

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**Corresponding Author**
E-mail: esmaeilpoorsaeid@yahoo.com
rasulghorbani@gmail.com

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## Abstract

With about 750 km of coastline along the southern Caspian Sea, Iran holds substantial potential for coastal aquaculture. Overfishing and other anthropogenic pressures have caused a sharp decline in valuable fish stocks, prompting the government to explore cage fish farming as an alternative to reduce pressure on wild populations, ensure food security, and support local livelihoods. This review synthesizes national efforts, policies, and scientific studies on cage aquaculture in the southern Caspian Sea, highlighting the key factors behind its limited progress. Between 2018 and 2023, cage aquaculture in the southern Caspian produced nearly 1,940 tonnes, with 1,850 tonnes recorded across central coastal counties (Mazandaran) in the 2023–2024 period, while provincial and national datasets show a wider but uneven distribution of production. These figures suggest that less than half of the region's estimated carrying capacity is currently utilized. Environmental concerns, economic instability, stakeholder conflicts, and insufficient legal and technical frameworks continue to constrain sustainable growth. Nevertheless, targeted adoption of eco-friendly technologies, strengthened governance, and community-based management could unlock substantial capacity and lead to resilient development of cage aquaculture in Iran's Caspian region. This review integrates ecological, socio-economic, and policy perspectives to provide a forward-looking framework for sustainable aquaculture planning in the southern Caspian Sea.

## Introduction

Aquaculture has become one of the fastest-growing food production sectors worldwide, providing high-quality animal protein, employment, and income opportunities (Hasan, 2007; Tacon and Forster, 2002; Barraza-Guardado et al., 2013). Global aquaculture production has expanded rapidly over the past four decades, surpassing capture fisheries for the first time in total aquatic animal output (FAO, 2024a).

Coastal aquaculture, in particular, plays a crucial role in supporting livelihoods and food security in developing regions, especially across Asia and Latin America (FAO, 2022). However, the expansion of land-based aquaculture systems is increasingly constrained by high economic and energy costs, and similar limitations apply to the coastal lands along the Caspian Sea (Langan, 2012; Chua, 1992; Shaik and Thuvanismail, 2024). Consequently, there is growing attention toward more efficient production methods such as marine cage farming (Halwart et al., 2007; Hu, 1994).

The Caspian Sea—the world's largest enclosed inland water body—provides both unique opportunities and challenges for such development. Stretching

between Eastern Europe and Central Asia, its $3.7x10^6$ $km^2$ drainage basin includes more than 130 rivers (Rodionov, 1994). Iran, with about 750 km of southern Caspian coastline, has pursued cage farming as a strategy to enhance fish production while reducing pressure on wild stocks (Kalbassi et al., 2013). Government initiatives have included the establishment of research centers, provision of financial incentives, and pilot projects to evaluate suitable fish species and farming technologies (FAO, 2024b; Azizpour et al., 2025).

Despite progress, cage aquaculture in the southern Caspian still faces ecological, economic, and social challenges, including water pollution, disease risks, high investment costs, and limited community acceptance (Farabi et al., 2021; Azizpour et al., 2025).

The aim of this paper is to review the development efforts, current status, and future prospects of cage aquaculture along Iran's Caspian coast. To achieve this goal, we adopted a mixed descriptive and narrative review approach based on a desk analysis of scientific publications, national and regional reports, and fisheries statistics related to marine cage aquaculture in the southern Caspian Sea.

**The Importance of Cage Culture in the Caspian Sea**

Iran has recently been grappling with two significant challenges: water scarcity and food security (Risk et al., 2021). To address concerns about the future protein availability for its population, the government has recently encouraged the development of net-pen fish farming in the Persian Gulf, the Caspian Sea and inland water bodies. The development of cage fish farming in Iran has encountered various challenges, leading to fluctuations in production levels in this sector (as shown in Figure 1).

The Caspian Sea, with 750 km coastline in Iran, holds significant ecological, economic, and cultural value (Pak and Farajzadeh, 2007; Nasrollahzadeh, 2010). The three provinces of Gilan, Mazandaran, and Golestan are located in northern Iran along the southern coasts of the Caspian Sea. The waters of these provinces are rich in aquatic resources, including species like the beluga sturgeon (*Huso huso*, Linnaeus, 1758), Caspian kutum (*Rutilus kutum*, Kamensky, 1901), Caspian trout (*Salmo caspius*, Kessler, 1877), Caspian kilka (*Clupeonella cultriventris*, Nordmann, 1840), and more. Additionally, 122 coastal fishing cooperatives are active in these areas (Hosseinjani et al., 2024). Traditional fishing practices in the region have been vital for local communities but have also led to overfishing and the depletion of key species such as sturgeon, known for its highly prized caviar (Pourkazemi, 2006). Cage farming offers a sustainable alternative that helps reduce pressure on wild stocks while simultaneously creating new employment opportunities. Moreover, it has the potential to play a transformative role in this area.

Economically, the development of cage farming in the Caspian Sea region can significantly boost local and national economies (Azizpour et al., 2025). Iran, with its extensive coastline along the Caspian Sea, stands to benefit greatly from this aquaculture practice. By increasing fish production through controlled and efficient methods, cage farming can create new employment opportunities, support local livelihoods, and contribute to food security. The introduction of high-value species, such as sturgeon and Caspian trout, into cage farming systems can also enhance export potential, bringing in foreign exchange and stimulating economic growth.

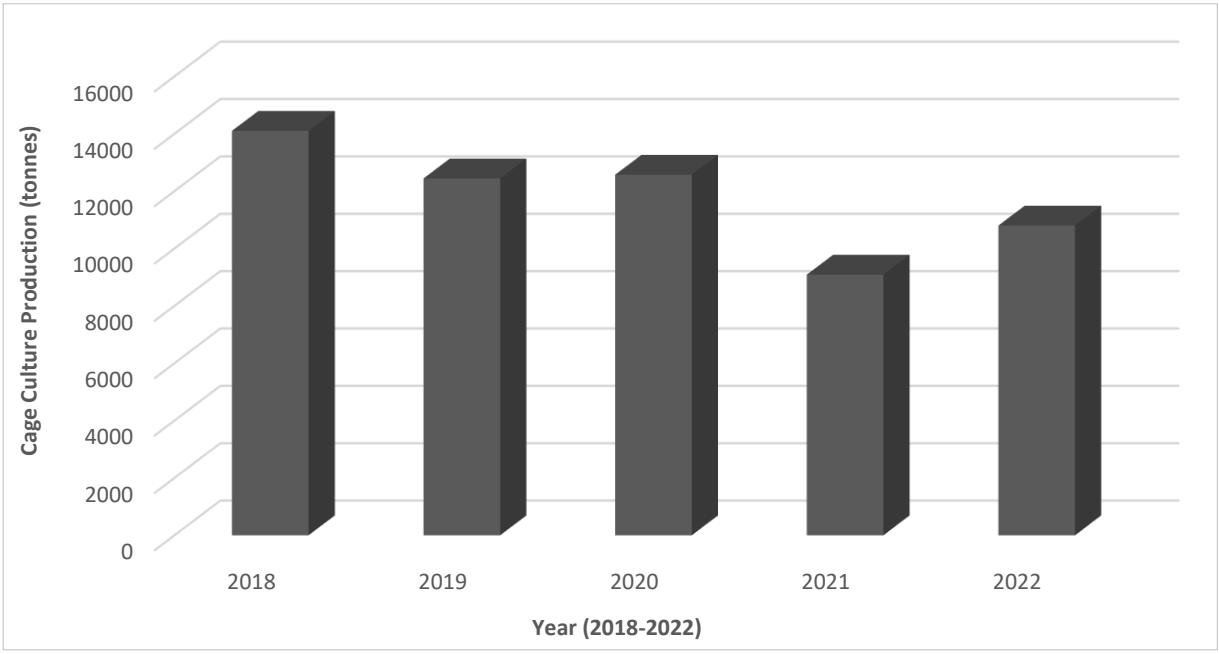


**Figure 1.** Annual fish production from cage aquaculture in Iran during 2018–2022. The vertical axis represents production volume (tonnes), and the horizontal axis indicates the production year.

