

Review

Recommendations and Strategies to Mitigate Environmental Implications of Artificial Island Developments in the Gulf

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Abstract: Artificial island development (AID) to tackle rampant urbanization on scarce land puts all marine biodiversity at huge risk and is recognized as a global conservation issue worldwide. This study critically reviews the gaps that undermined biodiversity and ecology during construction activities of the artificial islands in the Gulf region that could be alleviated if apposite environmental values and sustainable strategies of different regions of the world had paid enough heed to economic and social aspects. The method used for this study was an analytical descriptive literature survey, and the resources were chosen after three phases of quality assessment. This survey found various barricades to sustainable AID, such as lack of scientific data, adequate site selection, ineffective environmental evaluations, noncompliance with legislation, and economic gains over the environmental aspects. It was concluded that to protect the marine ecosystem from inevitable degradation, strict compliance with international and national legislation, research and baseline data collection, strengthening of the existing environmental assessment, continuous capacity building, and modern practices of different countries should be brought to the forefront. Furthermore, this study aims to provide guidance to policymakers and governmental organizations to mitigate emerging environmental issues during AID through strategic decision-making processes.

Keywords: artificial island development; environmental implications; land reclamation; marine ecology; mitigation strategies; sustainable development



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1. Introduction

1.1. Gulf Artificial Island Developments (AID)

Rapid economic development and social prosperity has played a noteworthy role in transforming the Gulf from an insignificant desert to ultra-modern nations with continuously growing coastal cities [1]. However, due to rapid population expansion and urbanization, as well as increased energy and water needs, this places a great strain on land resources, which are constantly at the point of depletion [2–6]. Authorities find it challenging to develop infrastructure on scarce land to accommodate the growing population. To alleviate the problem, marine resources have attracted considerable attention. Hence, Gulf countries are developing artificial islands, as shown in Table 1, in the surrounding Gulf waters to tackle the swift urbanization and population challenges followed by other industrial, commercial, economic, and strategic benefits [7,8]. The Kingdom of Bahrain is a prominent example of an archipelago, an extensive network of islands [9], having a commercial zone offshore or within the sea to cope with land-scarcity issues [10].

Unlike natural islands, an artificial island is basically a manmade formation that has been constructed by humans over water bodies rather than formed through natural processes. They are constructed by different methods such as land reclamation, extending existing islets, rocks, or coral reefs, or linking small groups of islets into one bigger island using different construction materials [11]. The phenomena behind the construction of artificial islands are to support people, economy, energy needs, defense infrastructure, and

mainly to promote tourism, which is common in Asia and Gulf countries. The United Arab Emirates (UAE) is the pioneer in developing artificial islands [12]. In 2001, UAE started to build an archipelago, Palm Islands and World Islands, followed by Jebel Ali and Deira, each bigger than the last. This tremendous achievement of the UAE encouraged other Gulf countries such as Qatar, Oman, Bahrain, and Kuwait to utilize their existing coastlines as artificial islands, which can later serve as tourist spots, economic hubs, petroleum reserves, and residents for the growing population [13].

Table 1. Some major artificial island developments across the Gulf region [14].

Gulf Country	Artificial Island	Development Status	Purpose
United Arab Emirates	Palm Jumeirah Island	Completed in 2008	Commercial, residential, tourism
	Bluewater Island	Completed in 2018	Hospitality, residential
	Pearl Jumeirah Island	Completed in 2012	Residential area
	Burj Al Arab Island	Completed in 1999	Commercial, hospitality, tourism
Bahrain	Jumeirah Bay Island	Completed in 2016	Residential
	Amwaj Island	Completed in 2016	Residential
	Durrat Al Bahrain Reef Island	Completed in 2009 Completed in 2010	Residential, commercial, tourism Residential, commercial
Qatar	Pearl Island	Completed in 2006	Residential, commercial
	Ras Laffan	Established in 1996	Industrial harbor
Kuwait	Green Island	Completed in 1988	Recreational, tourism
	Sabah Al Ahmad Sea City	The first phase was completed in 2004	Residential
Saudi Arabia	Jazan Economic City	The first phase was completed in 2010	Residential, industrial

Although the Gulf region is home to the world's largest and most modern artificial islands, these islands come at a greater cost to nature, facing incessant environmental degradation [15]; in 2016, the construction of oceanic islands was identified as a "global conservation issue" due to unsustainable development [16].

