Assessment of Site Suitability and Capacity for Sustainable Aquaculture Development Along the Northern Persian Gulf Coast

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ABSTRACT

Marine fish cage culture (aquaculture/mariculture) is a rapidly growing food production method globally and in the Persian Gulf, yet it is highly sensitive to site selection. A sustainable approach to site selection can result in nutrient-rich, healthy, and continuous food production yields. Conversely, poor site selection can lead to excessive pollution, low yields, and operational failures, which can severely degrade the coastal/marine environment. Although the Persian Gulf has a history of aquaculture, suitable site identification and capacity assessment remain underexplored. Targeted research is crucial to optimize sustainable aquaculture, supporting both economic and ecological goals. This research presents a comprehensive sustainable method for probing and selecting appropriate sites for mariculture along the northern Persian Gulf coastlines. The selection process considers various factors, including hydrodynamic and meteorological parameters that impose restriction on mariculture practice as well as environmental parameters that affect fish production, potential environmental impacts, infrastructure availability, and the interests of other coastal users. Considerations also include the impact on coastal security, environmentally protected areas, recreational activities, tourism, navigation, and other fishery interests. By integrating all geographic data layers into GIS, suitable areas and potential capacity for the practical implementation of sustainable fish cage culture along the northern Persian Gulf coastlines were revealed. The analysis reveals the identification of six distinct regions along the northern shoreline of the Persian Gulf, encompassing a total area of one million square kilometers. These delineated areas currently are able to facilitate a cage culture production capacity estimated at approximately 200 kilotons per annum.

KEYWORDS
Site Selection, Mariculture, Fish Cage Culture, GIS.

1. Introduction

Marine aquaculture is recognized as one of the fastest-growing and most vital industries globally [1], [2], [3], [4], offering a means to alleviate pressures on marine and coastal ecosystems while meeting essential food demands [5]. Furthermore, marine aquaculture plays a significant role in enhancing food security [6], [7]. According to the United Nations Food and Agriculture Organization, "Food fish has a nutrient profile superior to all terrestrial meats, serving as an excellent source of high-quality animal protein and highly digestible energy". It also provides abundant omega-3 polyunsaturated fatty acids (PUFAs), fat-soluble vitamins (A, D, and E), water-soluble vitamins (B complex), and essential minerals (calcium, phosphorus, iron, iodine, and selenium).

Fish is considered a staple animal protein source with the potential to address various aspects of global malnutrition. When mariculture operations are both sustainable and profitable, they enhance food availability and access, essential for alleviating poverty and bolstering economic resilience. Additionally, mariculture can reduce the pressure on wild fish populations, allowing these stocks to stabilize if properly managed, thereby supporting the traditional fishing industry. Success in the practice of mariculture of various animal and plant species in terms of both quantity and value and maintaining a diverse production portfolio ensures a stable food supply amidst fluctuating prices and the availability of wild fish [8]. Moreover, a profitable commercial aquaculture industry generates employment, supports ancillary businesses, contributes to tax revenues, and fosters further investment in the science and technology of sustainable aquaculture.

Commercial mariculture can have devastating impacts on coastal environments, particularly coral reefs. Eutrophic pollution from mariculture operations has been documented to affect coral reefs up to 80 kilometers away [9]. Several commercial mariculture operations worldwide have caused significant environmental degradation and destruction to coral reefs [10], [11], [12], [13], [14]. In response, regional and national governments have had to permanently shut down these operations. These failures resulted from exceeding the environmental carrying capacity of their locations, leading to eutrophic “Dead Zones” characterized by decreased dissolved oxygen levels and the accumulation of inhospitable hydrogen sulfide in both the benthic environment and water column. However, some commercial mariculture operations near coral reefs have demonstrated minimal environmental impacts. These successful operations typically ensure that mariculture activities do not exceed the environmental carrying capacity of the location and actively reduce the enrichment load of the operation to maintain this balance. Determining the environmental carrying capacity of a proposed mariculture site is crucial for designing sustainable operations. Despite this, environmentally sustainable mariculture density levels are often not optimal for profitability or product yields. As a result, many operations increase fish density and growth rates to enhance profitability, which can gradually lead to environmental degradation. Gao and Dong [15] reviewed the technical, environmental, spatial, and governance challenges associated with expanding mariculture offshore. Their findings suggest that site selection must integrate ecological sustainability with socio-economic factors. Their study underscores the importance of robust regulatory frameworks and stakeholder engagement in ensuring the long-term viability of offshore fish cage culture.

wave and current dynamics play a crucial role in site selection. Properly understanding and modeling these forces can prevent structural failures and optimize fish cage placement for better stability and productivity. The environmental carrying capacity for sea cage culture in the Persian Gulf, emphasizes the importance of current velocity and other hydrodynamical characteristics and their effect on rate of deposition of organic matter onto sediment, in site selection. Therefore, careful consideration of such parameters can significantly enhance fish production while minimizing ecological impacts. This approach ensures sustainable development in aquaculture by balancing productivity with environmental protection. Lapenkov et al. [16] investigated the seasonal dynamics of geochemical characteristics in sediments around fish farms in Lake Ladoga, Russia. Their findings reveal that seasonal variations in organic pollution can influence site suitability. The study advocates for current speed being an important parameter in site selection, as it plays the most significant role in transporting out the pollutants. Jiang et al. [17] modeled the impact of aquaculture

facilities on hydrodynamics and solute transport in the North Yellow Sea. Their research highlights the importance of understanding the interactions between culture systems and the marine environment. Proper site selection considering hydrodynamic characteristics such as minimum and maximum current speed in the region should account for these interactions to prevent adverse effects on water quality and marine ecosystems. Liu et al. [18] utilized numerical simulation and similarity theory to model the settling flux of biodeposition in cage culture environments. Their research, conducted in a bay setting, provides insights into managing nutrient loads and maintaining water quality. This methodology is pivotal for sustainable cage culture practices, emphasizing the need for detailed hydrodynamic studies in site selection processes.

The importance of effects of extreme sea conditions on cage structure, mooring loads, carrying capacity and fish yields have been probed by many researchers [19], [20], [21], [22], [23]. Lee et al. [21] examined the dynamic responses of floating fish cages to waves and currents, crucial for structural integrity and fish health. Their simulation studies indicate that careful consideration of hydrodynamic forces is essential in site selection to prevent structural failures and ensure the safety and productivity of the aquaculture operations. Lader et al. [22] conducted an experimental investigation on the wave response of closed flexible fish cages. Their findings are crucial for selecting sites that minimize wave-induced stress on cage structures. By understanding the interactions between waves and cage systems, aquaculture operators can choose locations that enhance the structural stability and safety of their operations. Swift et al. [23] focused on the effects of biofouling on the carrying capacity of marine fish cages. Their experimental work suggests that biofouling can significantly increase drag forces, leading to structural stress and reduced water flow. This study emphasizes the need for considering both minimum and maximum current speeds in site selection in areas with substantial biofouling risks to ensure the longevity and efficiency of fish cages.