From an environmental perspective, cage farming, if managed sustainably, can reduce the impact of overfishing on natural ecosystems. Over the past few decades, the population of economically important species in the Caspian Sea, such as sturgeon, kilka, and even the Caspian seal, has faced a sharp decline (Bodini et al., 2024). By providing a controlled environment for fish cultivation, cage farming minimizes the need for wild catch and can lead to the restoration of overexploited fish populations. Moreover, advancements in aquaculture technology and practices, such as the development of eco-friendly feeds and integrated multi-trophic aquaculture (IMTA)—a system that combines species from different trophic levels such as fish, shellfish, and seaweeds—to recycle nutrients and reduce waste—can mitigate the environmental footprint of cage farming. IMTA systems, which combine different species to create balanced ecosystems, can help recycle nutrients and reduce waste, promoting a more sustainable approach to fish production (Farabi et al., 2020; Azizpour et al., 2025).

In summary, the importance of cage farming for the Caspian Sea region lies in its potential to address overfishing, boost local economies, promote environmental sustainability, and support social resilience. As the region continues to navigate the challenges of balancing economic development with ecological conservation, cage farming presents a viable path forward that can harmonize these objectives. Continued research, innovation, and policy support will be essential to fully realize the benefits of cage farming in this unique and valuable region.

**Historical Development and Government Initiatives**

The development of cage farming along the Caspian Sea, particularly on the Iranian coastline, has been shaped by a series of strategic efforts and government initiatives. Historically, the region's reliance on traditional fishing practices led to overexploitation of key fish species, necessitating alternative methods to sustain fish production and conserve biodiversity. Recognizing the potential of cage farming, the Iranian government has taken significant steps to promote this practice.

Cage fish farming in Iran has developed almost simultaneously with the commercial growth of this industry worldwide. The first floating cages for fish farming were established in 1970s in the Gulf of Gorgan on the southeastern coast of the Caspian Sea. The objective of this project was to study the feasibility of growing and cultivating rainbow trout in the Caspian Sea. Two decades later, an experimental project for cage farming of Caspian trout (*Salmo caspius*) was initiated. Despite initial successes, this project faced significant losses when the temperature in the Gulf of Gorgan rose to 27°C (AREEO, 2020).

The establishment of research institutions in fisheries and aquaculture sciences, along with collaboration with international researchers for studies related to aquaculture in inland and coastal waters, were among the initial steps taken by the Iranian government to understand the country's potential in cage aquaculture. In this regard, the Norwegian company REFA conducted a study in 2001, commissioned by the Iranian Fisheries Organization (IFO), to explore the feasibility of marine fish farming in cages in Iran. This study examined environmental characteristics, suitable locations for cage installation, suitable species for cultivation, required cage farming technologies, marketing and economic aspects of fish production, facilitation of permit issuance, specialized training courses on cage farming, launch and operation of pilot cage culture systems, job creation opportunities, and other social impacts of cage farming in Iran. Additionally, it assessed the development prospects of cage farming in the waters of the Caspian Sea, the Persian Gulf, and the Oman Sea. Based on the findings from this comprehensive study, the potential production capacity of marine fish in cages was estimated at 300,000 tonnes (AREEO, 2018 and 2020).

As part of the government's efforts to develop cage fish farming in the Caspian Sea, conferences were held to attract investor participation, and subsequently, several permits for fish farming in the Caspian Sea were issued by IFO. For example, in 2010, with financial support from IFO, two floating cages with a diameter of 16 meters and a production capacity of 60 tonnes were installed in Jefrud, Anzali County, Gilan Province. These cages were used for the experimental farming of Caspian trout and beluga sturgeon (AREEO, 2020).

**Experimental Trials and Research**

Collaborative research initiatives between academic institutions, government agencies, and private sectors have facilitated knowledge exchange and capacity building. These collaborations have resulted in the development of best practice guidelines, standard operating procedures, and policy recommendations to support the sustainable growth of cage farming in the region. Continuous research and innovation are essential to address emerging challenges and ensure long-term success of cage farming along the Caspian Sea.

In the last two decades, three national projects were also carried out by the Iranian Fisheries Science Research Institute, as follows:

***Comprehensive Study of the Ecosystem in the Southern Caspian Sea for Cage Installation and Marine Aquaculture Development***

This included site selection, species suitability, appropriate cages identification, economic and social evaluation, fish feeding methods, and analysis of physical and chemical factors of the waters.

***Investigation of Biological, Non-Biological Parameters, and Environmental Pollutants in the Vicinity of Fish Farming Cages (Before Stocking) in the Southern Caspian Sea***

This included determining levels of metal and oil pollutants, dynamics of plankton populations, study of benthic communities, and monitoring of nutrients in sediments.

***Formulation of Biological Criteria and Standards for Marine Cage Fish Farming***

This encompassed criteria and standards related to determining suitable species, environmental indicators, and identifying appropriate locations for cage installation.

The findings of these studies ultimately led to the identification and selection of 17 sites along the southern coastal waters of the Caspian Sea with their carrying capacity (Table 1). Out of these, 9 stations were located in the central region (Mazandaran Province), 7 stations in the western region (Gilan Province), and 1 station in the eastern region (Golestan Province) (Figure 2). Important criteria for selecting these locations included the depth of more than 20 meters, a minimum distance of 3 kilometers from major rivers with flood potential, the suitable distance from fishing grounds for bony fish, sturgeon, and kilka, and the availability of support facilities and infrastructure on the coastal areas. Based on these criteria, the central part of the southern Caspian Sea coast had the highest potential for establishing cage fish farming operations.

The study results also indicated that, given the eco-biological conditions of the Caspian Sea, rainbow trout is currently the best species for cage farming in this region. It appears that using native fish species such as Caspian trout, pikeperch, common carp, and beluga sturgeon is also of high importance due to both the sensitive conditions of these species in the Caspian Sea and their economic value. However, at present, the farming of these species is not feasible due to the lack of appropriate infrastructure. Additionally, researchers and experts from the IFO estimated that more than 15 kilograms of rainbow trout can be produced per cubic meter in floating cages in the southern Caspian Sea. Therefore, floating cages with a diameter of 20 meters and a height of 8 meters can yield over 30 tonnes of fish (AREEO, 2020).