1.2. Potential Environmental Impacts of AID

The construction of Gulf artificial islands using different dredging methods and land reclamation [17] might affect the productivity of numerous marine ecosystems. Like many other island countries, the Gulf faces uninterrupted environmental degradation of coastal and marine habitats due to human-induced interventions [18]. Similarly, sediments and heavy metals contaminate the water quality and constantly enhance its turbidity, which poses serious threats to seagrasses and coral reefs, burying oyster beds and causing disturbance to natural water currents that ultimately erode shorelines [19,20]. However, sustainable practices, including ecoengineering, adaptation management, and hybrid approaches, can reduce some of these impacts. Moreover, another offset is the rising sea level due to climate change [1], which is likely to inundate the artificial islands of Dubai in the future, which are just 4 m above sea level. Therefore, the construction of artificial islands must be according to the relevant legislation (The Convention on the Law of the Sea, 1982) and sustainable enough to foresee current and future environmental challenges [21].

1.3. Objective and Scope

This study focuses on the environmental impacts and the possible mitigation measures of AID. Therefore, the scope of this review is to systematically analyze the literature that includes the environmental implications of artificial island development followed by effective strategies to protect environmental degradation in Gulf countries. This study will provide a comprehensive literature review to investigate and respond to the following research question identified as a gap in the literature:

What strategies can be used to reduce or mitigate the environmental implications of Artificial Islands Development in the Gulf to ensure sustainable development?

This work will guide the mitigation of emerging environmental issues during the development of artificial islands through strategic decision-making processes.

2. Literature Review Approach

The main critical evaluation phases of this research work involve:

- To identify the scope of the study and research question;
- To search and conduct a quality assessment of resources;
- To systematically review, summarize, and interpret the gaps and findings of existing resources.

Figure 1 illustrates an overview of the method followed in the study.

