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# Spatial Economic Valuation of Marine Ecosystem Services Provided by Coral Reefs and Seagrasses in Iran

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## ABSTRACT

Coral reef and seagrass ecosystems are an essential component in marine ecosystems, the full value and spatial distribution of which is fundamental to sustainable management. This study is primarily focused on the economic valuation of marine ecosystem services (coral reefs and seagrass) in Iranian territorial waters in the Persian Gulf. To this end, coral reef and seagrass habitat areas within the political boundaries of the Persian Gulf in Iran were extracted and classified by province, city, and island using the Allen Coral Atlas remote sensing product within the Google Earth Engine platform based on habitat-specific remote sensing classification. These two habitats were then economically assessed using Robert Costanza's ecosystem service valuation model. The results indicate that Iran encompasses 6018.63 hectares of coral reefs and 2054.01 hectares of seagrass, corresponding to $2 billion and $59 million in economic value, respectively. The province of Hormozgan, Bandar Lengeh city, and Qeshm Island had the largest share of coral reef areas, corresponding to 4251.11, 2288.95, and 515.26 hectares and respective economic values of $1.497 billion, $806 million, and $181 million. Hormozgan Province, Konarak City, and Larak Island, on the other hand, showed the largest area of seagrass beds, equal to 958.81, 951.43, and 47.72 hectares, respectively. The economic value of seagrass in these areas has been estimated at $27 million, $27 million, and $1 million, respectively.These results highlight the significant ecological and economic importance of coral reef and seagrass ecosystems in supporting coastal sustainability in the Persian Gulf. Furthermore, the findings can support marine spatial planning, ecosystem conservation strategies, and policy-making in Iran’s coastal and marine management.

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## 1. Introduction

Today, human activities continue to threaten the ecological systems on which our survival depends. In response to the urgent need to protect and monitor the environment, the concept of ecosystem services has emerged as a central framework (Townsend *et al*., 2018). Ecosystem services provide a framework for linking natural systems with human well-being and represent the many benefits that humans derive from ecosystems and continuously require for their survival (Ashournejad *et al*., 2019$_{b;}$ Mahdlo & Pourebrahimi, 2023). Therefore, the spatial assessment of ecosystems and their services is essential for a comprehensive understanding of these frameworks (Costanza *et al*., 2014). The most widely used method for evaluating ecosystems and related services is economic valuation, since ecosystem services have value only when people assign them a monetary equivalent (Frör., 2018).

Proponents of ecosystem service valuation emphasize its potential to improve our understanding of ecosystem-related issues, directly inform decision-making processes, clarify the costs and benefits of these services, and promote the use of tools for sustainable ecosystem management (Aylward & Barbier, 1992; Daily *et al*., 1997; Daily *et al*., 2000). Despite these benefits, ecosystem services are often undervalued in decision-making because they are realized only to a limited extent in commercial markets, making quantitative comparisons with economic services and productive capital quite difficult. Nevertheless, scientists argue that ecosystems and their services play a crucial role in supporting human economies (Costanza *et al*., 1997; Ashournejad *et al*., 2019$_{a}$;Ghabelnezam *et al*., 2022). Therefore, evaluating ecosystem services, which have been largely overlooked so far, is beneficial for transforming decision-making processes and improving natural resource management. This approach serves as a tool for integrating natural capital into the economic development framework (Chee *et al*., 2004).

The components of ecosystems, including species and habitats, form the basis for ecosystem functioning and the maintenance of ecosystem services (Bryhn *et al*., 2020). Marine ecosystems such as seagrass beds and coral reefs, in particular, stand out as invaluable biomes (Costanza *et al*., 2014), characterized by high biodiversity, productivity, and economic importance (Fanning *et al*., 2021). In addition to their recreational and biodiversity value, these ecosystems play a central role in supporting the livelihoods of millions of people, especially in developing countries. More than 500 million people in 109 countries depend directly on these ecosystems for their economic well-being. They also provide services such as fisheries and marine aquaculture activities, the production of raw materials and nutrients, the provision of habitats for marine species, coastal protection from storms, and the reduction of coastal erosion (Ngoc, 2019).

National, regional, and international indicators of ecosystem services have attracted considerable attention since the publication of the Millennium Ecosystem Assessment (Reid et al., 2005) and the Economics of Ecosystems and Biodiversity report (TEEB, 2010). Recognizing ecosystem services can increase awareness of their importance and thus contribute to their conservation and management. Overall, the need to study ecosystem services is well recognized, as reflected in the growing number of studies (Hossain & Hashim, 2019).

Over the past two decades, several studies have investigated the services provided by coral reef and seagrass ecosystems worldwide. In the Caribbean, Failler *et al*. (2015) used a market-based valuation technique to assess the economic value of marine and coastal ecosystem services, including commercial activities such as fishing, diving, and tourism, as well as individuals' willingness to pay for environmental quality improvements. Their study identified three main ecosystems—coral reefs, seagrasses, and mangroves—with respective areas of 55, 50, and 20 square kilometers, generating approximately $250 million annually, of which around

60% was attributed to tourism and fisheries. Similarly, Spalding *et al*. (2017), in a global assessment of coral reef tourism, estimated that the economic value of these services reaches nearly $36 billion, representing more than 9% of the total global coastal tourism value in reef-associated countries. Trégarot *et al*. (2017) conducted an economic valuation of ecosystem services provided by coral reefs, seagrass, and mangrove forests in Mayotte. Their results indicated an annual economic value of approximately $124 million, which could increase to $162 million under optimal conditions. Their valuation approach was based on the number of visitors and tourism expenditures within a 30 km buffer zone around reef systems, excluding urban areas. Tamayo *et al*. (2018) also assessed the economic value of coral reef ecosystem services in the Philippines, using data from the Department of Fisheries and Aquatic Resources to estimate fisheries value, and data from the Department of Tourism to evaluate willingness to pay for conservation and overall tourism value. Their findings showed a total economic value of approximately $4 billion, with fisheries contributing the largest share, followed by tourism services. Pandelaki *et al*. (2020) examined the economic value of seagrass ecosystems on Nain Island, Indonesia, through interviews and questionnaire surveys. They estimated the total value of seagrass ecosystem services at 284 billion Indonesian Rupiah. Finally, Ashournejad (2022) conducted an economic evaluation of tourism-related ecosystem services across Iranian biomes using the Costanza valuation model. The results indicated that the economic value of coral reefs and seagrass ecosystems in Iran is approximately $1.127 billion and $70 million, respectively.

However, various natural and human disturbances threaten these ecosystems (Lalas *et al*., 2023). Over the past two decades, coral reef areas have declined considerably (Rosedy *et al*., 2023). These valuable habitats have been degraded by numerous factors such as overfishing, coastal development, sedimentation, excessive tourism, climate change, ocean acidification (Ngoc, 2019), and the discharge of municipal sewage and industrial effluents, all of which have placed significant pressure on the resilience of these ecosystems (Vaughan *et al*., 2019). In Iran, these habitats are considered among the most valuable and ecologically sensitive areas of the Persian Gulf. The Persian Gulf environment is inherently stressed due to its unique natural conditions and intensive coastal development. Factors such as oil exploration, the passage of oil tankers, the discharge of domestic wastewater directly or via rivers, and maritime accidents significantly affect the water quality of the Gulf (Ghasemi Bajd, 2022). Persistent pollution of the Gulf is likely to lead to the degradation of vast portions of these vital resources (Mohammadi Roozbahani, 2009). This highlights the importance of economic valuation of ecosystems, as their degradation can significantly reduce ecosystem performance and the services they provide. It also emphasizes the sensitivity of these environments to anthropogenic pressures, which should be prioritized at the national level (Ahmadian *et al*., 2009; Rosedy *et al*., 2023; Miandej et al., 2024).