Moreover, academic Iranian researchers have conducted studies in this area. Azizpour et al. (2025) investigated the environmental impacts of fish farming in cages in the Caspian Sea. They reported that cages did not have a significant impact on the hydrodynamics and physical parameters of the surrounding water and caused a slight decrease in flow velocity within a few tens of meters of the cages. The results of their study also showed that the water quality was safe and of no concern based on the levels of phosphate, nitrite, nitrate, ammonium, BOD5 and COD. Kazemi et al. (2021) examined the impact of cage farming rainbow trout on the water quality characteristics around the cages in the southern Caspian Sea. They found that water quality parameters within a 50-meter radius of the cages showed significant increases, and the organic load of the surrounding water increased noticeably. Similarly, Karimian et al. (2018) studied the effect of cage farming rainbow trout on the plankton population structure in the water around the cages. They reported that due to the water movements and currents in the study area, fish farming had a relatively minor impact on water quality and nutrient concentration but did not have a significant effect on the surrounding zooplankton

**Table 1.** Selected locations and estimated carrying capacities for marine cage fish farming along the southern Caspian Sea, Iran

| Provinces | Suitable areas to support fish farming in cages | Carrying capacity in tonnes |
|---|---|---|
| Mazandaran Province | Amirabad | 400 |
| | Larim | 900 |
| | Babolsar Fishing Port | 11000 |
| | Mahmudabad | 5000 |
| | Toskatok | 23000 |
| | Chalus | 7000 |
| | Kelarabad | 10000 |
| | Abbasabad | 10000 |
| | Tonekabon | 6000 |
| Gilan Province | Chaboksar | 5000 |
| | Chamkhaleh | 4000 |
| | Kiashahr Fishing Port | 8000 |
| | Caspian Anzali | 12000 |
| | Anzali Fishing Port | 21500 |
| | Dinachal | 15000 |
| | Haviq | 10000 |
| Golestan Province | Khvajeh Nafas | 5000 |
| Sum Total | | 160500 |

Note: Data are based on site selection studies conducted by the Iranian Fisheries Science Research Institute (AREEO, 2020). Carrying capacity values represent the estimated annual fish production potential for each location.

communities. Bagheri et al. (2018) also investigated the variation of phytoplankton communities and nutrients near fish breeding cages in the Caspian Sea. A total of 19 phytoplankton taxa belonging to diatoms (12 species), chlorophytes (2 species), cyanophytes (2 species), and dinoflagellates (3 species) were identified in the study area. The finding of this study showed that the abundance of exotic species as diatoms *Pseudosolenia calcar-avis* and *Pseudo-nitzschia seriata* were dominated in the stations beside the fish cage culture comparing with the control stations. The Principal Component Analysis (PCA) confirmed significant difference between abundance of phytoplankton in the stations near the fish cage culture and the control stations.

Although these studies collectively enhance understanding of environmental interactions in cage farming, their findings show some variation. Such differences likely stem from distinct research designs, cage densities, and site-specific hydrodynamic conditions. For instance, studies conducted in nearshore areas with limited water exchange and higher stocking densities (e.g., Kazemi et al., 2021) reported greater increases in organic load and nutrient concentrations compared with those located farther offshore (e.g., Azizpour et al., 2025), where stronger currents enhance dilution and dispersal of wastes. Moreover, variations in sampling distance, frequency, and analytical methods could also explain discrepancies among studies. Addressing these methodological inconsistencies through standardized monitoring protocols will be essential to accurately assess and mitigate the environmental effects of cage aquaculture in this region.

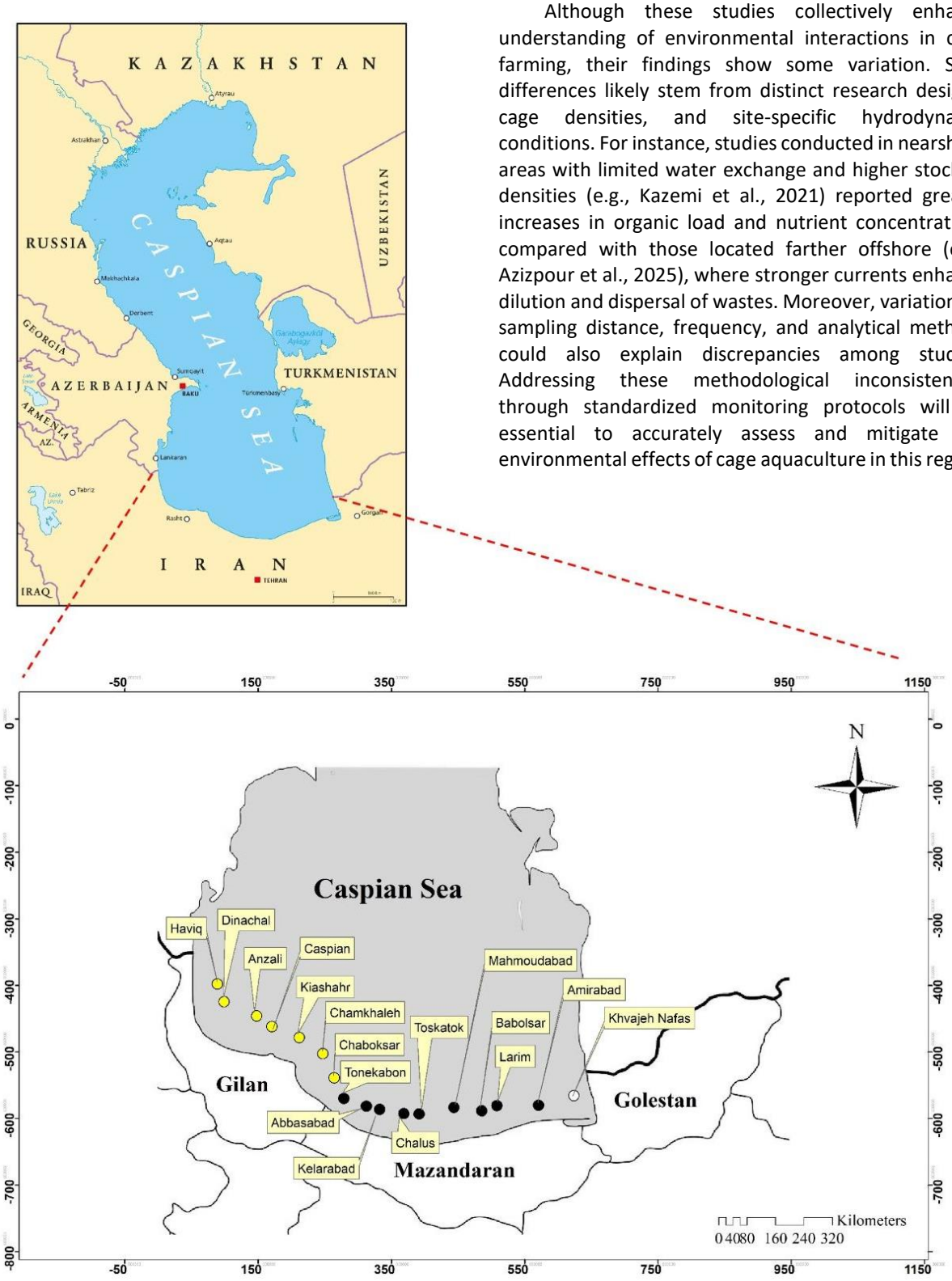


**Figure 2.** Predicted suitable sites for marine cage aquaculture along the southern Caspian Sea coast, Iran. Map showing the spatial distribution of 17 identified sites suitable for cage fish farming based on hydrological, ecological, and infrastructural criteria.