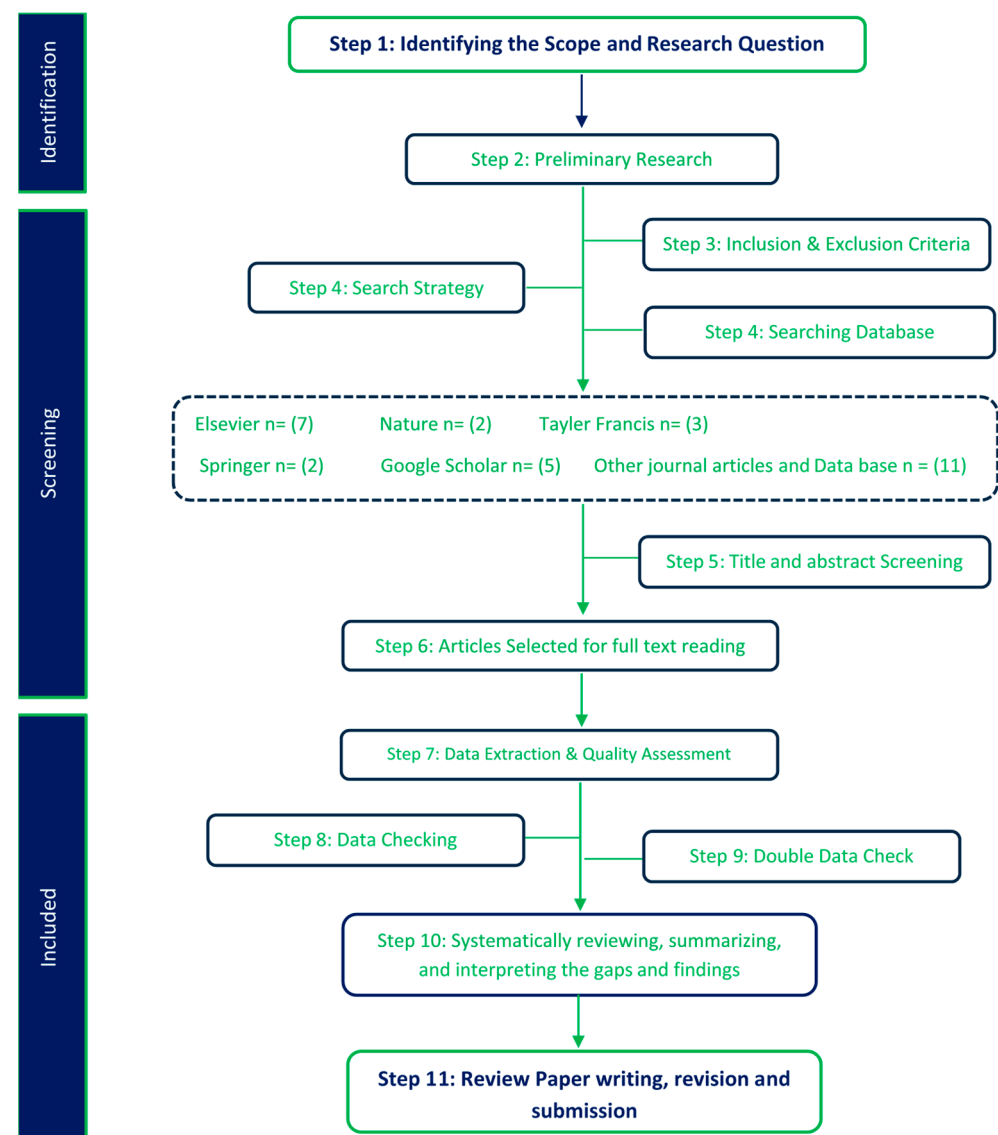


Figure 1. Steps pursued to develop the literature-reviewing procedure adopted in this research work.

2.1. Identifying the Scope of the Study and Research Question

A growing population, followed by rapid urbanization on scarce land, has emphasized authorities to switch to artificial islands and coastal development [2]. During development, unlike environmental implications, industrial, commercial, economic and strategic benefits were given huge importance [7], resulting in continuous environmental degradation. Hence, this study aims to review and identify the gaps that undermined the biodiversity and ecology during construction activities of the artificial islands, which could be mitigated and

avoided if appropriate environmental values were given enough heed. Through a detailed literature review, the research question (What strategies can be used to reduce and mitigate the environmental implications of Artificial Islands Development in the Gulf to ensure sustainable development?) is to be answered for effective management of artificial islands.

2.2. Search and Quality Assessment of Resources

The analytical-descriptive method was used in this study based on the extensive literature survey. A comprehensive search was conducted using a range of scholarly databases, peer-reviewed journals, conference papers, scientific articles, search engines, and other online resources to retrieve all published studies and reports to gather the substantial works that fit the research inclusion criteria (see Table 2). This review included studies that implemented quantitative and qualitative methods on the subject. However, the political and economic benefits of these studies were excluded. As this topic is under research, the publication-date-limitation criteria were not used. These resources for the study were gathered through various phases of screening:

- Primary screening—various keywords were used across all database searches to retrieve data that include artificial islands in Gulf countries, artificial islands in European countries, environmental impacts of artificial islands, unsustainable development of artificial islands, sustainable practices for artificial island developments, environmental assessment tool, a legal overview of artificial island developments, strategies to mitigate impacts of AID;
- Secondary screening—removal and deletion of unreliable, insignificant, and irrelevant research material;
- Tertiary screening—evaluation of literature relevant topics for eligibility by title, abstract, and full text.

Table 2. Reviewed scientific studies on environmental impacts of AID in the Gulf and other world countries and strategies to mitigate environmental implications of AID.

Category	Studies	Total
Environmental Impacts of AID among Gulf Countries	[9,17,22–26]	7
Environmental Impacts of AID among other World Countries	[20,27–31]	6
Strategies to mitigate environmental implications of AID	[23,24,28,29,32–39]	12

Eligible topics were critically assessed based on their external and internal validity. This screening phase was accomplished gradually and in detail to exclude unimportant topics. From each eligible topic of sufficient validity, information on the study subject and findings were synthesized narratively. While performing this review, all the steps were carried out as shown in Figure 1.

3. Detailed Analysis of the Literature

Urbanization followed by economic advancement place a considerable burden on the available land resources to meet the innumerable needs of urban centers. However, in recent years, the concept of artificial islands has been widely being used for housing, commercial, industrial purposes, trade, tourism, and strategic motives to manage the inevitable increase of urban space volumes [40]. These mega coastal projects will threaten the existing marine ecosystems if appropriate measures are not considered intently [41].