Beyond providing a spatial assessment of coral reef and seagrass ecosystems in the Persian Gulf, this study develops an integrated and transferable analytical framework that combines high-resolution remote sensing data with ecosystem service valuation to quantify both the spatial distribution and economic value of marine habitats. By operationalizing the Costanza ecosystem service model within a GIS-based environment, the research enables multi-scale assessment of ecosystem services at provincial, city, and island levels, providing a consistent and harmonized approach for spatial economic evaluation. Unlike conventional valuation studies that rely on aggregated or site-specific estimates, this framework explicitly links habitat mapping with economic valuation, allowing for a more detailed understanding of spatial heterogeneity in ecosystem service provision. Furthermore, the study demonstrates the applicability of remote sensing–based ecosystem accounting as a decision-support tool for marine spatial planning and coastal resource management. The proposed approach is scalable and transferable to other coastal and marine environments, offering a standardized methodology for integrating ecological data with economic valuation. In doing so, thereby enhancing the relevance of spatial ecosystem valuation for both national policy and international environmental governance.

## 2. Method

### *2.1. study area*

Corals require water temperatures between 22°C and 32°C and are typically found from the sea surface to depths of approximately 30 m (Eslami & Hasanlou, 2019). They mainly occur in tropical regions between 25°N and 25°S latitude. The Persian Gulf is a semi-enclosed, shallow tropical sea where summer temperatures can exceed 34°C (Bolouki *et al*., 2021). Its high evaporation rate, combined with low precipitation and shallow bathymetry, has led to the formation of a highly saline water mass (Ramak *et al*., 2023). Similarly, seagrasses are primarily distributed in saline tropical and subtropical marine environments (Gharanjik., 2019). This explains why the present study assessed the ecosystem services of coral reefs and seagrasses in three southern Iranian provinces along the Persian Gulf coast—Bushehr, Hormozgan, and Sistan and Baluchestan—which provide suitable environmental conditions for the development of these ecosystems (Fig. 1). These ecosystems are found in the cities of Kangan, Asaluyeh, and Bushehr in Bushehr Province, as well as Parsian, Qeshm (including the islands of Qeshm, Hengam, and Larak), and Abu Musa (including Abu Musa, Lesser Tunb, Greater Tunb, Lesser Farvar, Greater Farvar, and Sirri), along with Bandar Lengeh in Hormozgan Province. In addition, Konarak city in Sistan and Baluchestan Province, as well as the islands of Khark, Farsi, and Kharko in Bushehr Province and Lavan, Shidvar, Hendorabi, Kish, Lesser Farvar, Greater Farvar, Sirri, Lesser Tunb, Greater Tunb, Abu Musa, Qeshm, Hengam, and Larak in Hormozgan Province, host coral reef and seagrass ecosystems.

### *2.2. Data*

Remote sensing, with its characteristics such as global coverage, high accuracy, and easy access to data—often free of charge—has become one of the most important sources of geospatial information in the modern era and continues to advance rapidly in various dimensions(Ashournejad., 2023; Miandej *et al*., 2026). In this context, the Allen Coral Atlas dataset within Google Earth Engine was utilized in the present study to estimate the spatial extent of coral reef and kelp forest ecosystems. This dataset provides a pre-classified benthic habitat map with seven classes including sand, rubble, rock, seagrass, coral reefs and microalgae mats. The classification was originally produced using supervised machine learning (Random Forest) and object-based refinement techniques based on high-resolution Planet Dove imagery. This product was created by the Arizona State University Center for Global Discovery, a global-scale coral habitat mapping project. The product consists of two parts: geomorphic and benthic, which were generated using Planet Dove satellite imagery with a spatial resolution of 5 meters. The images underwent several processing steps, including Top of Atmosphere Radiance (TOAR), flat-field correction, debayering, sensor and radiometric calibration, orthorectification, and surface reflectance correction. To map coral reefs in this product, areas with a water depth of less than 20 meters, located between 30°N and 30°S, characterized by clear water and low pollution, were extracted. Atmospheric correction was also applied to eliminate atmospheric effects and achieve accurate light-reflection conditions below the water surface. This reflectance information supports the identification and classification of coral habitats. The method used four spectral bands (blue, green, red, and nearinfrared) from Planet Dove satellite imagery, enriched with bathymetric data. Bathymetry maps were generated using Sentinel-2 surface reflectance data within Google Earth Engine (GEE) at a spatial resolution of 10 meters. Sentinel-2 images with low cloud cover over a 12-month period were selected and composited into a clean mosaic, with mean depth values used as the final output. Areas with insufficient Sentinel-2 coverage were supplemented with Landsat-8 and Planet Dove imagery to derive depth information and generate a composite dataset. To assess the accuracy of the water depth model, field-based reference measurements were compared with corresponding locations in the product map, and regression analysis was performed based on the observed differences. It should be noted that reference data were derived from independent datasets collected in previous studies. A Random Forest machine learning algorithm was used for the initial classification, which was subsequently refined using a standard object-based classification refinement framework. This was implemented through object-based analysis (OBA) rules to improve map accuracy and spatial consistency. These adjustments were performed considering environmental conditions and spatial relationships among classes. The overall accuracy of the product ranges between 60% and 90%, depending on mapping regions and environmental characteristics such as habitat complexity, water depth, water clarity, and the quality of image mosaics and training datasets used for classification and validation. Accuracy was assessed using field observations and validation points derived from

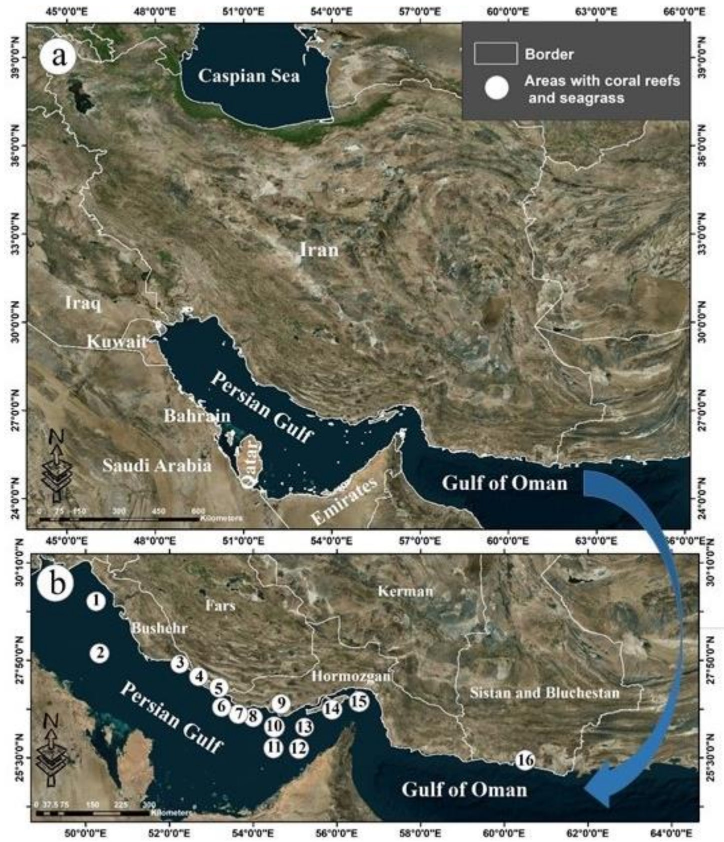


**Figure 1.** Study area, a)Iran b) Includes the following places: 1- Khark and Kharko islands 2- Farsi island 3- Kangan city 4- Asalouye city 5- Parsian city 6- Lavan and Shidvar islands 7- Hendorabi island 8- Kish island 9- Bandarlangeh city 10- Minor Farvar and Major Farvar Islands 11- Sirri Island 12- Abu Musa Island 13- Minor Tunb and Major Tunb Islands 14- Qeshm and Hengam Islands 15- Larak Island 16- Konarak City.

the United Nations Environment Programme's Global Coral Reef Reference Map (Ivanova, 2010). The mapping team and partner institutions collected field data from multiple coral reef sites, including geo-referenced photo quadrats (1 m × 1 m BioBase images) taken across different coral regions. GPS coordinates and timestamps were used to determine the exact location of each image. Historical datasets from multiple coral regions were also used to validate and improve map accuracy. In this study, the benthic dataset, which includes seven classes (sand, rubble, rock, seagrass, coral reefs, and microalgae mats), was used to calculate the total area of coral reefs and seagrass in the study region (Allen Coral Atlas, 2020). The dataset was integrated into a GIS environment with a pixel area of 25 m² (5 m × 5 m), and extracted boundaries of coral reef and seagrass areas in Iran were analyzed. In this way, the area of each reef and seagrass habitat was calculated separately for each province, city, and island (Equation 1).

$$S/CA_{ij} = NP_{ij} \times A \quad (1)$$

where $S/CA_{ij}$ is the area of coral reefs and seagrass in the $j^{\text{th}}$ province, and $i^{\text{th}}$ city or island. $NP_{ij}$ is the number of pixels for the corresponding coral reefs and seagrass, and $A$ is the pixel size of the product used.