**Current Status of Cage Culture Farms**

Contrary to the findings from feasibility studies on cage fish farming in the Caspian Sea, as well as the expectations of fisheries and aquaculture managers and policymakers, cage fish farming in the southern Caspian Sea region has not met favorable conditions. Due to various reasons, the production levels and investments made in this sector have not been satisfactory.

According to a report by the IFO, by 2017, there were 5 active fish farming stations in the central part of the Caspian Sea (Mazandaran Province) with a total of 15 cages for rainbow trout farming. These stations included Abbasabad with 7 cages, each with a diameter of 20 meters; Toskatok with 5 cages, each with a diameter of 16 meters; and Kalarabad, Nowshahr, and Ramsar, each with 1 cage of 20 meters in diameter. The rainbow trout production of these 5 stations in 2017 was reported to be 465 tonnes (IFO, 2018). In recent years, the number of cages in this area has increased to 42 cages, and their production has reached 1,850 tonnes in 2024. This part of the Iranian coast of the Caspian Sea is more actively engaged in cage farming.

The latest report from the General Administration of Fisheries in Golestan Province shows that there are a total of 3 farms with 75 cages operating in the southeastern part of the Caspian Sea. The level of fish production in cages in the southeastern Caspian Sea has fluctuated. The total production of rainbow trout in 2022 was 300 tonnes and decreased to 80 tonnes in 2023.

Additionally, in the western part of the Caspian Sea (Gilan Province), efforts were made to establish cage farming, all of which failed. In 2016, four cages with a diameter of 22 meters were installed on the Jefrud Coast of Anzali County, but after several farming periods and lack of economic efficiency, the cages were removed from the water. Similarly, on the Caspian coast of Anzali, four cages were set up for rainbow trout farming, which were also later removed from the sea. Furthermore, two attempts were made in Kiashahr for this purpose, both of which failed. According to information from the Gilan Province Fisheries Department, strong water currents in this area have severely damaged some equipment and cages, rendering them inaccessible. This suggests that the site selection process overlooked critical hydrodynamic factors such as current and wind speed, reflecting an incomplete technical assessment.

Data obtained by the research team showed that a total of 1,940 tonnes of fish have been produced in the cages located in the southern Caspian Sea region by 2023. In other words, cage farming operations are now only active in the central part of the southern Caspian Sea coast (Table 2), except a few in the southeastern part. However, their production levels are significantly below their full capacity. Moreover, Figure 3 presents the fish production data from cages in the provinces of Gilan, Mazandaran, and Golestan during the years 2014 to 2018, highlighting the peak period of activity in this industry.

Among the three provinces, Mazandaran accounted for nearly 60% of total cage aquaculture production, followed by Gilan (25%) and Golestan (15%). Over the five years, total production increased by approximately 35%, while the number of active cages grew by 22%, indicating a modest improvement in capacity utilization. However, the ratio of actual production to estimated carrying capacity suggests that less than 40% of the available potential is currently being utilized across the southern Caspian region. The relatively higher performance in Mazandaran can be attributed to better infrastructure, calmer hydrodynamic conditions, and proximity to supply networks.

It should be noted that information about cage farming is not readily accessible to academic researchers, and the available data only partially reflect the realities of cage farming in the southern Caspian Sea region. However, what is clear is that the cage farming project in Iran has largely been a trial-and-error process, and the current conditions are not favorable, with most installed cages being unused. Therefore, it is essential to address the obstacles and challenges associated with this issue to gain a clear understanding of cage farming in the Caspian Sea.

**Table 2.** Current status of active marine cage farms along the central southern Caspian coast (Mazandaran Province), 2023–2024.

| County | Number of active farms | Number of cages | Final production in tonnes |
|---|---|---|---|
| Tonekabon | 2 | 2 | 92 |
| Abbasabad | 4 | 8 | 271 |
| Chalus | 3 | 4 | 530 |
| Nowshahr | 5 | 7 | |
| Mahmoudabad | 1 | 1 | 44 |
| Fereydunkenar | 1 | 1 | 43 |
| Babolsar | 3 | 7 | 315 |
| Juybar (Larim) | 6 | 12 | 555 |
| Sum Total | 24 | 42 | 1850 |

Note: Data were obtained from field observations and the Iran Fisheries Organization (IFO, 2024). Production refers to the total annual yield of rainbow trout from operational cages in each county.

**Challenges and Obstacles**

Fish cages provide an effective method for feeding and harvesting fish while also offering protection from predators. As cage culture operations become more intensive and lead to significant nutrient loading, it is crucial to gain a better understanding of the interactions between wild fisheries and cage culture. In addition, understanding the effects of this type of cultivation on water quality and native species can ensure the sustainable coexistence of these two practices (Kashindye et al., 2015). Cage aquaculture across the southern Caspian coastline presents significant potential to boost fish production and strengthen local economies. Nevertheless, this sector still faces multiple environmental, economic, and regulatory constraints that must be overcome to ensure long-term sustainability (Figure 4). The most important challenges and obstacles are discussed below:

**Environmental Concerns**

One of the primary challenges of cage aquaculture is its potential environmental impact. High fish density in confined cages increases the release of organic and dissolved nutrients from uneaten feed and waste (Masser, 2008). Such discharges can degrade environmental quality by causing oxygen depletion in sediments and stimulating eutrophication in surrounding waters. Additionally, it may lead to eutrophication as a result of nutrient enrichment in the water column. These changes can, in turn, alter the abundance and composition of invertebrate populations (Ngupula and Kayanda, 2010; Ngupula et al., 2012).

On the other hand, the use of non-native species such as trout, Chinese carp, and tilapia has gained attention among fish farmers due to their easier cultivation and faster growth. However, non-native species can pose potential risks and have negative effects on native fish populations. If these species escape from the cages, they could threaten native species by competing for food resources. Additionally, the escape of farmed fish raises significant concerns regarding genetic and ecological impacts. Escaped farmed fish may affect wild populations through disease transmission, increased competition and predation, and genetic interactions such as breeding and hybridization (Diserud et al., 2012. Kashindye et al., 2015). The same concern exists in the Caspian Sea, as almost all active farms in the southern Caspian Sea are raising rainbow trout. This fish is a non-native species in the Caspian Sea, and their escape from cages could have adverse effects on wild fish populations. Unfortunately, the exact rate of escape of this species from the cages is unknown. Iran's Organization of Environmental Protection has issued temporary permits for the cage farming of rainbow trout. Consequently, aquatic ecologists in Iran recommend that native species of this sea be prioritized for cultivation. Species such as the beluga sturgeon, Caspian trout, and even the Caspian kutum, all of which are endangered, could benefit from cage farming, which could also support conservation efforts for these species.