Inland facilities and supporting infrastructure are crucial for the successful operation of aquaculture facilities. Despite being theoretically perfect for aquaculture, the majority of coastal areas require extensive infrastructure development before they can realize their full production potential [24]. Key infrastructure components include access to all-weather roads to facilitate efficient transportation of operational supplies, personnel, and harvested fish. Additionally, proximity to an electrical supply is essential for powering water pumps, office air-conditioning, and ice-making facilities, especially at nurseries and fish landing sites. Furthermore, cage culture sites should be equipped with a jetty featuring sufficient water depth to safely accommodate boats carrying feed and harvested fish, even under adverse weather conditions. The effects on recreation and tourism, as well as the impact on navigation and other fishery interests, must be carefully considered to ensure that the selected site is suitable for cage aquaculture and does not adversely affect other important coastal activities and interests.

Geographic Information Systems (GIS) can significantly aid in solving site selection problems by analyzing spatial data to identify optimal locations based on various criteria such as proximity to resources, geophysical constraints, environmental conditions, and infrastructure availability. Micael et al. [25] utilized Geographic Information Systems (GIS) in a multi-criteria decision-making tool for mariculture site selection. Their approach integrates physical, chemical, and socio-economic factors, providing a holistic framework for identifying optimal sites. This study underscores the value of advanced spatial analysis techniques in making informed site selection decisions. A study by Salama et al. [26] identified suitable sites for finfish cage farming along the eastern Red Sea coast of Saudi Arabia. The research utilized GIS-based models to analyze water quality,

temperature, and current patterns. Their approach highlights the importance of site-specific environmental assessments to optimize fish growth and minimize ecological disturbances. Jayanthi et al. [27] employed a spatial analysis method to map coastal lagoon characteristics, crucial for determining suitable sites for aquaculture. Their study on the southeast coast of India highlights the importance of environmental parameters such as salinity, water depth, and substrate type. This comprehensive approach ensures optimal site selection that minimizes ecological impact while maximizing aquaculture productivity.

The study area of this study encompasses the northern shoreline of the Persian Gulf (Figure 1). The Persian Gulf is a shallow, semi-enclosed water body with a total surface area of 251,000 km². It is situated between the Arabian Peninsula and Iran, extending 1,259 km from the Arvand River delta to the Strait of Hormuz. The deepest point of the basin reaches 120 meters near Small Tunb Island, with potentially greater depths in the Strait of Hormuz. The shallowest points range from 0 to 30 meters. Despite the longstanding utilization of the Persian Gulf for aquaculture, a comprehensive understanding of the most suitable locations and the actual capacity for such practices remains inadequately explored. This oversight hinders the optimization of aquaculture potential in the region, underscoring the necessity for targeted research and assessment. Identifying ideal sites and quantifying their capacities are essential steps toward enhancing sustainable aquaculture practices in the Persian Gulf, thereby fostering both economic growth and ecological balance.

In the Persian Gulf, local resistant fish species include Gilthead Seabream (Sparus aurata), European Seabass (Dicentrarchus labrax), and Sobaity Seabream (Sparidentex hasta) [28]. Additionally, several candidate species have been identified for potential cage culture development, such as Silver Pomfret (Pampus argenteus), Milkfish (Chanos chanos), Cobia (Rachycentron canadum), Asian Seabass (Lates calcarifer), Rabbitfish (Siganus canaliculatus), and other Seabream species (Sparidentex hasta ‘sheim’ and Acanthopagrus latus ‘sobiaty’) [29]. At present, no comprehensive site selection study or authoritative reference exists specifically addressing the details of cage culture of any above-mentioned species within the Persian Gulf. The data and results presented in this study aim to provide a preliminary framework for investors, planners, and policymakers to support the strategic development of the marine aquaculture sector. The threshold values for environmental and technical parameters used in this assessment were derived from widely accepted scientific and official sources and relevant literature.

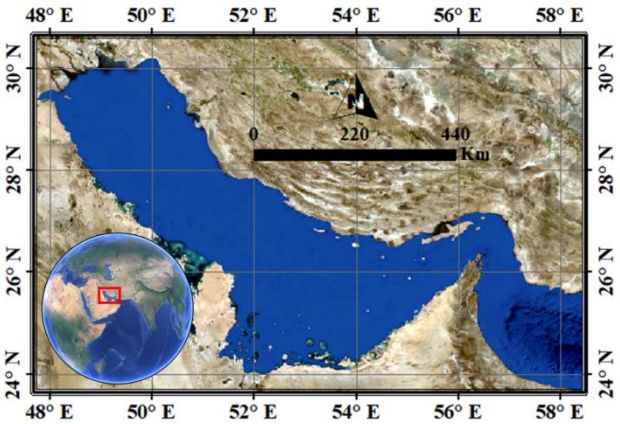


Figure 1: Study Area, the Persian Gulf

Jahani et al. [30] explored the impacts of cage aquaculture on the benthic environment in the Persian Gulf. Their research demonstrated that organic enrichment from fish farming significantly affects sediment quality. The study highlights the need for site selection criteria that consider sediment health to mitigate negative environmental impacts, advocating for more stringent regulatory measures in the site selection process. Risk et al. [28] developed a hydrodynamic circulation model for the Persian Gulf, allowing the tracking of dissolved material paths. In a model run simulating one year of full operation for the proposed number of fish farms, it is estimated that most reefs on the Iranian side will be exposed to nutrient levels too high for reef survival. Significant trans-border movement of nutrients is expected, affecting the waters of neighboring countries. In fact, within a few years, the entire Gulf will be impacted. These planned aquaculture projects have the potential to damage mangroves and destroy all reefs in the Persian Gulf in a very short period of time. Abbasian et al. [14] conducted a numerical experiment, along with data gathering from sediment samples, showing that the farms' "footprint" of anoxic bottom conditions extends much beyond the actual size of the farms (exceeding 2 km) in the Persian Gulf, due to dominant tidal currents. These studies indicate that it is essential to consider the hydrodynamic characteristics of the study area, including currents, waves, winds, and surges, as the primary limiting factors for selecting sites for fish cage culture.

Despite the valuable efforts made to identify various aspects of cage aquaculture in the Persian Gulf, a comprehensive site selection study that considers all effective parameters is still unavailable. This study developed a comprehensive and sustainable methodology for selecting appropriate sites along the northern Persian Gulf coastlines, aiming to identify optimal locations for mariculture activities. The process requires evaluating multiple parameters, including environmental factors influencing fish production, potential ecological impacts, infrastructure availability, and the interests of other coastal stakeholders. By integrating and visualizing data layers using GIS, it became possible to evaluate multiple factors simultaneously, streamline the selection process, and make informed, data-driven choices aligned with the scope of this study. Specific considerations, such as hydrodynamic and meteorological restrictions, proximity to conservation areas, operational techniques, local planning context, landscape impacts, and access to essential infrastructure, were implemented as the main criteria. This inclusive approach ensures that the proposed mariculture sites are environmentally sustainable while addressing the needs and concerns of all parties involved in the management of coastal resources.