### *2.3. Evaluation model*

The Costanza model, presented by Costanza *et al*. (1997, 2014), provides a comprehensive overview of ecosystem services and biomes at a global scale without focusing on specific regions, services, or ecosystems. Accordingly, the Costanza model was used in this study to assess the ecosystem services of coral reefs and seagrasses in the study area. Costanza *et al*. applied various methods, such as basic value transfer, expert-corrected value transfer, statistical value transfer, and spatially explicit functional modeling, to determine the value of ecosystem services. In addition, a combination of land area changes and revised unit values was used to estimate the global value of ecosystem services. This model enables the assessment of ecosystem service values for each biome. This study specifically examines the value of ecosystem services of coral reefs and seagrasses among the 16 global biomes. According to Costanza *et al*. estimates, coral reefs have the highest ecosystem service value among the world's biomes, with each hectare valued at over $352,000 per year. Seagrasses, on the other hand, have a value of $26,226 per hectare per year. Table 1 shows the ecosystem service values of coral reefs and seagrasses per hectare based on the Costanza model.

Equations 2, 3, and 4 were used to assess the ecosystem service values of coral reefs and seagrass based on the Costanza model.

$$\frac{S}{CESV_p} = \sum_{p=1}^{m} CESV_p \quad (2)$$

$$\frac{S}{CESV_p} = \sum_{p=1}^{m} CESV_p \quad (3)$$

$$S/CESV_t = \sum_{t=1}^{j} CESV_t \quad (4)$$

$S/CESV_{c/i}$ in Equation 2 represents the economic value of coral reef and seagrass ecosystem services for each city and island. $A_{c/i}$ denotes the area of coral reefs and seagrasses for each city and island, and $VC_f$ is the coefficient representing the economic value of coral reef and seagrass ecosystems for each type of ecosystem service. In Equation 3, the total area of coral reefs and seagrasses for each province is represented by $S/CESV_p$, while Equation 4 denotes the total area of all coral reefs and seagrass ecosystems in Iran, formulated as $S/CESV_t$.

**Table 1**. The value of ecosystem services provided by seagrass and coral reefs per hectare based on the Costanza model.

| Ecosystem services | Seagrass (in dollars) | Coral reefs (in dollars) |
|---|---|---|
| Gas regulation | 0 | 0 |
| Climate regulation | 479 | 1188 |
| Disturbance regulation | 0 | 16991 |
| Water regulation | 0 | 0 |
| Water supply | 0 | 0 |
| Erosion control | 25368 | 153214 |
| Soil formation | 0 | 0 |
| Nutrient cycling | 0 | 0 |
| Waste treatment | 26223 | 85 |
| Pollination | 0 | 0 |
| Biological control | 0 | 7 |
| Habitat/Refugia | 194 | 16210 |
| Food production | 2384 | 677 |
| Raw materials | 12 | 22000 |
| Genetic resources | 180 | 33048 |
| Recreation | 256 | 96302 |
| Cultural | 43 | 12535 |

## 3. Results

### *3.1. Spatial distribution of coral reefs and seagrass in Iran*

The provinces, cities, and islands within the study area were evaluated separately to determine the extent of coral reefs and seagrass ecosystems (Tables 2 and 3). The findings reveal that Iran has a total of 6018.63 hectares of coral reefs and 2054.01 hectares of seagrass. Hormozgan Province contains the largest extent of these ecosystems, with 4251.11 hectares of coral reefs, accounting for 70% of the total coral reef area. Bushehr and Sistan and Baluchestan provinces have 954.56 (15%) and 812.96 (13%) hectares of coral reefs, respectively. In terms of seagrass, Hormozgan Province also has the highest extent, with 958.81 hectares (47%), followed by Sistan and Baluchestan and Bushehr provinces with 951.43 (46%) and 143.77 hectares, respectively. Among the cities and islands in Hormozgan Province, Bandar Lengeh has the largest coral reef area, with a total of 2288.95 hectares. Additionally, Parsian, Abu Musa, and Qeshm cities have coral reef areas of 662.38, 504.55, and 780.48 hectares, respectively. In Bushehr Province, Bushehr, Kangan, and Asaluyeh cities have coral reef areas of 351.77, 401.41, and (value as provided), respectively. Furthermore, Konarak City in Sistan and Baluchestan Province contains 812.47 hectares of coral reef. This city also has the highest seagrass extent, with 951.43 hectares, while Bushehr City has the lowest extent, with 22.02 hectares. Kangan and Asaluyeh cities have 26.01 and 95.73 hectares of seagrass, respectively, while Parsian, Bandar Lengeh, Abu Musa, and Qeshm have seagrass areas of 356.65, 456.86, 29.29, and 113.91 hectares, respectively (Fig. 2). Qeshm Island contains the largest coral reef area, with 515.26 hectares, while Lesser Farvar Island has the smallest area, with 16.46 hectares. Khark, Kharko, and Farsi Islands have 84.74, 65.25, and 25.14 hectares of coral reefs, respectively. Lavan Island has 296.29 hectares, Shidvar 125.50 hectares, Hendorabi 170.09 hectares, Kish 366.57 hectares, Greater Farvar 54.74 hectares, Siri 145.74 hectares, Greater Tunb 67.06 hectares, Lesser Tunb 29.01 hectares, and Abu Musa 191.52 hectares. Larak Island and Lesser Tunb have 127.19 and 138.03 hectares of coral reefs, respectively.

**Table 2.** Coral reef and seagrass distributions in the Persian Gulf and Gulf of Oman within the provincial and municipal boundaries of Iran.

| Political unit | | The area of the seagrass ecosystem (hectares) | | The area of the coral reef ecosystem (hectares) | |
|---|---|---|---|---|---|
| Province | City | Area of seagrass in each city | Total | Area of coral reef in each city | Total |
| Hormozgan | Persians | 358.65 | 958.81 | 662.38 | 4251.11 |
| | Bandar Lengeh | 456.86 | | 2288.95 | |
| | Abu Musa | 29.29 | | 504.55 | |
| | Qeshm | 113.91 | | 780.48 | |
| Bushehr | Kangan | 26.01 | 143.77 | 351.77 | 954.56 |
| | Asaluyeh | 95.73 | | 402.41 | |
| | Bushehr | 22.02 | | 190.90 | |
| Sistan and Baluchestan | Konarak | 951.43 | 951.34 | 812.47 | 812.96 |
| Total | | 2054.01 | | 6018.63 | |

**Table 3.** The area of coral reefs and seagrass ecosystems in the Persian Gulf and Gulf of Oman within Iran's territorial waters, classified by islands.