3.1. Environmental Impacts of Artificial Islands Development (AID) among Gulf Countries

In recent years, UAE has started reducing its dependence on oil for economic growth and emphasizing tourism for revenue. By 2006, Dubai's GDP had reached 22% because of the high number of hotels in the coastal areas [17]; hence, Dubai needed to create more hotels on the coasts to promote the tourism industry. In line with this policy, artificial island development has caused severe degradation of numerous natural ecosystems. Dredging

high volumes of sand in island construction has resulted in increased turbidity, whereas land-reclamation activities have shown a conspicuous loss of many fish species [42–44]. Due to these anthropogenic interventions, coral reefs, shells, and oyster beds are buried under the sediment. High levels of sediment, nutrients, and heavy metals in the marine water have played a significant role in increasing the toxicity, turbidity, temperature, and salinity, which have accelerated the degradation of the economically high-valued coral reefs [45,46]. Although the “Convention on the Law of the Sea” gives Dubai the right to construct these islands, the loss and environmental degradation led by these islands require dire attention of policymakers to design the artificial islands meticulously by considering all the environmental effects, promoting sustainable development, and securing the rights of other neighboring countries [17].

Unsustainable development, weak regulatory compliance, and lack of environmental impact-assessment (EIA) studies are seriously threatening the ecosystem along the Gulf’s coast. The rapid development of artificial islands in the Gulf between the Arabian Peninsula and Iran has transformed the entire coastline. In the project of Palm Jumeirah, around 94 million cubic meters of sediments were dredged up to make the islands, badly affecting the marine life, as the species of fish were not the same as before the project. The water remained stagnant for weeks, increasing the risk of algal blooms [23]. Since 2001, the region has diminished around 70% of its coral reefs and put severe threats on the rest. Due to the poor compliance with legislative and regulatory frameworks in the said projects, environmental assessments could take years to seek approval from Western Union, which might be conducted in ten weeks in the Gulf. Similarly, the lack of environmental monitoring and scientific data in the projects is another area that requires attention [22].

United Nations University launched a policy report on human-induced interventions in the coastal marine ecosystems in 2011, in which uncontrolled coastal development and its impacts on marine ecosystems were highlighted [23]. These ecological interventions led to the permanent loss of many fish species. Similarly, pollution due to coastal development can disrupt shore and offshore habitats [34]. Dredged material for coastal development construction can lead to decreased water transparency and accelerate the process of sedimentation. It can also be a source of numerous contaminants that may bioaccumulate in a species and become a part of the food web. Dredged sand has been found to disrupt water-current patterns near the shoreline (Figure 2). Several studies revealed that natural patterns of water movement could be disturbed due to construction activities along the coast, such as dredging, that alters sediment distribution. This variation increases the probability of erosion by changing the shape of a shoreline [23].



Figure 2. Interruption in natural sediment drift: the red arrow on the left indicates the increased sedimentation that might modify the natural shape of the shoreline (Source: Umm Suqeim 2 Harbor 25°09′08.01″ N and 55°11′50.46″ E) [47].

Nearshore habitats play a prominent role in lowering species diversity by affecting their early stages of development. This might increase the probability of lowering the diversity of commercial fisheries; similarly, sedimentation due to developmental activities

contributes to high levels of turbidity and is known to alter species composition, leading to stress and badly affecting their growth [48]. High turbidity followed by suspended particles at the top surface of the water badly disrupts the amount of light required for the photosynthesis process to support benthic communities such as seagrasses, algae [19], and sensitive corals. However, the magnitude of these known damages and ecological implications is still unknown because of limited knowledge of artificial islands in the Gulf [25]. Figure 3 illustrates the environmental implications of an artificial island in the Gulf.