2. Materials and methods

It is necessary to determine the most effective criteria in site selection for cage aquaculture. Based on reviews in the literature, the selection of suitable sites for mariculture is influenced by several factors. Environmental (chemo-physical) parameters are crucial in determining a site's suitability for fish production. Additionally, potential environmental impacts must be considered, along with the infrastructure needed to service aquaculture operations. Safeguarding the interests of other users of coastal waters is also essential. Proximity to existing fish farms, which may influence the viability and sustainability of the proposed site, must be thoroughly evaluated. Proximity to nature conservation interests, including coral reefs and environmentally protected areas, is another critical consideration. The planning context, including local plans or coastal zone designations and existing aquaculture zones or plans, plays a significant role in determining the feasibility of a new site. Potential impacts on the landscape and visual seascape must be evaluated, along with the availability of land access and necessary infrastructure. Additionally, the impact and proximity to areas of coastal security and other activities or restrictions, such as

environmental protected areas or military zones, are important factors.

The capacity for fish production by cage culture depends on several parameters, and fish farms cannot be placed very close together. The primary reason for this spacing is to allow sufficient water current to pass along the cages, flushing out bio-deposits. Another major concern is to maintain a contingency plan for epidemic diseases, preventing widespread infections among adjacent farms. Laws and regulations vary significantly worldwide. In this study, a minimum distance of 3 km between medium-sized farms with a capacity of 1500 tons per year is assumed to be sufficient, according to FAO/World Bank [31]. Such a farm would comprise 12 floating cages, each with a capacity of 125 tons per year, featuring a high-density polyethylene (HDPE) collar diameter of 28 meters and a net depth of 10 meters. This cage size is commonly used by local fish industries. This estimation approach yields a nominal production capacity based on the suitable sea surface area. However, many of these sea areas are adjacent to undeveloped lands that lack the infrastructure necessary to support a viable mariculture industry. Accordingly, a practical capacity should also be estimated, as it is substantially lower than the nominal figures. Finally—and importantly—this study does not address the total carrying capacity of the Persian Gulf. As a semi-enclosed water body, it has a finite ability to absorb biomass discharges without compromising its ecological integrity. Accurately estimating this overall carrying capacity would require extensive environmental monitoring and detailed biogeochemical analyses, which lie beyond the scope of this study.

A good data collection method for the Persian Gulf's metocean in relation to aquaculture should combine direct measurements, satellite observations, and numerical model outputs. Instruments like ADCPs, buoys, tide gauges, and CTDs help measure currents, waves, sea level, and water quality. Satellite data (e.g., from MODIS [32]) provide useful large-area information like sea surface temperature and chlorophyll. Additionally, local and global ocean models (such as HYCOM [33]) can supply continuous and historical datasets needed for planning and monitoring aquaculture operations. Satellites such as MODIS help monitor sea surface temperature and algae. Weather stations add wind and air data. Aquaculture sites should be checked often for temperature, oxygen, pH, and ammonia. GIS can help choose safe and useful locations. All data should be stored in one system, checked for accuracy, and used to make models and simple reports. This helps farmers and planners protect the sea and grow healthy fish.

Site selection in this study is based on a set of geophysical, environmental, and logistical criteria aimed at identifying areas suitable for fish cage culture. These include water depth and distance from the shoreline. Sea surface temperature, wind and wave conditions, and current speed limits are dynamic variables that can exhibit significant seasonal and interannual variability, potentially influencing operational feasibility and productivity. In this study, a general approach has been adopted to avoid the complexities associated with accounting for interannual variations. For example, a conservative temperature range was defined to ensure that environmental conditions remain broadly suitable for the cultivation of conventional aquaculture fish species throughout the year, thereby minimizing the risk of temperature-related production limitations. Additionally, the analysis excludes areas that would interfere with coastal and navigational activities or overlap with designated environmental protected areas, which are typically fixed but may be subject to future regulatory changes. Acknowledging the temporal nature of some criteria is essential for understanding the robustness and adaptability of proposed sites. It should be noted that this study aims to estimate the aggregative total capacity for mariculture along the northern shoreline of the Persian Gulf, rather than to prescribe specific site-level recommendations. While the applied

criteria help identify broadly suitable areas, a detailed investigation and feasibility study would be essential for each prospective sub-area to account for localized environmental, technical, and regulatory conditions.

The primary approach adopted in this study for identifying suitable zones for fish cage culture assumes that all areas along the coastline are initially considered appropriate. However, any area that fails to meet the acceptable range for any of the specified criteria is excluded from consideration. In other words, all criteria are treated equally, and failure to satisfy even one constraint results in the disqualification of that region as a potential site.

A comprehensive economic feasibility assessment of all potential cage culture projects was beyond the scope of this study. It is important to note that the economic viability of aquaculture initiatives is influenced not only by site-specific physical, socio-political and socio-economic conditions but also by investor-specific factors such as financial capacity, operational background, and strategic goals. Such variables that are not accessible to the authors at this stage. Therefore, the focus of the present study is limited to identifying coastal areas that are biophysically and hydrodynamically suitable for fish cage culture, providing a foundational framework for further, more detailed investigations.

The identification and selection of sites for coastal and marine aquaculture (mariculture) involved integrating satellite imagery with various mapped datasets, including environmentally protected areas, navigation routes, infrastructure (e.g., ports and offshore facilities), and coastal features such as bathymetry and topography, wind and wave and current characteristics. Geographic Information Systems (GIS) were employed to conduct spatial analysis on the collected datasets, enabling the identification of suitable aquaculture sites through a stepwise process. This process included data collection and compilation, database integration and preparation, initial mapping via database analysis, conversion and transfer of information layers to ILWIS software, elimination of unsuitable areas based on predefined criteria, and finally, the export of areas meeting the acceptable site characteristics. The essential criteria that were considered on a broad scale for the selection of potentially appropriate sites for cage aquaculture include the following items:

2.1. Water Depth and Distance from Shoreline

Water depth is likely the most critical criterion for the siting of cages, as it facilitates the dispersion of particulate matter and enhances water exchange. Additionally, deeper nets can maintain more stable water quality and temperature while reducing water movement during storms [7]. Bathymetric data were collected from various sources, including the National Cartographic Center (INCC), ETOPO, and the General Bathymetric Chart of the Oceans (GEBCO). Based on our field investigations and interviews with industry professionals actively engaged in fish cage culture, it is evident that the most prevalent type of cages used in the Persian Gulf region are HDPE floating cages with nets extending to a depth of 10 meters. Consequently, we recommend a depth range of 20 to 60 meters for identifying optimal aquaculture sites for these fish species.