| Political unit | | | Area of seagrass ecosystem (in hectares) | | | Area of coral reef ecosystem (in hectares) | | |
|---|---|---|---|---|---|---|---|---|
| Province | City | Island | Area of seagrass for each island | Total (City) | Total (Province) | Area of coral reef for each island | Total (City) | Total (Province) |
| Hormozgan | Bandar Lengeh | Lavan | 34.19 | 79.13 | 222.34 | 296.29 | 958.46 | 2243.5 |
| | Bandar Lengeh | Shidvar | 5.64 | | | 125.50 | | |
| | Bandar Lengeh | Hendorabi | 13.01 | | | 170.09 | | |
| | Bandar Lengeh | Kish | 26.28 | | | 366.57 | | |
| | Abu Musa | Greater Farvar | 0.57 | 29.29 | | 54.74 | 504.55 | |
| | Abu Musa | Lesser Farvar | 0.95 | | | 16.46 | | |
| | Abu Musa | Sirri | 21.60 | | | 145.74 | | |
| | Abu Musa | Greater Tunb | 2.14 | | | 67.06 | | |
| | Abu Musa | Lesser Tunb | 2.21 | | | 29.01 | | |
| | Abu Musa | Abu Musa | 1.79 | | | 191.52 | | |
| | Qeshm | Qeshm | 37.09 | 113.91 | | 515.26 | 780.48 | |
| | Qeshm | Hengam | 29.09 | | | 127.19 | | |
| | Qeshm | Larak | 47.72 | | | 138.03 | | |
| Bushehr | Bushehr | Khark | 16.94 | 22.01 | 22.01 | 84.74 | 175.13 | 175.13 |
| | Bushehr | Farsi | 0.44 | | | 25.14 | | |
| | Bushehr | Kharko | 4.63 | | | 65.25 | | |
| Total | | | 244.35 | | | 2418.63 | | |

The seagrass area in Bushehr Province islands, including Khark, Farsi, and Kharko, is 16.94, 0.44, and 4.63 hectares, respectively. In Hormozgan Province, seagrass areas include 34.19 hectares on Lavan Island, 5.64 hectares on Shidvar, 13.01 hectares on Hendorabi, 26.28 hectares on Kish, 0.57 hectares on Greater Farvar, 0.95 hectares on Lesser Farvar, 21.60 hectares on Siri, 2.14 hectares on Greater Tunb, 2.21 hectares on Lesser Tunb, 1.79 hectares on Abu Musa, 37.09 hectares on Qeshm, 29.09 hectares on Hengam, and 47.72 hectares on Larak Island (Fig. 3). The maps showing the distribution of coral reefs and seagrasses in cities are presented in Fig. 4, while Figs. 5 and 6 illustrate their distribution across the islands. It is important to note that due to natural differences in island sizes, it was not possible to present all islands at the same cartographic scale. Additionally, technical limitations in map design made it difficult to standardize a uniform scale for all islands.

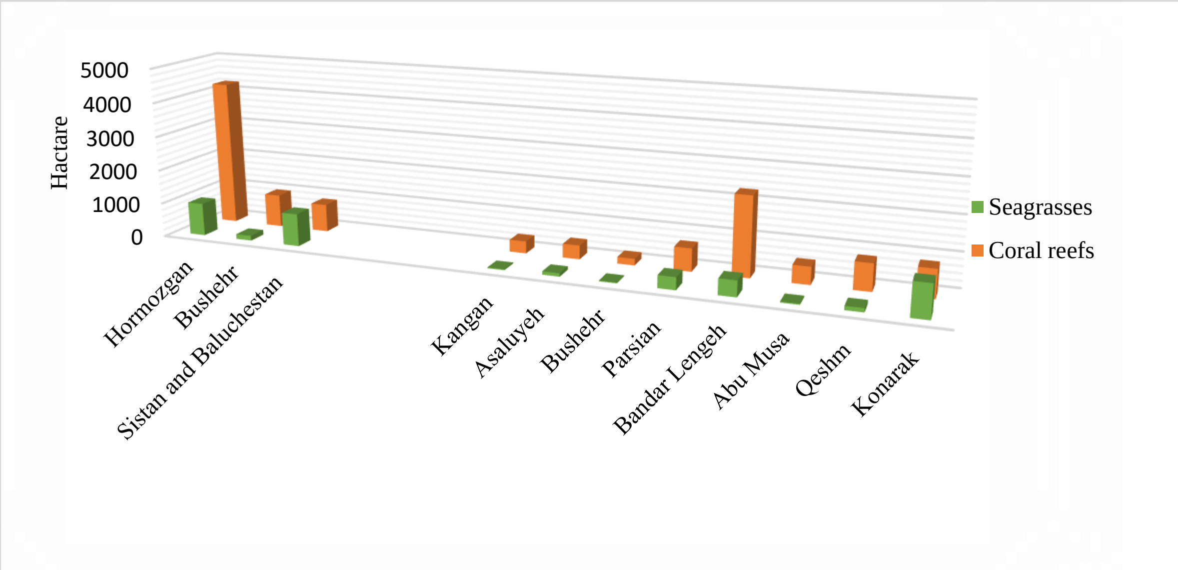


**Figure 2.** Coral reef and seagrass areas in the Persian Gulf and Gulf of Oman within the territorial waters of Iran, classified by province and city.

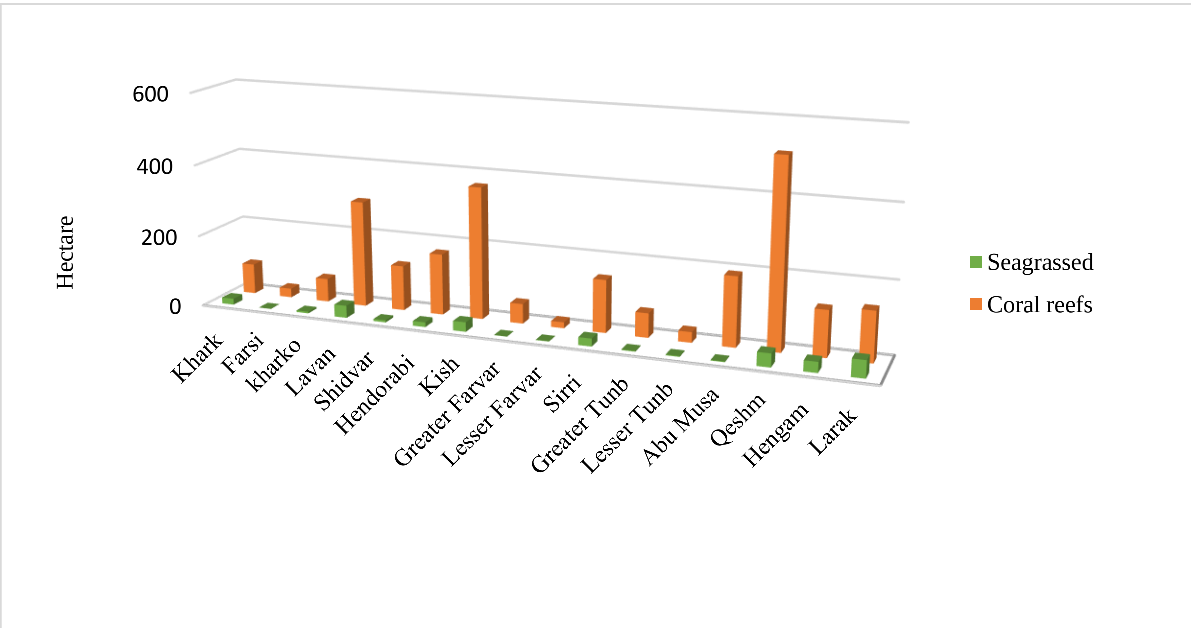


**Figure 3.** Coral reef and seagrass ecosystems in the islands of the Persian Gulf and the Gulf of Oman within Iranian territorial waters