**Economic and Social Challenges**

The economic viability of cage culture is influenced by several factors such as high start-up costs, unstable

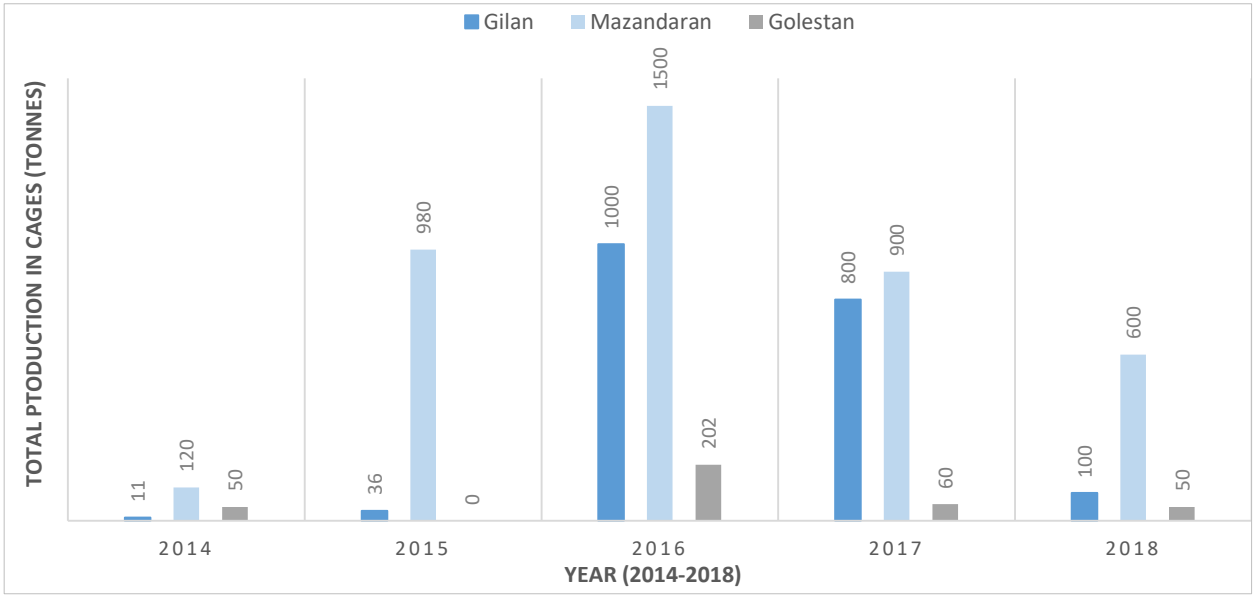


**Figure 3.** Cage fish production trends across Gilan, Mazandaran, and Golestan provinces (2014–2018). Bar chart showing provincial cage aquaculture production (tonnes). The x-axis represents the year, while the y-axis indicates production volume. Data were compiled from Iran Fisheries Organization annual reports. The figure highlights the dominance of Mazandaran Province in total output during the study period.

market prices, and competition with wild-caught fish. These financial burdens often prevent small-scale farmers and coastal communities from participating effectively in the sector. Additionally, market fluctuations and cheaper wild-caught fish can affect the profitability of farmed fish, posing a challenge for sustaining cage culture businesses (Aura et al., 2024; Syda Rao et al., 2013).

The biggest barrier to cage fish farming in the Caspian Sea is the economic challenge. Among the most significant are the high costs of cage farming equipment, the need for specialized labor such as divers and boat operators, the high value of coastal land in northern Iran, the instability of fish fry and feed prices due to economic instability in Iran, fluctuations in foreign currency exchange rates, and the constantly changing prices of imported equipment (Hosseinjani et al., 2024). These factors, as well as economic sanctions against the government in Iran, are the main reasons for the failure of the cage aquaculture projects in the Caspian Sea. Other challenges include the overlap of farming and harvesting periods with wild fishing, conflicts with other land uses, and disputes with local fishermen.

In addition, Social acceptance of cage culture is another critical challenge. Traditional fishing communities may view cage farming as a threat to their livelihoods and cultural practices (Conway et al., 1989). Since establishing cage fish farms in the Caspian Sea requires substantial investment and a large scale of operation, local fishermen are unable to undertake such projects. This situation exacerbates conflicts between investors and coastal residents. Hence, ensuring that the benefits of cage farming are equitably distributed and that local communities are actively involved in decision-making processes is essential for gaining social acceptance and support. Capacity-building initiatives, training programs, and awareness campaigns can help address these concerns and promote community engagement.

**Regulatory and Policy Issues**

In recent years, the fragile state of marine resources in the Caspian Sea has been compounded by the problem of illegal, unregulated, and unreported (IUU) fishing. Despite efforts and investments from both