The location of fish breeding sites should be in proximity to a port with a pier, allowing boats from the farm to berth in a sheltered area. This proximity ensures efficient access for distributing farm products, transporting food, juvenile fish, fuel, equipment, and other necessary materials [24]. It also facilitates increased site inspections by farm managers and experts. To ensure timely transportation, the travel duration from the port to the farm should not exceed 2 hours, corresponding to a maximum distance of 20 kilometers assuming a typical boat speed of 7 knots. Practically, suitable harbors for berthing farm boats should accommodate vessels of at least 15 meters in length. This approach accounts for the currently available production capacity. However, to estimate

the ultimate (nominal) aquaculture potential of the northern Persian Gulf coastline, proximity to existing ports and harbors must be excluded from consideration, and only the distance to the nearest shoreline should be applied. Consequently, fish production capacity is calculated for both scenarios: the ultimate capacity based on geographic potential alone, and the current capacity constrained by existing infrastructure.

2.2. Sea Surface Temperature

The temperature range of the water must be appropriate for the species being cultured. Consequently, seawater temperature data should be collected and analyzed to inform species selection. Temperature directly influences fish metabolism and, subsequently, their oxygen consumption, activity levels, and the production of ammonia and carbon dioxide. In general, sea surface temperatures in the Persian Gulf have shown significant variability, ranging from about 22°C to 35°C, influenced by seasonal and climate-related factors [34], [14]. Recent studies suggest that the optimal water temperature for marine fish cage culture in the Persian Gulf ranges from approximately 20°C to 32°C.A research conducted in northwestern parts of the Persian Gulf indicates that water temperatures varied from 11.8°C to 32.5°C, with significant environmental and ecological impacts observed within this range [30]. These temperature ranges are consistent with general recommendations for marine aquaculture, emphasizing the importance of monitoring and managing water temperatures to ensure the sustainability of fish stocks in the region. In this study, although resilient fish species are considered, regions with a temperature range of 13-30°C are presumed suitable for aquaculture. In this study, oceanographic data were obtained from HYCOM [35].

2.3. Wind and Wave Conditions

Strong winds, such as typhoons and cyclones can destroy all structures above the water and may damage in-water structures. The optimal wind speed range for cage aquaculture in the Persian Gulf has been identified to ensure effective water circulation, minimize structural stress on cages, and maintain water quality. Wind speeds between 3 to 6 m/s are ideal for these conditions. Recent studies suggest that for floating cages, the maximum permissible wind and wave limits are 40 km/hr (11.11 m/s) and 1 m respectively [36]. Another implication of high wind speeds is the consequent wave induced turbulence which drastically degrade the fish production quality and quantity. For instance, research by Barbier et al. [37] highlights that high wind speeds can lead to significant turbulence, which may cause increased stress on cage structures and potentially disrupt the growing environment for aquatic species. Similarly, a study by UNDP/FAO [38] emphasizes that maintaining wind speeds below 10 knots (5.14 m/s) for floating cages helps in balancing water circulation and minimizing the risk of damage to the cages. Accordingly, the wave heights should not exceed 1.0 m. The wind field dataset (ERA5) was collected from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP) data center [39]. In the current study, weather condition surveys were conducted, and areas with wind speeds below 15 nautical miles per hour (7.7 m/s) were identified as suitable for the construction of cage aquaculture sites.

Besides the cage structure stability, there is a more restricting criterion imposed by waves. Based on interviews with farmers and experts, it was determined that delaying fish feeding for three to five days annually poses no issues in the breeding process. In rudimentary feeding methods, boat activity is restricted to maximum wave heights of less than one meter. Jedari Attari et al. [40] developed a comprehensive wave hindcasting/forecasting system for the Persian Gulf. Analysis on the 25-year long wave climate data reveals that some areas in the study area experience severe wave heights repeatedly, making them inappropriate for cage culture practice.

Therefore, locations in the Persian Gulf experiencing storm events with waves exceeding 1 meter and lasting longer than three days are deemed unsuitable. This determination ensures additional security by excluding areas where such events occur more than six times in 25 years (approximately every four years on average).

2.4. Current Speed limits

Adequate water exchange in cage culture systems is vital for oxygen supply and waste removal, but strong currents can deform cages and reduce their volume. Maintaining optimal current speeds ensures water quality, effective waste dispersion, and reduced stress on both cages and cultured species. The currents within the Persian Gulf are primarily tide-dominated, meaning tidal forces largely govern their movement and circulation patterns. [41], [42], [43]. López et al. [44] conducted a study to on structural stress imposed on the collar HDPE pipe of the fish nets and suggested that while existence of minimum currents maintain the quality of surrounding water, current speeds beyond 1 m/s exert excessive stresses on the structure of the nets. Huang et al., [45] also suggested that farming sites should be positioned in zones where the current velocities are below 1 m/s. Prema [36] suggests a range between 0.05 m/s to a maximum of 1 m/s would be satisfying current velocity for cage culture. Analysis on hydrodynamic current data [46] reveals that the Persian Gulf experiences tide-dominated currents, with typical velocities in coastal areas ranging from 0 to 0.8 m/s. In certain locations, such as areas characterized by funneling and shallowness, current velocities can reach up to 1.2 m/s. In this study, a flow current range of 0.3 (a minimum to ensure adequate carrying capacity of the site) to 0.8 m/s (a maximum to avoid imposing stress both on structures and fish) has been identified as suitable for the construction of cage aquaculture sites. Maintaining current speeds within this range ensures efficient waste removal and optimal oxygen levels, which are critical for the health of the cultured species.

2.5. Avoiding interference with Coastal and Navigational Activities

Mariculture site selection must consider several exclusion zones to ensure operational safety and environmental protection [47]. Sites should be located at least 1 km away from waste dumping points and coastal underwater pipe outlets to prevent contamination. Additionally, areas with underwater cables or conduits should maintain a minimum distance of 200 m to avoid interference with moorings or cages. Due to potential military activities, such as navigation routes or firing ranges, a buffer zone of 5 km is recommended around areas of military importance. Furthermore, aquaculture cages should be kept at least 500 m away from vessel anchorage areas, typically found near harbors or industrial zones, where marine traffic standby anchorage is managed. For optimal fish production and safety considerations, fish cage licenses should be situated at least 1 km away from designated navigation routes to mitigate disturbances caused by large vessels, including waves and underwater engine noise. Additionally, to minimize potential conflicts with tourism activities, mariculture sites should be located at least 3 km away from tourist hotels and beaches, particularly in areas where tourism is integrated with residential districts near major urban centers. Furthermore, due to security sensitivities, aquaculture facilities should avoid placement near national border areas.