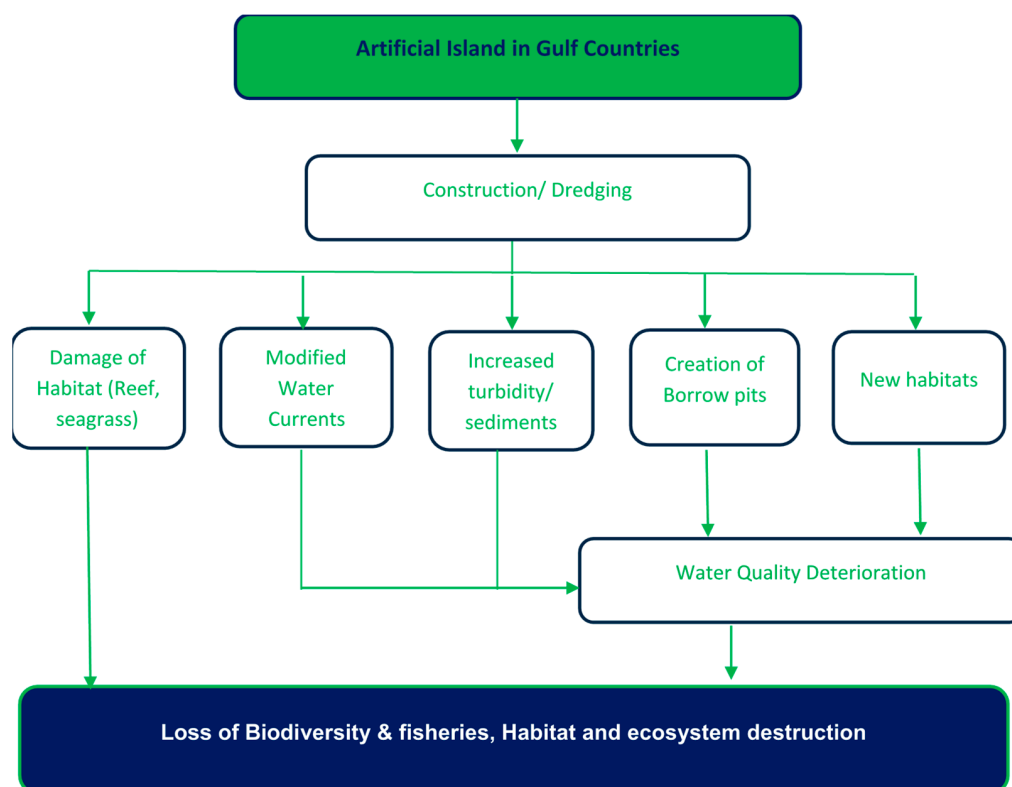


Figure 3. Summary of artificial island developments' impacts on the marine environment.

Over the past five decades, the population of coral reefs has been diminishing at an enormous rate worldwide. Unlike other countries, the Gulf, having 1.5% of the global reef species, is one of the major regions affected by anthropogenic activities; 70% of reef cover is expected to be lost. In contrast, the remaining 27% is on the verge of extinction (see Figure 4) [49].

Artificial islands and coastal developments are the major contributors to the sedimentation that affects the coral reefs' population. Hence, to overcome this irreversible loss, authorities should heed this very issue before the construction phase of any coastal development projects. Palm Jumeirah is a few miles away from the beachfront; hence, it sought regular monitoring and replenishment activities to tackle intrusions in sediment drift [23].

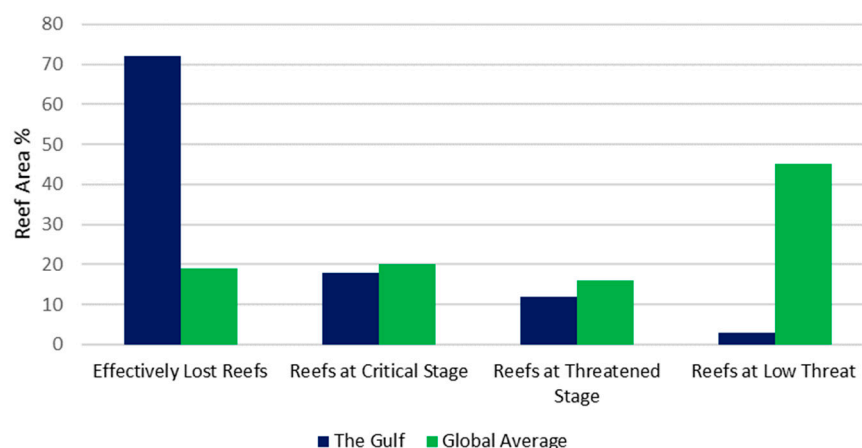


Figure 4. Comparison of reefs affected by anthropogenic activities in the Gulf and at the global level.