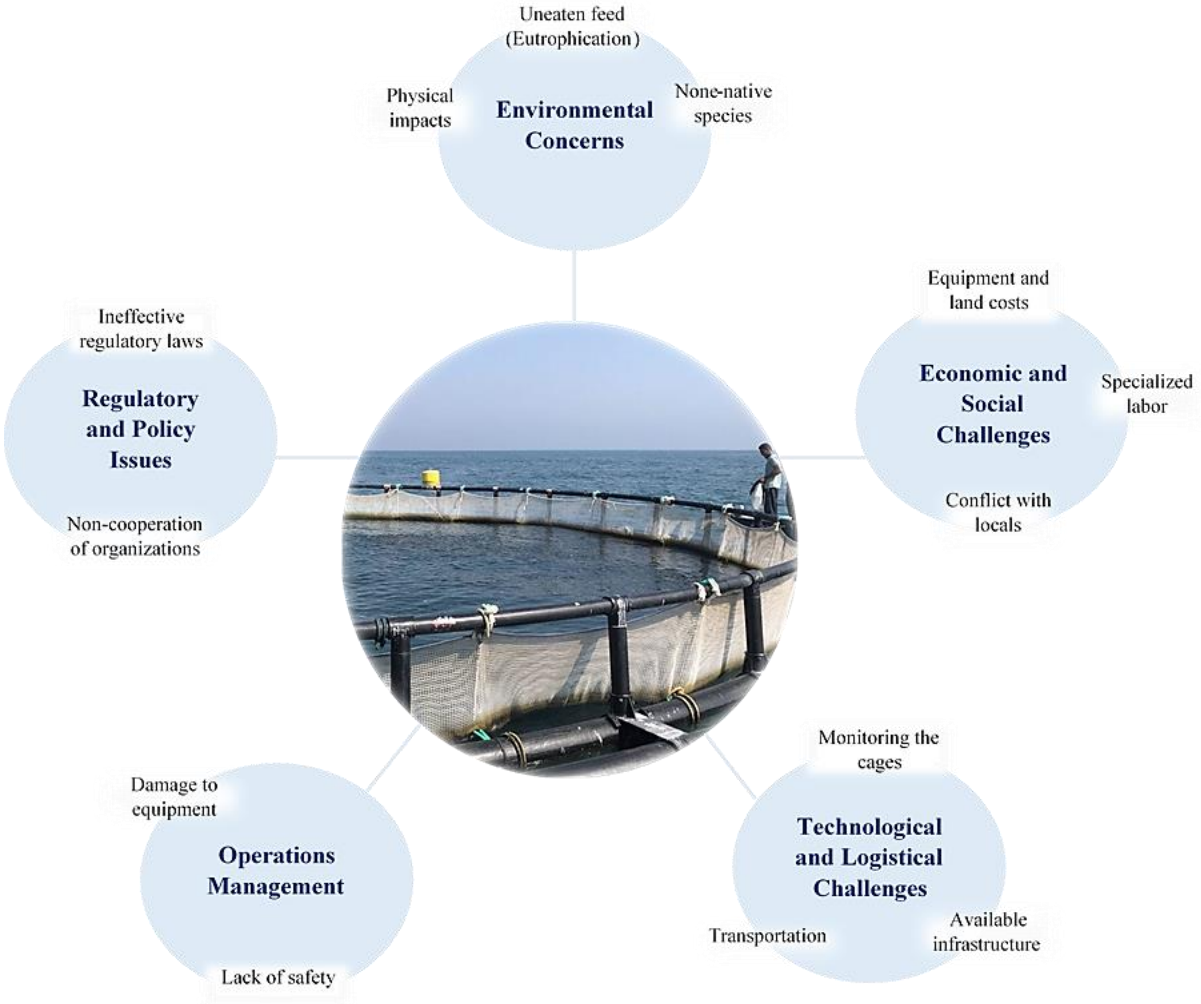


**Figure 4.** Main environmental, economic, social, and regulatory challenges affecting cage aquaculture in the southern Caspian Sea. Diagram summarizing key constraints identified in literature and field observations. Categories include environmental concerns (pollution, species escape), economic challenges (high investment cost), social conflicts (stakeholder disputes), and policy gaps.

private and public sectors to enforce laws and regulations, IUU fishing continues to deplete fishery resources. The number of licensed fishers and fishing boats far exceeds what the marine resources can sustain. Reducing the fisherman population will be difficult unless alternative income sources are provided, particularly for those living in remote coastal regions. Aquaculture in Iran is often based on traditional methods, and the expertise needed to identify and explore new opportunities is still developing. The productivity of aquaculture farms in Iran falls below the global average. Training programs have not effectively imparted practical skills to all those in need, and scientific research has only modestly contributed to the growth of aquaculture or the enhancement of existing farms (FAO, 2024b).

Sound legal frameworks underpin the rule of law and ultimately help to create the possibility for achieving sustainable development. National laws for managing the extraction and use of natural resources, including fisheries and aquaculture legal frameworks, govern the complex relationships between the multiple actors in this sector (FAO, 2020). IFO is responsible for management of aquatic resources and development of aquaculture in Iran. This organization is also in charge of legislating and overseeing the proper enforcement of laws related to fisheries and aquaculture. To this end, Iran has joined various regional and global organizations and commissions focused on fisheries management, including the Caspian Sea Commission for Aquatic Resources, where the five Caspian coastal countries collaborate on fisheries management. However, it seems that these laws are either not being implemented or there is insufficient oversight to ensure their proper enforcement.

Effective regulatory frameworks are crucial for the sustainable development of cage culture. However, if not properly managed and regulated, cage aquaculture may become unsustainable, resulting in conflicts with other water users, environmental degradation, and financial losses for aquaculture businesses (Aura et al., 2024). In the Iranian context, the regulatory environment governing aquaculture is still evolving, and there are challenges related to licensing, compliance, and enforcement. Clear and consistent regulations are needed to ensure that cage farming operations adhere to environmental standards and best practices. Additionally, streamlined licensing processes can reduce bureaucratic hurdles and encourage investment in the sector.

Coordination between different governmental agencies and stakeholders is also vital for addressing regulatory and policy issues. Overlapping jurisdictions and lack of communication can lead to fragmented management and oversight of cage farming activities. Establishing a coordinated and integrated approach to governance can enhance the effectiveness of regulatory frameworks and support the sustainable growth of the industry (FAO, 2017).

**Operations Management**

Compared to many other aquaculture systems, marine cage culture offers the advantage of utilizing the natural environment as the growth environment for fish. The continuous movement of water through the cages, driven by tides or coastal currents, ensures high productivity of the farming system. However, it can also pose risks to the equipment and cages in place. The extent of damage can be minimized through careful site selection, skilled operation, and effective management (Chua, 1979). In this context, the improper site selection for the installation of fish farming cages in Gilan Province has resulted in the loss of a significant portion of equipment and cages in recent years.

Cage culture operates in a high-risk environment, making it essential to implement all necessary safety precautions to prevent injuries and fatalities during cage installation and stock management. Sufficient lifebuoys and other life-saving equipment must be readily available at the cages and on the vessels used for accessing them. Workers should always wear life jackets while working in or near the water. Additionally, emergency life-saving kits and first-aid boxes should be kept at the cages, boats, floating huts, or field camps. Safety measures should be guided by international conventions on ‘safety at sea’ and the procedures outlined in the FAO Code of Conduct for Responsible Fisheries (FAO-CCRF). It is also important to protect the cage stock from poaching or unauthorized access by maintaining vigilant surveillance (NFDP, 2016).

Moreover, management must be efficient enough to ensure that farmed fish grow at the expected rate given the feeding rate and stocking density, minimize losses from disease and predators, monitor environmental parameters, and maintain the efficiency of technical facilities. Storage facilities are also essential, especially to keep feed bags away from moisture and prevent fungal attack. Cage farming on the Caspian Sea coast is traditionally practiced, with few exceptions. There is a serious lack of infrastructure and equipment to better manage cages and increase the productivity of fish raising on farms.

**Technological and Logistical Challenges**

Aquaculture is more diverse than other agricultural sectors and faces considerable pressure to keep innovating for sustainability. This includes increasing fish production, selecting appropriate species, mitigating diseases, reducing waste, preventing environmental pollution, and creating more jobs worldwide (Rowan 2024). Some of the transformative solutions in this field include alternative protein and oil for fish feed, offshore farming, recirculating aquaculture systems, oral vaccines, genome editing, solar energy innovations, novel marketing strategies, disease mitigation technologies, monitoring tools, and use of artificial intelligence and blockchain for developing

business models, including cybersecurity (Xia et al., 2020).

Technological advancements are essential for improving the efficiency and sustainability of cage culture. For example, Research has shown that water quality in cages and large tanks can be monitored in three dimensions using autonomous vehicles. These vehicles move sensors up and down to create 3-D data profiles (Rather et al., 2024). However, the adoption of advanced technologies can be limited by the availability of resources, technical expertise, and infrastructure. Developing and maintaining modern cage farming systems, such as automated feeding and monitoring equipment, requires investment and skilled personnel. Ensuring access to these technologies and providing training for local farmers are critical for overcoming these challenges. As mentioned in the previous sections, aquaculture in the Caspian Sea and in Iran in general is based on traditional methods, and this has an adverse effect on the productivity of cage farms.

Logistical challenges, such as transportation and supply chain management, also play a significant role in the success of cage farming. The remote and dispersed nature of many coastal communities along the Caspian Sea can complicate the distribution of inputs and outputs. Efficient logistics and supply chain networks are needed to support the timely delivery of feed, equipment, and harvested fish, ensuring the economic viability of cage farming operations.