2.6. Avoiding Environmental Protected Areas

The Persian Gulf coast supports coral reefs extending from Khark Island in the northwest to Qeshm and beyond in the southeast [48]. Recent field observations indicate that the northern coastline of the Persian Gulf harbors more coral than previously reported [28]. These reefs are critically important for fisheries, serving as nurseries for juvenile fish and refugia for adults. Fisheries yields from reef areas are significantly higher than those from adjacent sediment plains. The major threats to the

reefs of the Persian Gulf include sedimentation, pollution, nutrient enrichment, and overfishing [49]. These threats are well-documented globally [50]. Overfishing is considered a significant factor in the global decline of coral reefs [51], while others argue that nutrient increases are a major driver of this decline [52]. Harmful algal blooms, such as red and brown tides driven by nutrient influx, pose a threat to the Persian Gulf reefs and those in other regions. For example, Namin et al. [53] reported widespread coral mortality near the Strait of Hormuz following a red tide event in 2008-2009.

The development of aquaculture in environmentally sensitive areas necessitates a meticulous approach to minimize potential risks to these ecosystems [54] [55]. It is imperative to recognize that the restoration of natural habitats can be a protracted process, often demanding significant time and resources [56]. Stakeholders must prioritize sustainable practices that not only enhance aquaculture productivity but also preserve the ecological integrity of affected regions. Through careful planning and responsible management, we can ensure that the benefits of aquaculture do not come at the expense of our vital natural resources. To safeguard protected areas, a minimum distance of 5 km from these sites has been adhered to. The dataset identifying marine protected areas was compiled through collaboration between consulting teams and the Department of Environment, likely based on GPS positions and distributed in GIS format. It is crucial to prioritize the protection of sites of particular ecological significance, including marine protected areas, conservation areas, habitats crucial for bird populations, wetlands supporting waterfowl, coral reefs, tidal flats and mangrove forests.

3. Result and Discussion

In this study, we employed a Geographic Information System (GIS) platform to identify suitable areas for cage aquaculture in the Persian Gulf. Various constraining parameters were collectively considered, including navigational corridors, oil and gas pipelines, protected areas, unsuitable current speeds and wave heights, inconvenient water depths, and distance from the shoreline. Figure 2 maps the spatial distribution of these restricting criteria.

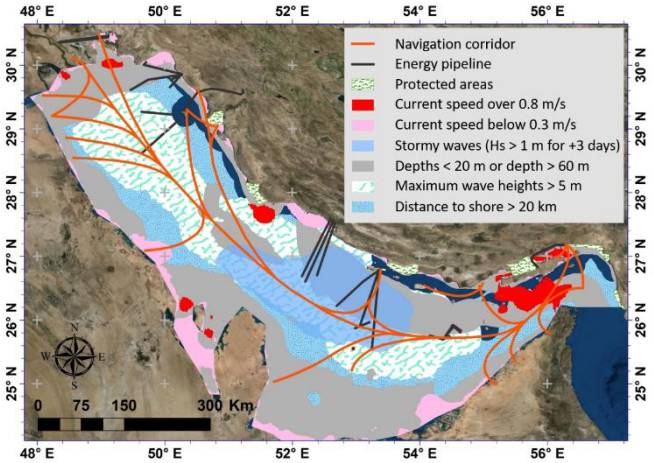


Figure 2: Mapping restricting criteria.

Unfortunately, there is a lack of scientific evidence or official documentation to ascertain the extent of capacity utilization within the fish cage culture sector in the Persian Gulf. According to a report from a reputable news agency, the current production from fish cage culture in this region amounts to approximately 40 kilotons [56]. Despite this production figure, an evaluation of the existing roadways and land

infrastructure indicates that there remains substantial potential for further investment in the industry, suggesting an opportunity for growth and enhancement of production capabilities. Figure 3 depicts the areas identified as suitable for cage culture based on GIS layer analysis. After excluding non-favorable regions, six distinct areas (A to F) have been identified as potentially suitable for profitable and sustainable fish cage culture practices, ensuring the protection of environmentally valuable areas. Table 1 lists the geographical characteristics and hydrodynamical properties of the proposed selected sites, along with current and future nominal potential fish cage culture capacity. Based on calculations, it is estimated that the northern shoreline of the Persian Gulf currently possesses the capacity to support up to 200 kilotons of fish production through cage culture. This estimation takes into account the accessibility of inland facilities and transportation routes essential for the efficient utilization of these areas.

However, should the entirety of the coastline be developed and suitable infrastructure (powerline, roads, harbors, …) be established along the shoreline, the nominal potential capacity for fish aquaculture yields could reach nearly one million tons annually. This ambitious projection underscores the significant opportunities available within the sector, contingent upon strategic planning and investment in sustainable practices. Such developments would not only enhance food security but also contribute to the economic vitality of coastal communities. It should be carefully noted that the estimated value presented herein serves as a highly hypothetical approximation, derived primarily from the geometric assessments and spatial evaluations of identified desirable regions. This estimate does not take into account the ecological constraints that inherently influence biological systems. A comprehensive investigation into nutrient cycling and the intricate biogeochemical processes at play would be essential to elucidate the practical maximum capacity for aquaculture within the specified area. Understanding these dynamics is critical for informed decision-making regarding sustainable practices in aquaculture development [57].

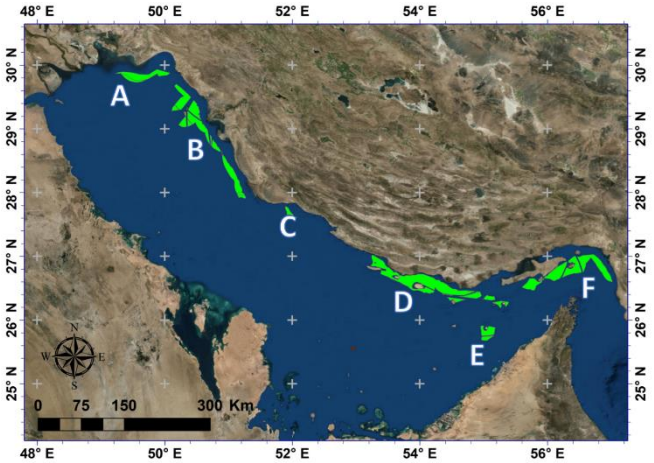


Figure 3: Suitable Areas (A~F) for fish cage culture along the northern coastlines of the Persian Gulf.