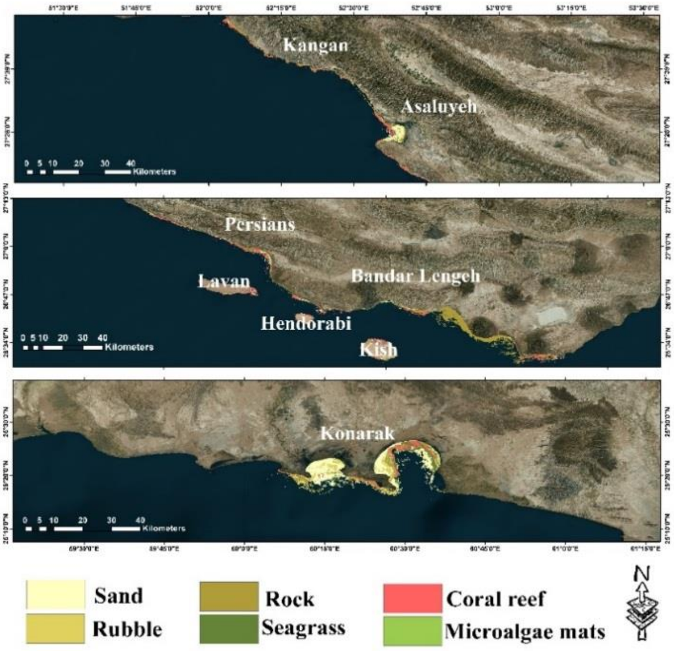


**Figure 4.** Spatial distribution of coral reefs and seagrass along city coasts.

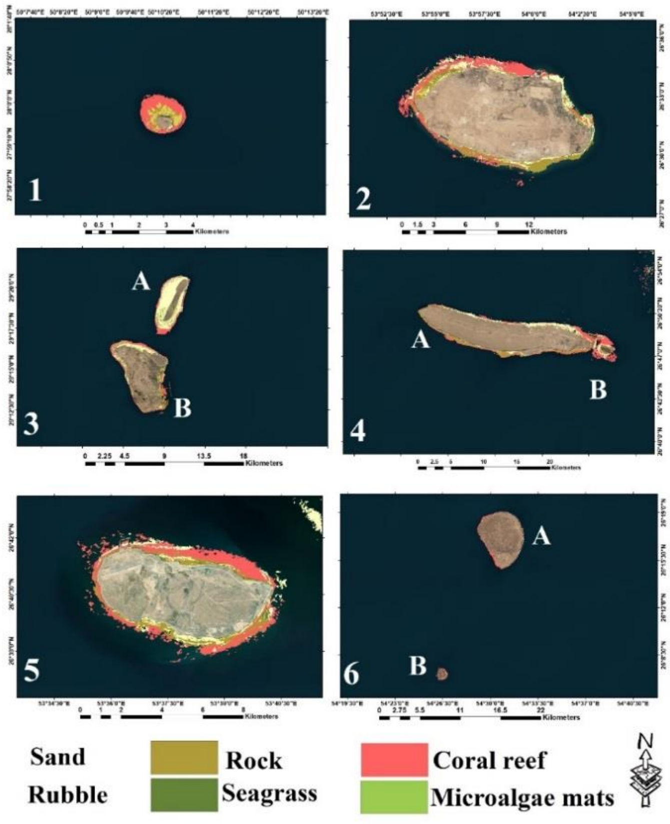


**Figure 5.** Spatial distribution of coral reefs and sea grasses in islands of the Persian Gulf. The order of the islands is as follows: 1- Farsi 2- Kish 3- A: Kharko B: Khark 4- A: Lavan B: Shidvar 5- Hendorabi 6- A: Greater Farvar B: Lesser Farvar.

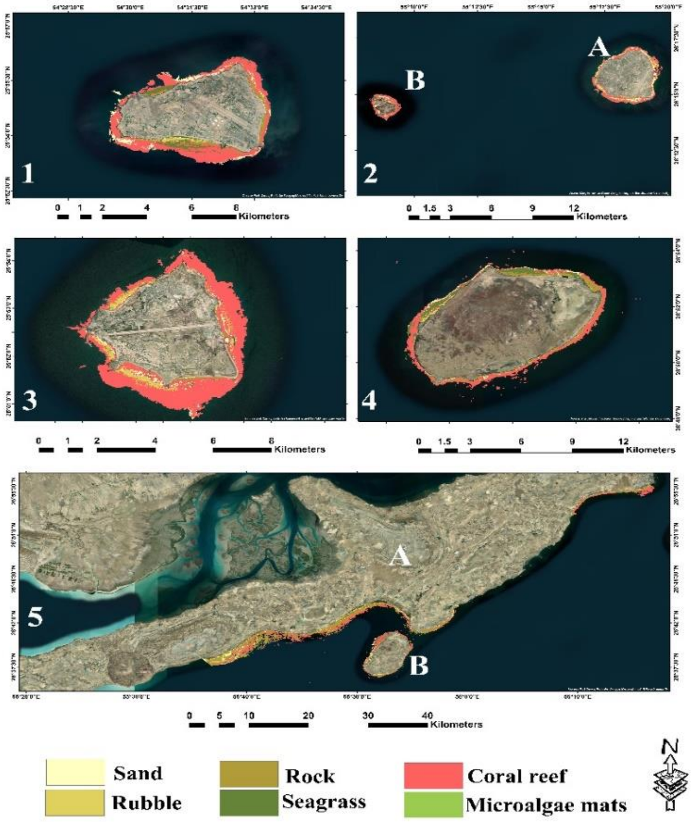


**Figure 6.** Spatial distribution of coral reefs and sea grasses in islands of the Persian Gulf. The order of the islands is as follows 1-Sirri, 2- A: Greater Tunb, B: Lesser Tunb, 3- Abu Musa, 4- Larak, and 5- A: Qeshm, B: Hengam.

### *3.2 Evaluating Economic Value of Ecosystem Services Provided by Coral Reefs and Seagrasses in the Persian Gulf in Iran*

After calculating the area of coral reefs and seagrass ecosystems in the study area, the results were input into the Costanza valuation model. This allowed the estimation of the economic value of ecosystem services provided by these habitats for each province, city, and island separately. The results are presented in Tables 4, 5, 6, and 7. The economic value of coral reef ecosystem services in Iran is estimated at $2.12 billion, while the economic value of seagrass ecosystems is $59.393 million. In Hormozgan Province, the economic value of coral reef ecosystem services is $1.497 billion. In Bushehr and Sistan and Baluchestan provinces, the values are $336 million and $286 million, respectively. The economic value of seagrass ecosystem services in these provinces is $27.724 million, $4 million, and $27.511 million, respectively. As can be observed, the economic value of coral reef ecosystem services varies across cities. Bandar Lengeh in Hormozgan Province has the highest value at $806 million. Bushehr has a value of $67 million, Asaluyeh $141 million, Kangan $123 million, Parsian $233 million, Abu Musa $177 million, Qeshm $274 million, and Konarak $286 million. The results of the economic valuation of seagrass ecosystem services show that Konarak has the highest value at $27.511 million. Bandar Lengeh's seagrass services are valued at $13.210 million, Parsian at $10.370 million, Qeshm at $3.290 million, and Asaluyeh at $2.768 million. The values for Bushehr, Kangan, and Abu Musa are $636, $752, and $846, respectively (Fig. 7).

Among the islands, Qeshm Island is the most valuable in terms of coral reef ecosystem services, with a value of $181 million. The economic value of coral reef ecosystem services for Khark Island is $29 million, Kharko $8 million, Farsi $14 million, Lavan $114 million, Shidvar $44 million, Hendorabi $59 million, Kish $129 million, Greater Farvar $19 million, Lesser Farvar $5 million, Sirri $51 million, Greater Tunb $23 million, Lesser Tunb $10 million, Abu Musa $67 million, Hengam $44 million, and Larak $48 million. The results indicate that Larak Island has the highest economic value of seagrass ecosystem services at $138 million. Additionally, seagrass ecosystem services on Qeshm Island have an economic value of $1,072,000, while on Khark Island the value is $480,000; Kharko $133,000; Lavan $980,000; Shidvar $163,000; Hendorabi $376,000; Kish $759,000; Sirri $624,000; Hengam $841,000; Farsi $12,000; Greater Farvar $16,000; Lesser Farvar $27,000; Greater Tunb $62,000; Lesser Tunb $63,000; and Abu Musa $51,000 (Fig. 8). The coral reef ecosystem provides various services, of which 43.49% is directly related to erosion control, 27.33% to tourism and recreation, 9.38% to genetic resources, 6.25% to the production of raw and primary materials, 4.82% to the regulation of human and natural disturbances, 4.60% to habitat provision, 3.56% to cultural services, 0.34% to climate regulation, 0.19% to food production, 0.02% to waste treatment, and 0.0019% to biological control. In general, coral reefs play a vital role in controlling erosion in the Persian Gulf and have high potential for supporting tourism and recreational activities. Similarly, seagrass ecosystems show the highest contribution to erosion control, accounting for 87.72%, followed by food production (24.8%), cultural services (14%), climate regulation (1.6%), tourism (0.88%), habitat services (0.67%), genetic resources (0.62%), and raw and primary materials (0.04%) (Fig. 8).