The distance between the farm site and essential land facilities has a direct impact on operational costs. If the distance is too great, it can lead to (i) longer transfer times, reducing the amount of time available for work on the farm; (ii) increased fuel expenses; and (iii) heightened risks during fingerling transportation. Distance can also be a critical factor in emergencies, such as accidents or damage to the nets, where a swift response is crucial. It's important to assess the available infrastructure at cage-site locations to determine any potential advantages or disadvantages related to the site's position. This includes considering the presence of roads, piers, harbors, jetties, available workspace on land, and storage or warehouse facilities (Cardia and Lovatelli, 2015).

In summary, while cage culture along the Iranian coasts of the Caspian Sea offers significant potential for enhancing fish production and supporting local economies, it faces serious challenges and obstacles. Addressing environmental concerns, economic and social challenges, regulatory and policy issues, operation management, technological and logistical barriers will be essential for the sustainable development and success of the aquaculture practice. Collaborative efforts among government agencies, research institutions, private sector stakeholders, and local communities will be crucial in overcoming these challenges and realizing the full potential of cage culture in the region.

## Future Prospects and Opportunities

### Sustainable Practices and Innovations

The long-term success of cage aquaculture along the Iranian coasts of the Caspian Sea depends on adopting sustainable practices and technological innovations. Emphasizing sustainability will minimize environmental impacts and enhance the long-term viability of cage farming operations. Key areas of focus include (Figure 5).

#### *Eco-Friendly Technologies and Innovations*

Adopting eco-friendly technologies is vital to reduce the environmental footprint of cage farming. For instance, integrated multi-trophic aquaculture (IMTA) combines species from different trophic levels to recycle nutrients and enhance ecological balance. For instance, combining fish with shellfish or seaweed can help recycle nutrients and reduce waste, leading to a more sustainable and efficient farming system (FAO, 2018). By extracting nutrients from the surrounding supplementary aquafeed, they significantly contribute to filtering the water column, demonstrating sustainable properties (Buck et al., 2017; Naylor et al., 2021). Incorporating seaweed and shellfish into fish cage farming can assist in lowering the risk of eutrophication.

Another innovation is the use of cages made of high-density polyethylene (HDPE) cages — durable plastic structures resistant to corrosion and marine conditions— instead of metal cages (mainly made of copper), which are prone to corrosion and metal contamination. Metal particles, when ingested through food, can accumulate in the fish body through bioaccumulation processes. HDPE cages have a long lifespan and are highly resistant to corrosion chemicals. They are also resilient in harsh marine conditions and against waves, currents, and typhoons.

#### *Advanced Monitoring and Management Tools*

The use of advanced monitoring and management tools can significantly improve the efficiency and sustainability of cage farming (Wei et al., 2020). Real-time water quality monitoring systems, automated feeding devices, unmanned aerial vehicles and health management software enable farmers to optimize feeding regimes, maintain optimal water conditions, and promptly address any health issues. These technologies can reduce feed wastage, enhance fish growth, and prevent disease outbreaks, ultimately improving farm productivity and sustainability.

Advanced technologies such as the Internet of Things (IoT) and artificial intelligence (AI) are also being integrated to predict and analyze environmental data. Such technologies will increase productivity and pave the way for the development of intelligent systems

across the aquaculture industry. The use of modern software for data management and system performance analysis can also provide accurate insights into production status, water quality conditions, and fish growth, helping managers make informed decisions.

***Research and Development***

Research and development (R&D) drives developments and innovations in the aquaculture industry, providing solutions that increase the efficiency of aquaculture production and reduce the adverse effects of aquaculture on the environment.

Ongoing research and development are essential for the continuous improvement of cage culture practices. Collaborative efforts between research institutions, universities, and the private sector can lead to innovations in cage design, breeding techniques, and feed formulations. By investing in R&D, the industry can develop more resilient and productive aquaculture systems that are better suited to the unique conditions of the Caspian Sea.

**Market Development and Economic Potential**

To address the existing challenges and make cage fish farming along the Iranian coasts of the Caspian Sea more cost-effective, several strategies must be considered. These include developing standards and regulations, identifying suitable locations for cage farming sites, providing low-interest loans, encouraging investment, promoting sustainable development to prevent the conversion of valuable agricultural lands, focusing on exports, and introducing globally marketable species for cultivation (Hosseinjani et al., 2024). The economic potential of cage culture on the Iranian coasts of the Caspian Sea is substantial, with opportunities to expand both domestic and international markets. Key strategies for market development include:

***Diversification of Aquaculture Species***

Species diversification can facilitate aquaculture growth through multiple mechanisms and enhance the