The main scope of this study was to spot suitable sites for conducting cage culture practice. We have not considered the biogeochemical processes involved in aquaculture. Consequently, rough estimation of aquaculture production capacity just based on geometry, physical and general environmental restrictions may result in extraordinary huge numbers which does not match with biogeochemical carrying

capacity of the study area. For future research, it is recommended to focus on enhancing the sustainability and resilience of mariculture operations through a robust monitoring framework. A comprehensive approach should involve assessing current fish farm monitoring initiatives, designing a tailored program suitable for the Persian Gulf environment, establishing standardized data collection protocols, leveraging collected data for impact evaluations, and crafting a specialized monitoring guide that addresses the region's distinct geographic characteristics. These efforts are pivotal for maintaining operational viability and environmental harmony amidst dynamic challenges and changing circumstances. Additionally, integrating principles from Integrated Multi-Trophic Mariculture (IMTM) could optimize environmental conservation efforts which involves cultivating multiple species across different trophic levels to utilize eutrophic waste, particularly from finfish. This approach mimics natural nutrient cycling, reducing eutrophic input and maintaining environmental capacity [58], [59]. By implementing IMTM strategies, future studies can effectively mitigate environmental impacts, sustain operational viability, and preserve biodiversity in coral reefs and seagrass beds amid evolving challenges [60], [61].

Table 1. Geographical, hydrodynamical, and fish production characteristics of selected proposed sites.

Areas	A	B	C	D	E	F	Total
Total Area (km2)	758.01	2591.4	183.55	3561.66	405.61	2440.49	9940.72
Average Depth (m)	14	28	32	38.1	45	34.2	-
Average Distance to Shoreline (km)	17.5	12.7	14.3	7.7	7.6	8.6	-
Average No. of Excess Wave Events in 25 years	1	1.3	1.4	1.5	3	1	-
25-Year Significant Wave Height	3.53	3.18	3.91	4.42	4.87	3.33	-
Averaged Maximum Current Speed (m/s)	0.53	0.5	0.41	0.6	0.62	0.53	-
Averaged Distance to Environmentally Protected Areas (km)	269.5	202.7	64.7	183.9	271	184	-
Averaged Distance to Wild-Life Habitat Areas (km)	67.8	52.2	178.7	112.3	197	175	-
Current Fish Yield (kt/year) [a]							40 [a]
Current Fish Production Capacity (kt/year) [b]	6.8	66	7.4	65	6.4	48.4	200 [b]
Nominal Ultimate Fish Production Capacity (kt/year) [c]	45	355	17	380	39	160 [d]	996 [c]

a) This value was obtained based on estimates reported by news agencies [56]. To date, no official reports from authorized institutions or peer-reviewed scientific references have been published to verify this figure.

b) It is important to note that the current potential capacity is contingent upon the availability of essential inland infrastructure, including transportation routes, power lines, harbors, utilities, and industrial support services.

c) This estimation is derived from geometric analysis and a limited set of criteria considered in this study. Three key assumptions underpin these projections: (1) that all prerequisite infrastructure along the coastline is fully developed, and (2) that the overall carrying capacity of the Persian Gulf (being a semi-enclosed water body) has not

been accounted for. A thorough ecological and biophysical assessment is needed to understand the cumulative impact of organic loading in an environment with limited self-purification capacity. Additional factors, such as the emergence of contagious diseases that can significantly reduce yields, must also be considered. Furthermore (3), socio-economic conditions will inevitably influence the extent to which this industry can sustainably expand.

d) Regarding Site F, despite its considerable spatial extent, it has been assigned a lower future nominal capacity. This assessment is primarily due to its dependence on a few remote and relatively small islands for land-based infrastructure support. Even under the assumption that these islands are fully developed and populated, they are unlikely to offer the level of logistical and industrial support required for the intensive demands of cage culture operations.

4. Conclusions

In this study, a set of scientifically grounded criteria was applied to identify suitable sites along the northern coastline of the Persian Gulf. These criteria included water depths ranging from 20 to 60 meters, proximity to ports within 20 kilometers, and sea surface temperatures between 13°C and 30°C. Sites were limited to areas with maximum wind speeds of 7.7 m/s and excluded zones frequently affected by waves during storm conditions (defined as wave heights exceeding 1 meter for more than three consecutive days occurring more than once every four years). Additionally, acceptable current speeds ranged from 0.3 to 0.8 m/s, and a 5-kilometer buffer zone was maintained to avoid interference with both navigation/coastal activity areas and environmentally protected zones. Using these criteria, GIS layers were generated wherein areas not meeting all criteria were excluded. The resulting GIS layers identified several suitable spots for establishing cage aquaculture farms, extending from the northwest coastal areas in front of Mahshahr (Khozestan Province) to the southeast, strait of Hormuz (Hormozgan Province). The developed approach not only enhances the potential for sustainable aquaculture development but also serves as a model for integrating spatial analysis with environmental management in coastal and marine ecosystems. Implementing the cage culture practice in the sites proposed by this study ensures a profitable and sustainable mariculture business and moreover mitigates the potential environmental hazards threatening the precious coral reefs and coastal habitats in the region. The findings of this study indicate that the northern coast of the Persian Gulf possesses the capacity to sustain approximately 200,000 tons of fish production annually through cage culture, given the constraints of existing infrastructure. Notably, the region's theoretical maximum potential could reach nearly one million tons per year, provided that spatial suitability is fully realized without logistical restrictions. However, it is imperative to acknowledge that this projection is based on a spatial analysis utilizing a limited array of physical and operational criteria and does not account for critical ecological factors, including the overall carrying capacity of the Persian Gulf as a semi-enclosed water body. Therefore, a comprehensive investigation into the biogeochemical processes and total carrying capacity of the region is essential prior to the implementation of aquaculture in all identified suitable areas proposed by this study. Nevertheless, integrating future ecological monitoring and feedback systems, such as Integrated Multi-Trophic Aquaculture (IMTA) and Life Cycle Assessment (LCA), is essential for promoting sustainable resource use and minimizing environmental impact [62], [63]. These systems enable real-time data collection, adaptive management, and informed decision-making to enhance ecosystem health, resilience, and long-term productivity.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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References