**Table 4.** Economic Value of Coral Reef and Seagrass Ecosystem Services in the Persian Gulf and Gulf of Oman (Iran) by Province and City (USD)

| Political Unit with Coral Reef | | Type of Ecosystem Service | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Province | City | Climate Regulation | Disturbance Regulation | Erosion Control | Waste Treatment | Biological Control | Habitat/ Refugia | Food Production | Raw Materials | Genetic Resources | Recreation | Cultural | Total of the province |
| Hormozgan | Persian | 786907 | 11254498 | 101485889 | 56302 | 4636 | 10737179 | 448431 | 14572360 | 21890334 | 63788518 | 8302933 | 1492289226 |
| | Bandar Lengeh | 2719275 | 38891591 | 350699568 | 194560 | 16022 | 37103920 | 1549620 | 50356955 | 75645302 | 220430703 | 28692019 | |
| | Abu Musa | 599408 | 8572851 | 77304506 | 42886 | 3531 | 8178796 | 341582 | 11100155 | 16674451 | 48589414 | 6324565 | |
| | Qeshm | 927210 | 13261135 | 119580462 | 66340 | 5463 | 12651580 | 528384 | 17170560 | 25793303 | 75161784 | 9783316 | |
| Bushehr | Kangan | 417902 | 5976924 | 53896088 | 29900 | 2462 | 5702191 | 238148 | 7738940 | 11625294 | 33876154 | 4409436 | 332912802 |
| | Asaluyeh | 478069 | 6837433 | 61655611 | 34205 | 2816 | 6523147 | 272434 | 8853130 | 13299010 | 38753369 | 5044272 | |
| | Bushehr | 226789 | 226789 | 29248552 | 16226 | 1336 | 3094489 | 129239 | 4199800 | 6308863 | 18384051 | 2392931 | |
| Sistan and Baluchestan | Konarak | 965217 | 965217 | 124482161 | 69060 | 5687 | 13170179 | 550043 | 17874395 | 26850591 | 78242726 | 10184342 | 286199125 |
| Total | 2111401158 | | | | | | | | | | | | |

**Table 5.** Economic Valuation of Coral Reef and Seagrass Ecosystem Services in the Persian Gulf and Gulf of Oman (Iranian Waters), by Island (USD)

| Political Unit with Coral Reef | | Type of Ecosystem Service | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Province | City | Iasland | Climate Regulation | Disturbance Regulation | Erosion Control | Waste Treatment | Biological Control | Habitat/ Refugia | Food Production | Raw Materials | Genetic Resources | Recreation | Cultural | Total(city) | Total(province) |
| Hormozgan | Bandar Lengeh | Lavan | 351995 | 5034305 | 45396159 | 25184 | 2074 | 4802901 | 200590 | 6518435 | 9791874 | 28533560 | 3714026 | 37626886 | 790288579 |
| | | Shidvar | 149102 | 2132497 | 19229506 | 10668 | 878 | 2034476 | 84968 | 2761165 | 4147771 | 12086623 | 1573236 | | |
| | | Hendorabi | 202069 | 2890041 | 26060552 | 14457 | 1190 | 2757199 | 115152 | 3742035 | 5621216 | 16380247 | 2132109 | | |
| | | Kish | 435491 | 6228475 | 56164422 | 31158 | 2566 | 5942180 | 248171 | 8064650 | 12114570 | 35301905 | 4595017 | | |
| | Abu Musa | Greater Farvar | 65034 | 930129 | 8387317 | 4653 | 383 | 887375 | 37060 | 1204335 | 1809130 | 5271812 | 686197 | 177732150 | |
| | | Lesser Farvar | 19554 | 279671 | 2521902 | 1399 | 115 | 266816 | 11143 | 362120 | 543970 | 1585130 | 206326 | | |
| | | Sirri | 173145 | 2476353 | 22330174 | 12388 | 1020 | 2362526 | 98669 | 3206390 | 4816580 | 14035534 | 1826913 | | |
| | | Greater Tunb | 79676 | 1139543 | 10275679 | 5700 | 469 | 1087164 | 45404 | 1475485 | 2216446 | 6458734 | 840691 | | |
| | | Lesser Tunb | 34466 | 492951 | 4445121 | 2466 | 203 | 470292 | 19641 | 638275 | 958805 | 2793961 | 363671 | | |
| | | Abu Musa | 227531 | 3254201 | 29344311 | 16279 | 1340 | 3104620 | 129662 | 4213550 | 6329518 | 18444240 | 2400765 | | |
| | Qeshm | Qeshm | 612128 | 8754782 | 78945045 | 43797 | 3606 | 8352364 | 348831 | 11335720 | 17028312 | 49620568 | 6458784 | 274929543 | |
| | | Hengam | 151101 | 2161085 | 19487288 | 10811 | 890 | 2061749 | 86107 | 2798180 | 4203375 | 12248651 | 1594326 | | |
| | | Larak | 163979 | 2345267 | 21148128 | 11732 | 966 | 2237466 | 93446 | 3036660 | 4561615 | 13292565 | 1730206 | | |
| Bushehr | Bushehr | Khark | 100671 | 1439817 | 12983354 | 7202 | 593 | 1373635 | 57368 | 1864280 | 2800487 | 8160631 | 1062215 | 61691643 | 61691643 |
| | | Farsi | 48598 | 695059 | 6267601 | 3477 | 286 | 663110 | 27694 | 899965 | 1351911 | 3939474 | 512775 | | |
| | | kharko | 77519 | 1108705 | 9997596 | 5546 | 456 | 1057743 | 44175 | 1435555 | 2156464 | 6283946 | 817940 | | |
| Total | | 851980222 | | | | | | | | | | | | | |

**Table 6.** Economic Valuation of Seagrass Ecosystem Services in the Persian Gulf and Gulf of Oman within Iran's Territorial Waters by Province and City (USD)

| Political Unit with Seagrass | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Province | city | Climate Regulation | Erosion Control | Habitat/ Refugia | Food Production | Raw Materials | Genetic Resources | Recreation | Cultural | Total of the province |
| Hormozgan | Persian | 171796.9425 | 9098423 | 69579 | 855039 | 4303 | 64558 | 91816 | 15422.2725 | 27722419 |
| | Bandar Lengeh | 218835.94 | 11589624 | 88630 | 1089154 | 5482 | 82234 | 116956 | 19644.98 | |
| | Abu Musa | 14029.91 | 743028 | 5682 | 69827 | 351 | 5272 | 7498 | 1259.47 | |
| | Qeshm | 54565.285 | 2889795 | 22099 | 271573 | 1366 | 20504 | 29162 | 4898.345 | |
| Bushehr | Kangan | 12459.9875 | 659885 | 5046 | 62013 | 312 | 4682 | 6659 | 1118.5375 | 4157181 |
| | Asaluyeh | 45857.065 | 2428605 | 18572 | 228232 | 1148 | 17232 | 24508 | 4116.605 | |
| | Bushehr | 10547.58 | 558603 | 4271 | 52495 | 264 | 3963 | 5637 | 946.86 | |
| Sistan and Baluchestan | Konarak | 455734.97 | 24389746 | 186518 | 2292067 | 11537 | 173058 | 246128 | 40911.49 | 27511549 |
| Total | 59391150.72 | | | | | | | | | |