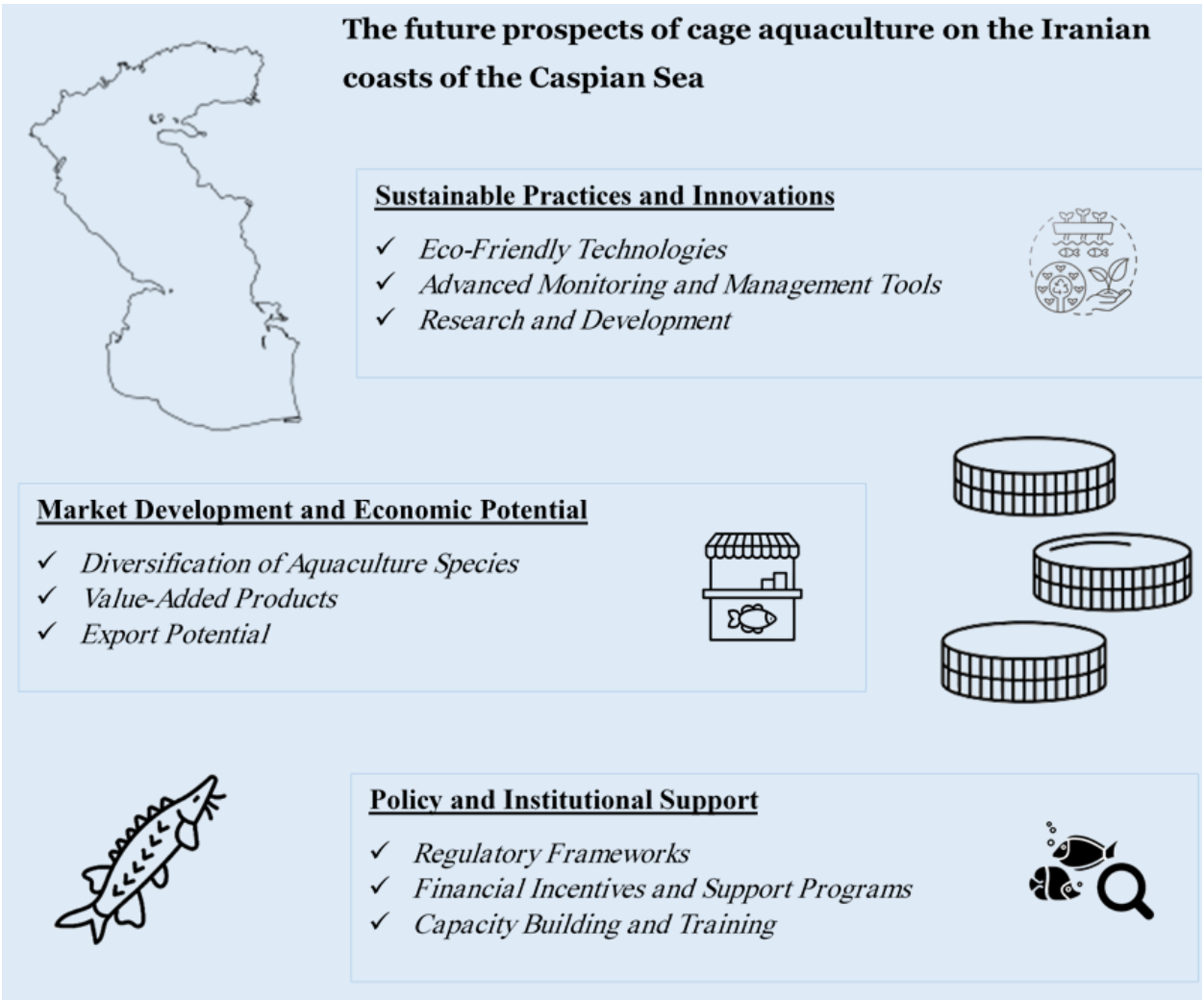


**Figure 5.** Framework of future prospects and sustainable strategies for cage aquaculture development in the southern Caspian Sea. Conceptual model illustrating potential strategies for sustainable growth, including eco-friendly technologies, advanced monitoring systems, policy reforms, and community-based management.

sector's resilience and long-term sustainability. In the face of increasing challenges from climate change, disease outbreaks, market volatility and other disruptions, species diversity has become a recognized and endorsed development strategy in policy and scientific communities for the growth and resilience of the aquaculture sector. However, many efforts to create new species have had little long-term success, and the private sector often focuses efforts on the most profitable species for rapid growth. It is therefore important to not only reduce the cost of species diversification for the private sector, but also to devote more public efforts to increasing its benefits and sustainability (Cai et al., 2023).

Diversifying the range of species cultivated in cages in the Caspian Sea can enhance market appeal and reduce economic risks associated with reliance on a single species. High-value and native species such as sturgeon, known for caviar production, as well as other commercially important species like Caspian trout, can be targeted to meet market demand and increase profitability.

***Value-added Products***

Developing value-added products from farmed fish can open new market opportunities and increase revenue. Processing fish into fillets, smoked products, or ready-to-eat meals can cater to changing consumer preferences and command higher prices. Additionally, the production of by-products such as fish oil and fish meal can contribute to the economic viability of cage farming operations (FAO, 2018).

Coastal residents in northern Iran often purchase and consume freshly caught fish. However, a significant portion of Iran's land has a hot and dry climate, making aquaculture in these areas very limited. As a result, the country relies on the northern and southern regions for its supply of aquatic protein. Therefore, with the potential increase in cage farming production, the development of seafood processing centers becomes essential. Additionally, it will also play a significant role in boosting exports to other countries.

***Export Potential***

With proper quality control and certification, farmed fish from the Caspian Sea can be positioned as premium products in international markets. Iran's strategic location and trade agreements with neighboring countries provide a gateway to lucrative markets in Europe, the Middle East, and Asia. Exporting high-quality, sustainably farmed fish can boost foreign exchange earnings and stimulate economic growth in the region.

Sturgeons and their caviar are among the most premium and expensive aquatic products in the world. The drastic decline in wild sturgeon catches has led to a significant reduction in the export of meat and caviar from this valuable species over the past few decades (Fazli et al., 2020). Cage farming presents an opportunity to cultivate native Caspian sturgeon species, potentially rebranding Iranian caviar in global markets.

**Policy and Institutional Support**

Effective policy and institutional support are vital for the sustainable development of marine cage farming in this region. Key areas of focus include:

***Regulatory Frameworks***

Well-designed regulations provide long-term, predictable regulatory frameworks for the industry. Such regulations protect a range of economic and operational parameters and protect both the environment and the public interest by controlling industrial activities. The process of developing regulations for aquaculture involves a wide range of interests and stakeholders, all with different knowledge and backgrounds. Therefore, the debate may lead to conflicts between stakeholders (Ervik, 2000).

Developing clear and comprehensive regulatory frameworks in the Caspian Sea is essential for ensuring environmental sustainability and operational efficiency. Regulations should cover aspects such as site selection, water quality standards, disease management, and waste disposal. Streamlined licensing processes and enforcement mechanisms will help facilitate compliance and promote responsible farming practices.

***Financial Incentives and Support Programs***

Government incentives and support programs can encourage investment in cage culture. Providing subsidies, low-interest loans, and grants for the establishment and expansion of cage farming operations can lower financial barriers for small-scale farmers and local entrepreneurs. Additionally, funding for research and innovation can drive advancements in sustainable aquaculture practices.

Large-scale aquaculture may also be developed in many areas through cooperatives, and in such cases financial assistance for production and marketing may be available from the cooperative sector. Foreign capital can also be attracted for large-scale aquaculture, especially for export-oriented production programs, through joint ventures.

***Capacity Building and Training***

Capacity building and training programs are crucial for developing a skilled workforce capable of managing advanced aquaculture systems. On the other hand, this is particularly important for the living, food and nutritional security of fishers and fish farmers. A successful capacity building program requires a careful functional design and a process that involves all

stakeholders. Initiatives should focus on technical training, best practices in cage farming, and business management skills. Capacity building should be based on methods that enable participants to work independently with aquaculture management issues and actively participate in the development of management plans in the area in which they work. Collaboration with academic institutions and international organizations can enhance knowledge transfer and build local expertise, ensuring the long-term success of cage culture in the region.

## Conclusion

Strengthening cage aquaculture in the Caspian Sea is essential for Iran's food security, employment generation, and for reducing pressure on wild fish stocks. Despite past efforts, the sector still faces environmental and economic constraints that limit sustainable development. Addressing these challenges requires closer collaboration among policymakers, researchers, and the aquaculture industry.

Key actionable recommendations and policy implications are as follows:

- Integrate fisheries, aquaculture, and environmental regulations within a unified coastal governance framework.
- Adopt eco-friendly innovations such as low-impact feed, waste treatment, and durable HDPE cages suited to Caspian conditions.
- Build capacity through technical training, stakeholder participation, and exchange of successful practices from other regions.
- Establish centralized monitoring systems to track production, environmental indicators, and regulatory compliance.
- Plan site-specific development based on ecological carrying capacity and social context to avoid environmental degradation and conflicts.

Implementing these measures would accelerate the sustainable growth of marine cage aquaculture in Iran's Caspian region while ensuring both environmental integrity and socio-economic resilience.

## Ethical Statement

We confirm that all the research meets the ethical guidelines, including adherence to the legal requirements of the study country.

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## Author Contribution

Conceptualization, Data curation, Investigation, Visualization, Writing - Original draft preparation: SEP, Resources: RG, Supervision, Project administration, Writing - Review and Editing: LZ, RG, and DK.

## Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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