1. Ma Z, Qin J. New techniques in marine aquaculture. J Mar Sci Eng. 2023;11(12):2239. https://doi.org/10.3390/jmse11122239
2. Li J, Shapira P, Gao L, Kwon S. Emerging development pathways of marine aquaculture: Key trends and dynamics. ICES J Mar Sci. 2021;78(1):315–326. https://doi.org/10.1093/icesjms/fsaa173
3. Føre H, Filgueira R, FAO. Towards environmental sustainability in marine finfish aquaculture. Frontiers in Marine Science. 2018.
4. Asche F. Farming the sea. Mar Resour Econ. 2008;23:527–547. https://www.journals.uchicago.edu/doi/abs/10.1086/mre.23.4.42629678
5. Lucas JS, Southgate PC. Reproduction, life cycles and growth. In: Lucas JS, Southgate PC, editors. Aquaculture: Farming Aquatic Animals and Plants. Chichester: John Wiley & Sons; 2012. p.113–126.
6. Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, Toulmin C. Food security: The challenge of feeding 9 billion people. Science. 2010;327:812–818. https://doi.org/10.1126/science.1185383
7. FAO. The State of World Fisheries and Aquaculture 2014: Opportunities and Challenges. Rome: Food and Agriculture Organization of the United Nations; 2014.
8. Flaaten O. Fisheries and Aquaculture Economics. Norway: Plant and Industry Management; 2018.
9. Loya Y, Lubinevsky H, Rosenfeld M, Kramarsky-Winter E. Nutrient enrichment caused by in situ fish farms at Eilat, Red Sea is detrimental to coral reproduction. Mar Pollut Bull. 2004;49:344–351. https://doi.org/10.1016/j.marpolbul.2004.06.011
10. Eng CT, Paw JN, Guarin FY. The environmental impact of aquaculture and the effects of pollution on coastal aquaculture development in Southeast Asia. Mar Pollut Bull. 1989;20:335–343. https://www.sciencedirect.com/science/article/abs/pii/0025326X89901574
11. Edinger EN, Jompa J, Limmon GV, Widjatmoko W, Risk MJ. Reef degradation and coral biodiversity in Indonesia: effects of land-based pollution, destructive fishing practices and changes over time. Mar Pollut Bull. 1998;36:617–630. https://www.sciencedirect.com/science/article/abs/pii/S0025326X98000472?via%3Dihub
12. Shaihidul I, Tanaka. Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management. Mar Pollut Bull. 2004.
13. Naylor RL, Hardy RW, Buschmann AH, et al. A 20-year retrospective review of global aquaculture. Nature. 2021;591:551–563. https://doi.org/10.1038/s41586-021-03308-6
14. Abbasian M, Haghshenas SA, Shah-Hosseini M, Farhangmehr A, Rezai H, Razavi Arab A, Risk MJ. Biodeposit dispersion around a deep cage finfish farm in the Northern Persian Gulf. Regional Studies in Marine Science. 2023;63. https://doi.org/10.1016/j.rsma.2023.102950.
15. Gao QF, Dong SL. Cage Farming of Fish in Open Waters. In: Dong SL, Tian XL, Gao QF, Dong YW, editors. Aquaculture Ecology. Singapore: Springer; 2023.
16. Lapenkov A, Guzeva A, Zaripova K, Slukovskii Z. The seasonal dynamics of geochemical characteristics of sediments in the impact zone of the fish farm (Lake Ladoga, Russia). Aquaculture Fisheries. 2023.
17. Jiang H, Ji Y, Zhang M. Modeling impact of culture facilities on hydrodynamics and solute transport in marine aquaculture waters of North Yellow Sea. Water Sci Eng. 2023.
18. Liu Y, Chen Y, Ge C. Numerical simulation of the settling flux of biodeposition in a bay with cage culture through similarity theory and a simplified pollution source. J Ocean

Univ China. 2024;23:247–254. https://doi.org/10.1007/s11802-023-5696-0
19. Johannesen Á, Patursson Ø, Kristmundsson J, Dam SP, Mulelid M, Klebert P. Waves and currents decrease the available space in a salmon cage. PLoS ONE. 2022;17(2):e0263850. https://doi.org/10.1371/journal.pone.0263850
20. Faltinsen OM, Shen Y. Wave and current effects on floating fish farms. J Mar Sci Appl. 2018;17:284–296. https://doi.org/10.1007/s11804-018-0033-5
21. Lee CW, Kim YB, Lee GH, Choe MY, Lee MK, Koo KY. Dynamic simulation of a fish cage system subjected to currents and waves. Ocean Eng. 2023.
22. Lader P, Fredriksson D, Volent Z, Decew J, Rosten T, Strand IM. Wave response of closed flexible bags. J Offshore Mech Arctic Eng. 2017;139. https://doi.org/10.1115/1.4036676
23. Swift MR, Fredriksson DW, Unrein A, Fullerton B, Patursson O, Baldwin K. Drag force acting on biofouled net panels. Aquac Eng. 2006. https://doi.org/10.1016/j.aquaeng.2006.03.002
24. FAO. Cage aquaculture, Regional reviews and global overview. Fisheries Technical Paper 498. 2007.
25. Micael J, Costa AC, Aguiar P, Medeiros A, Calado H. Geographic information system in a multi-criteria tool for mariculture site selection. Coast Manage. 2015;43(1):52–66. https://doi.org/10.1080/08920753.2014.985178
26. Salama AJ, Satheesh S, Balqadi AA, et al. Identifying suitable fin fish cage farming sites in the Eastern Red Sea Coast, Saudi Arabia. Thalassas. 2016;32:1–9. https://doi.org/10.1007/s41208-015-0001-7
27. Jayanthi M, Samynathan M, Thirumurthy S, et al. Mapping coastal lagoon characteristics for the aquaculture suitability using multi-criteria decision support (MCDS) spatial analysis: A case study from south-east coast of India. J Earth Syst Sci. 2021; 130:56. https://doi.org/10.1007/s12040-021-01560-y
28. Risk MJ, Haghshenas SA, Razavi Arab A. Cage aquaculture in the Persian Gulf: a cautionary tale for Iran and the world. Mar Pollut Bull. 2021; 166. https://doi.org/10.1016/j.marpolbul.2021.112079
29. Regunathan C, Kitto MR. Persian Gulf fish culture in Iran–pointers for success. Aquaculture Asia. 2005.
30. Jahani N, Nabavi SNB, Dehghan Madiseh S, Mortezaie SRS, Fazeli N. The effect of marine fish cage culture on benthic communities using BOPA index in Ghazale Creek. Iranian J Fisheries Sci. 2012;11(1):78–88. doi:10.22092/ijfs.2018.114186
31. FAO/World Bank. Aquaculture zoning, site selection and area management under the ecosystem approach to aquaculture. A handbook. Rome: FAO & The World Bank; 2017.
32. Yazdanbakhsh S, Koochakzaei A, Achachluei MM. Sclerochronology of Callista umbonella to extract the transfer function for reconstructing climates in some parts of Persian Gulf. Geo-Mar Lett. 2025;45(2):15.
33. Yao F, Johns WE. A HYCOM modeling study of the Persian Gulf: 2. Formation and export of Persian Gulf Water. J Geophys Res. 2010;115:C11018. doi:10.1029/2009JC005788.
34. Noori R, Tian F, Berndtsson R, Abbasi MR, Naseh MV, Modabberi A, Soltani A, Kløve B. Recent and future trends in sea surface temperature across the Persian Gulf and Gulf of Oman. PLoS One. 2019;14(2):e0212790. doi:10.1371/journal.pone.0212790
35. Chassignet EP, Hurlburt HE, Metzger EJ, Smedstad OM, Cummings J, Halliwell GR, et al. U.S. GODAE: Global Ocean prediction with the Hybrid Coordinate Ocean Model (HYCOM). Oceanography. 2009; 22(2):64–75. https://link.springer.com/chapter/10.1007/1-4020-4028-8_16
36. Prema D. Importance of water quality in marine life: cage culture. Tech Cent Mar Fish Res Inst. 2009.
37. Barbier E, Oppedal F, Hvas M. Atlantic salmon in chronic turbulence: Effects on growth, behaviour, welfare, and stress. Aquaculture. 2024; 582:740550. https://doi.org/10.1016/j.aquaculture.2024.740550.
38. UNDP/FAO. Site selection criteria for marine finfish netcage culture in Asia. UNDP/FAO Reg Seafarming Dev