**Table 7.** Economic Value of Seagrass Ecosystem Services in the Persian Gulf and Gulf of Oman within Iran's Territorial Waters by Island (USD)

| Political Unit with seagrass | | | Type of Ecosystem Service | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Province | City | Iasland | Climate Regulation | Erosion Control | Habitat/ Refugia | Food Production | Raw Materials | Genetic Resources | Recreation | Cultural | Total (city) | Total (province) |
| Hormozgan | Bandar Lengeh | Lavan | 16378 | 867395 | 6633 | 81514 | 410 | 6154 | 8753 | 1470 | 2288267 | 3771803 |
| | | Shidvar | 2705 | 143265 | 1095 | 13463 | 67 | 1016 | 1445 | 242 | | |
| | | Hendorabi | 6232 | 330101 | 2524 | 31021 | 156 | 2342 | 3331 | 559 | | |
| | | Kish | 12589 | 666734 | 5098 | 62657 | 315 | 4730 | 6728 | 1130 | | |
| | Abu Musa | Greater Farvar | 276 | 14650 | 112 | 1376 | 6 | 103 | 147 | 24 | 846949 | |
| | | Lesser Farvar | 458 | 24289 | 185 | 2282 | 11 | 172 | 245 | 41 | | |
| | | Sirri | 10347 | 548012 | 4190 | 51500 | 259 | 3888 | 5530 | 928 | | |
| | | Greater Tunb | 1027 | 54414 | 416 | 5113 | 25 | 386 | 549 | 92 | | |
| | | Lesser Tunb | 1058 | 56063 | 428 | 5268 | 26 | 397 | 565 | 95 | | |
| | | Abu Musa | 861 | 45598 | 348 | 4285 | 21 | 323 | 460 | 77 | | |
| | Qeshm | Qeshm | 17769 | 941089 | 7196 | 88440 | 445 | 6677 | 9496 | 1595 | 3293966 | |
| | | Hengam | 13935 | 738018 | 5643 | 69356 | 349 | 5236 | 7447 | 1250 | | |
| | | Larak | 22860 | 1210687 | 9258 | 113776 | 572 | 8590 | 12217 | 2052 | | |
| Bushehr | Bushehr | Khark | 8115 | 429797 | 3286 | 40390 | 203 | 3049 | 728 | 728 | 636585 | 636585 |
| | | Farsi | 210 | 11161 | 85 | 1048 | 5 | 79 | 18 | 18 | | |
| | | kharko | 2218 | 117517 | 898 | 11043 | 55 | 833 | 199 | 199 | | |
| Total | | | 7065769 | | | | | | | | | |

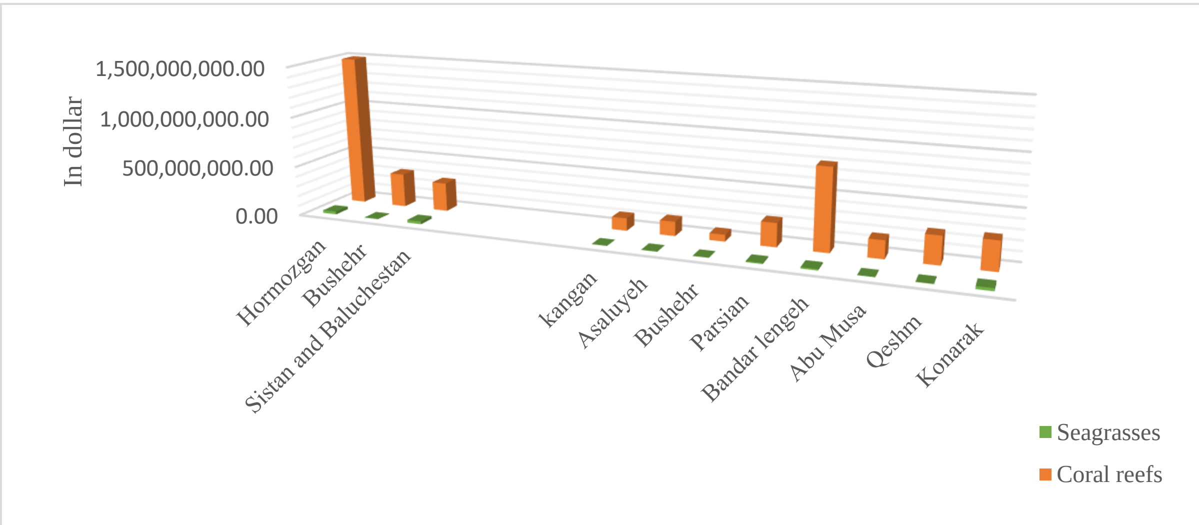


**Fig 7.** Economic valuation of coral reef and seagrass ecosystem services in the Persian Gulf and Gulf of Oman within the territorial waters of Iran, by province and city

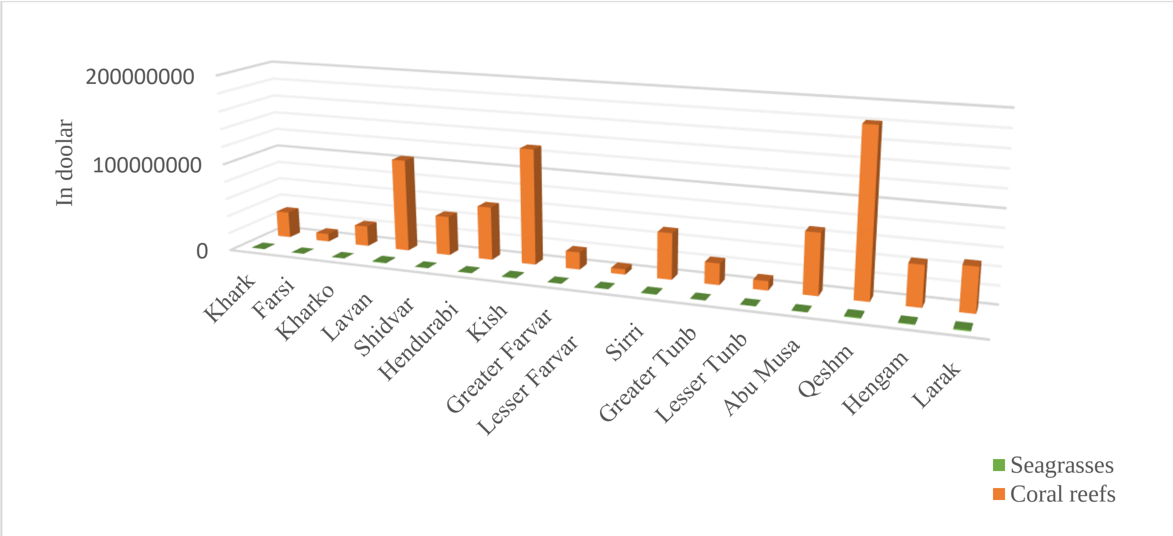


**Fig 8.** Economic value of ecosystem services provided by coral reefs and seagrasses in the Persian Gulf and Gulf of Oman within the Iranian territorial waters, disaggregated by islands.

## 4. Discussion

Compared with previous studies on the economic valuation and spatial assessment of marine ecosystems (e.g., Costanza *et al*., 1997; Spalding *et al*., 2017; Trégarot *et al*., 2017; Tamayo *et al*., 2018; Pandelaki *et al*., 2020; Ashournejad, 2022), this study advances the understanding of coral reef and seagrass ecosystem services in the Persian Gulf through a spatially explicit and high-resolution assessment framework. By integrating the Allen Coral Atlas benthic habitat product within a GIS environment, this research enables a detailed quantification of ecosystem extent and economic value across multiple administrative scales, including provinces, cities, and islands. Unlike previous studies that largely relied on site-specific surveys or generalized regional estimates, the present work provides a harmonized and consistent spatial framework for evaluating ecosystem services across the Iranian territorial waters of the Persian Gulf. The findings demonstrate that coral reef and seagrass ecosystems contribute substantially to the regional blue economy, with pronounced spatial heterogeneity in both extent and economic value, particularly concentrated in Hormozgan Province and key coastal islands such as Qeshm. By explicitly linking habitat distribution patterns with monetary valuation through the Costanza ecosystem service framework, this study provides a practical decision-support perspective that can support marine spatial planning, conservation prioritization, and sustainable coastal management in the Persian Gulf.