Demonstration Project. Network Of Aquaculture Centres in Asia; 1989.
39. Hersbach H, Bell B, Berrisford P, et al. Complete ERA5 from 1940: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service (C3S) Data Store; 2017. DOI:10.24381/cds.143582cf.
40. Jedari Attari M, Haghshenas SA, Soltanpour M, Allahyar MR, Ghader S, Yazji D, Razavi Arab A, Hajisalimi Z, Ahmadi SJ, Bakhtiari A. Developing the Persian Gulf wave forecasting system. J Coastal Mar Eng. 2018;1(1):13–18.
41. Ranji Z, Soltanpour M. Optimization of bottom friction coefficient using inverse modeling in the Persian Gulf. Ocean Sci J. 2021;56:331–343. doi:10.1007/s12601-021-00040-0
42. Razzaghi S, Haghshenas SA, Ghader S, Yagi D, Delkhosh E, Farhangmehr A. 3D numerical modelling of shallow and deep water currents in the Persian Gulf. Iran J Geophys. 2019;13(3):69–85.
43. Mashayekh Poul H, Backhaus J, Dehghani A, Huebner U. Effect of subseabed salt domes on tidal residual currents in the Persian Gulf. J Geophys Res Oceans. 2016;121:3372–3380. doi:10.1002/2015JC011421
44. López J, Hurtado CF, Toledo JP, Suazo G, Zamora V, Queirolo D, Gutiérrez A. Structural integrity of a submersible sea cage exposed to extreme oceanographic conditions. J World Aquac Soc. 2024;55(3):e13052. https://doi.org/10.1111/jwas.13052
45. Huang C, Tang H, Liu J. Effects of waves and currents on gravity-type cages in the open sea. Aquac Eng. 2008;38. https://www.sciencedirect.com/science/article/abs/pii/S0144860908000022
46. Jedari Attari M, Bakhtiari A, Haghshenas SA, Hamidian JE, Sasaki J. Long-term suspended sediment transport patterns over the North-Western part of the Persian Gulf, applying a three-dimensional hydrodynamic model. In: Book of abstracts, 13th Int Conference Cohesive Sediment Transport Processes; 2015 Sep.
47. Yoo SL, Jeong JC. Safe navigation distance between marine routes and aquaculture farms in South Korea using Gaussian mixture model. Sensors (Basel). 2020;20(5):1246. doi:10.3390/s20051246
48. Burt J, Hume B, D'Angelo C, Baker AC, Riegl B. Corals from the Persian/Arabian Gulf as models for thermotolerant reef-builders: prevalence of clade C3 Symbiodinium, host fluorescence and ex-situ temperature tolerance. Mar Pollut Bull. 2014. https://www.sciencedirect.com/science/article/abs/pii/S0025326X1200570X?via%3Dihub
49. Maghsoodi M, Soltanpour M, Haghshenas SA. Study of the effects of suspended sediment transport on coral reefs (case study–Chabahar Bay). In: Proceedings 11th Int Conference on Coasts, Ports & Marine Structures (ICOPMAS); Tehran; 2014.
50. Risk MJ, Edinger E. Impacts of sediment on coral reefs. In: Encyclopedia of Modern Coral Reefs. 2011.
51. Jackson J. Reefs since Columbus. Coral Reefs. 1997;(Suppl 1):S23–S32. https://doi.org/10.1007/s003380050238
52. Lapointe BE. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnol Oceanogr. 1997;42(5 Pt 2):1119–1131. https://doi.org/10.4319/lo.1997.42.5_part_2.1119
53. Namin KS, Risk MJ, Hoeksema BW, Zohari Z, Rezai H. Coral mortality and serpulid infestations associated with red tide, in the Persian Gulf. Coral Reefs. 2010;29:509. doi:10.1007/s00338-010-0601-x
54. Pérez OM, Telfer TC, Ross LG. Geographical information systems-based models for offshore floating marine fish cage aquaculture site selection in Tenerife, Canary Islands. Aquac Res. 2005. https://doi.org/10.1111/j.1365.
55. Piccolotti F, Lovatelli A. Construction and installation of hexagonal wooden cages for fish farming: A technical manual. FAO Fisheries and Aquaculture Technical Paper. 2013.
56. Khabar Farsi. https://khabarfarsi.com/u/20535945 [Accessed 2025 Jul 23].
57. Nasseri Doust Sh, Abbasian M, Haghshenas SA, Risk MJ, Downs CA. Integrating hydrodynamic modeling with ecological risk assessment for selecting sites for artificial reef deployment: avoiding coastal pollution risks in Kish Island, Persian Gulf.

Oceans. 2024;5(4):51. doi:10.3390/oceans5040051
58. Troell M, Joyce A, Chopin T, Neori A, Buschmann AH, Fang J-G. Ecological engineering in aquaculture—potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture. 2009;297:1–9. https://doi.org/10.1016/j.aquaculture.2009.09.010
59. Chopin T, Robinson SMC, Troell M, Neori A. Multitrophic Integration for Sustainable Marine Aquaculture. In: Jorgensen SE, Fath BD, editors. The Encyclopedia of Ecology. Ecological Engineering. Elsevier; 2014.
60. Hallock P. Global change and modern coral reefs: New opportunities to understand shallow-water carbonate depositional processes. Sediment Geol. 2005;175:19–33. https://www.sciencedirect.com/science/article/abs/pii/S0037073805000515
61. Neori A, Chopin T, Troell M, Buschmann AH, Kraemer GP. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture. 2004;231:361–391. https://doi.org/10.1016/j.aquaculture.2003.11.015
62. Hughes C, King JW. Habitat suitability modelling for an integrated multi-trophic aquaculture (IMTA) system along Europe's Atlantic coast. Ecol Model. 2023;484:110459. doi:10.1016/j.ecolmodel.2023.110459.
63. Hala AF, Chougule K, Cunha ME, Mendes MC, Oliveira I, Bradley T, Forbes J, Speranza LG. Life cycle assessment of integrated multi-trophic aquaculture: A review on methodology and challenges for its sustainability evaluation. Aquaculture. 2024;590:741035. doi:10.1016/j.aquaculture.2024.741035.

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