The results reveal a pronounced spatial heterogeneity in the distribution of coral reef and seagrass ecosystems across the Iranian portion of the Persian Gulf, indicating strong geographic variation in both ecosystem extent and ecological significance. Although these habitats are substantial at the national scale, their distribution is highly concentrated in a limited number of provinces, particularly Hormozgan, which accounts for approximately 70% of the total coral reef area. A similar concentration pattern is observed for seagrass ecosystems, where Hormozgan and Sistan and Baluchestan jointly represent the dominant share, while Bushehr contributes comparatively smaller extents. At finer spatial scales, key coastal cities and islands such as Bandar Lengeh, Konarak, and Qeshm Island emerge as major ecological hotspots, supporting extensive and ecologically productive habitats. In contrast, several smaller islands contain fragmented and spatially limited habitat patches, reflecting considerable ecological variability across the region. These findings are consistent with previous studies emphasizing that coral reef and seagrass ecosystems are commonly concentrated in environmentally favorable coastal zones rather than being uniformly distributed across marine environments (Failler *et al*., 2015; Trégarot *et al*., 2017). Similar spatial clustering of ecologically valuable marine habitats has been reported in tropical and subtropical coastal systems, where local geomorphological settings and oceanographic conditions strongly influence habitat persistence and productivity. Therefore, the observed spatial structure suggests that conservation priorities should focus on ecological hotspots where habitat concentration and ecological significance are greatest, thereby supporting more targeted and efficient marine spatial planning.

The economic valuation results demonstrate a markedly uneven distribution of ecosystem service values across the Iranian Persian Gulf, with coral reef ecosystems contributing the dominant share of total monetary value. Overall, coral reefs account for approximately $2.12 billion in ecosystem service value, substantially exceeding the $59.39 million estimated for seagrass ecosystems, highlighting a clear asymmetry in their economic contributions. This dominance aligns with previous global and regional assessments, which consistently recognize coral reefs as among the most economically valuable marine ecosystems due to their multifunctional roles in coastal protection, tourism, fisheries, and biodiversity support (Costanza *et al*., 1997; Spalding *et al*., 2017; Tamayo *et al*., 2018). In the present study, the predominance of coral reef ecosystem value is largely explained by their substantial contribution to erosion control, which accounted for the largest proportion of total ecosystem service value, emphasizing their importance for coastal stability and resilience in the Persian Gulf. Likewise, seagrass ecosystems exhibited their greatest contribution through shoreline protection functions, reinforcing their ecological significance despite their comparatively lower total monetary value. Furthermore, the estimated economic importance of coral reefs and seagrass ecosystems in Iran is broadly consistent with the findings of Ashournejad (2022), while the present study extends previous research through finer spatial resolution and sub-national assessment. At the provincial scale, Hormozgan emerges as the dominant economic hotspot, followed by Bushehr and Sistan and Baluchestan, which together represent secondary but important centers of ecosystem value. A comparable pattern is also observed for seagrass ecosystems, where Hormozgan and Sistan and Baluchestan account for the majority of economic value, while Bushehr contributes a relatively smaller proportion. At finer spatial scales, cities such as Bandar Lengeh and Konarak exhibit the highest economic returns due to their extensive and ecologically productive habitats, whereas island ecosystems contribute comparatively lower absolute values despite their ecological relevance. These findings collectively indicate that ecosystem service value is strongly governed by spatial variability in habitat availability and ecological productivity rather than uniform coastal distribution. From a management perspective, this uneven economic structure underscores the importance of prioritizing conservation investments in high-value ecological zones where both ecosystem functioning and economic returns are maximized, thereby improving the efficiency of marine spatial planning and blue economy strategies.

The application of the Costanza ecosystem service valuation model in this study provides an important bridge between ecological quantification and policy-relevant economic interpretation, enabling spatial ecosystem information to be translated into practical indicators for conservation prioritization, coastal zoning, and marine resource management. By assigning monetary values to coral reef and seagrass ecosystems, the results highlight the substantial contribution of these habitats to the regional blue economy and reinforce the importance of incorporating ecosystem service valuation into coastal planning and environmental governance frameworks in Iran. Similar applications of ecosystem valuation frameworks in marine environments have demonstrated that translating ecological functions into monetary terms can improve policy communication and strengthen conservation prioritization, particularly in regions facing competing coastal development pressures (Failler *et al*., 2015; Trégarot *et al*., 2017). In comparison with broader global assessments (e.g., Costanza *et al*., 1997; Spalding *et al*., 2017), the estimated values for the Persian Gulf support the wider recognition of coral reefs as one of the most economically valuable marine ecosystems worldwide while simultaneously revealing region-specific spatial patterns shaped by local environmental and geomorphological conditions. However, unlike many previous studies conducted at coarse spatial scales, the present research provides a high-resolution, sub-national perspective capable of identifying ecological and economic hotspots at provincial, city, and island levels. These findings emphasize the importance of embedding ecosystem service valuation within national marine policy frameworks, particularly in the context of Iran's increasing coastal development pressures, where fisheries, tourism, energy infrastructure, and conservation increasingly compete for marine resources. Therefore, integrating spatially explicit economic valuation with habitat mapping offers a practical decision-support tool for prioritizing conservation investments, optimizing land–sea planning, and promoting the long-term sustainability of marine ecosystems in the Persian Gulf.

Given the increasing pressure on coral reef and seagrass ecosystems in the Persian Gulf and the growing imbalance between ecosystem degradation and conservation capacity, implementing integrated and evidence-based marine management policies is essential. This study demonstrates that combining high-resolution remote sensing products with spatially explicit ecosystem service valuation substantially improves understanding of the spatial distribution and economic importance of marine habitats, while providing a robust scientific basis for decision-making in coastal and marine planning. Nevertheless, several limitations remain, including uncertainties associated with ecosystem service value transfer, spatial variability in valuation coefficients, and the need for additional ecological field validation to improve assessment accuracy. Future research should prioritize: (1) integrating higher-resolution and multi-source remote sensing datasets to improve habitat discrimination and mapping precision, (2) coupling machine learning approaches with ecological and economic models to better predict future ecosystem service dynamics under environmental change, and (3) assessing the long-term impacts of climate change, coastal development, and anthropogenic disturbances on coral reef and seagrass sustainability. In addition, strengthening regional cooperation among coastal management institutions and incorporating local ecological knowledge will be essential for improving conservation outcomes. Overall, this study provides a scalable framework for linking spatial ecosystem mapping with economic valuation and offers practical implications for marine spatial planning and sustainable blue economy development in Iran.

## 5. Conclusion

Over recent decades, coral reef and seagrass ecosystems in the Iranian Persian Gulf have played a key role in supporting coastal ecological stability and regional economic activity, yet they remain highly vulnerable to increasing environmental pressures. This study developed a spatial–economic framework by integrating high-resolution remote sensing data from the Allen Coral Atlas with the Costanza ecosystem service valuation model to assess both the distribution and economic value of these marine habitats. The results show a strong spatial concentration of ecosystem extent and value, particularly in Hormozgan Province and key hotspots such as Bandar Lengeh and Qeshm Island, indicating that ecosystem services are highly uneven and driven by local environmental conditions. The findings highlight that degradation of these ecosystems would lead to substantial ecological and economic losses affecting fisheries, tourism, and coastal protection. Accordingly, ecosystem service valuation can serve as an effective tool for integrating environmental costs into marine spatial planning and coastal governance. Remote sensing also provides a scalable approach for continuous monitoring and management of these vulnerable habitats. Overall, the long-term sustainability of coral reef and seagrass ecosystems depends on targeted conservation of ecological hotspots, integration of valuation into policy frameworks, and adaptive marine management strategies that support sustainable blue economy development in the region.

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**Authors Contribution**
All authors contributed to the study conception and design. Material preparation, data collection, analysis, and manuscript writing were performed by the authors. All authors read and approved the final manuscript.

**Ethics approval and Consent to participate**
This study did not involve human participants, animals, or personal data requiring ethical approval. The authors adhered to the principles of research integrity and avoided data fabrication, falsification, and plagiarism.

**Competing Interests**
The authors declare that they have no competing interests.

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**Consent for Publication**
Both of the authors have given their consent for the publication of this article and approved the final version of the manuscript

**Data Availability**
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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