A similar study was conducted in Bahrain, in which impacts of land reclamation and dredging activities for artificial island developments, waterfront cities, ports, and harbors on the environment of Bahrain were carefully analyzed [24]. The Kingdom of Bahrain consists of a group of almost 40 islands, an archipelago, and various islets and coral reef patches in the Arabian Gulf. Like other island countries, Bahrain is experiencing severe environmental repercussions such as degradation of the coastal and marine environment owing to human-induced interventions [18]. Among many other environmental challenges, the increasing demand for urban infrastructure for several residential, tourist, and other commercial-activity projects is a major threat to Bahrain's coastal and marine ecosystems [9]. Hence, coastal-reclamation activities and artificial island development at regular intervals to reduce the burden of land have significantly deteriorated the marine habitats that include reefs, seagrass, and mangroves, followed by several species of fish. These unsustainable or rapid developments without an adequate framework have affected Bahrain's fish industry. Through remote-sensing imaging technology, the loss of over 10.2 km² of seagrass beds was registered between 1985 and 1992, whereas a loss of 218,700 m² of corals in the largest reef (Fasht Al-adam) was recorded by [50]. The main reason behind these significant losses is dredging and reclamation activities that, in turn, increase the level of sedimentation and pollution to disrupt the marine environment [51,52].

Another study was conducted in Bahrain to examine the disastrous impact on the species and their habitats due to massive reclamation activities. For this purpose, a microcosm was tested to investigate the response of three common microbenthic invertebrates to mud burial using marine sediment extracted from a nearby burrow. These invertebrates were collected from the proposed reclaimed coastal location. A noteworthy difference in terms of survival was observed during the experiment. Of all the selected species, 41.8% survived. Studying and quantifying species' responses to sediment burial that occurred due to dredging and reclamation activities will help anticipate the ecological impacts of coastal developments. Through this approach, effects associated with coastal intervention are likely to be minimized. This, in turn, will lead to sustainable utilization of coastal and marine ecosystems of the Arabian Gulf [9].

Another state of the Gulf, Qatar, is well known for its complex network of islands and artificial island projects owing to the great interest of investors across the globe. One of the important and valuable artificial islands among others in the heart of the Doha Sea, Qatar, is Pearl Island, a state-of-the-art integrated city. In recent decades, continuous development activities over coastal ecosystems have experienced unprecedented environmental degradation due to massive land reclamation and dredging activities. These unsustainable actions have considerably changed the habitat of coral reefs, oysters, and mangroves and disrupted the seagrass meadows [25]. Due to these activities, the photosynthesis process can be disturbed with increased turbidity, which plays a significant role in clogging fish gills. In addition, coral health affects badly due to less available light for coral communities [53].

Development in coastal areas without considering the habitat, environmental conditions, impact assessments, and restoration plans provides the greatest threats to coral communities, mangrove ecosystems, and many other species such as xerophytes and halophytes [54]. Similarly, during the night, construction activities such as noise due to machinery might distract migratory birds and have the potential to cause collisions. One of the migratory birds in Qatar, the Socotra cormorant, a diving bird of the Al Aliyah Island, was disturbed due to the removal of seagrass during the construction phase [55].

A comprehensive study was conducted using a stakeholder participatory approach to evaluate the detrimental effects of major land-reclamation projects in Doha, Qatar. Pearl Island, Lusail City, and Hamad International Airport are major areas where massive land-reclamation projects have been planned in the recent decade. Stakeholders were divided into six major categories. Most of them had over 20 years of experience in the marine environment. These stakeholders involve officers from the navy, active fishermen, nonactive fishermen, coast guards, government officials, and recreational staff. After deliberate discussions with stakeholders, it was determined that unplanned land-reclamation projects have harmful and damaging impacts on the coastal environment, such as high levels of sedimentation, odor, and turbidity that might disturb the food chain and oxygen level required for the marine life. One of the stakeholders believed that three fish species such as parrotfish, stingrays, greasy groupers, as well as the turtle community, showed a significant decline since construction activities. To effectively manage these emerging impacts, a balanced approach, planned strategy, and a comprehensive study are essential to save nature from the menace of unplanned development in Qatar [26].

3.2. Environmental Impacts of Artificial Island Developments among Other World Countries

Rampant population growth is the omen of land shortage for future generations. Many countries on the map addressed their land-availability issues through land-reclamation activities or by creating new islands to accommodate the inevitable growth. While anticipating the needs of future generations, many other countries have developed artificial islands in coastal areas to ensure the provision of adequate basic necessities. Still, it puts a significant burden on marine ecology [56]. Even highly developed countries face environmental implications due to the development of artificial islands.

A comprehensive study was conducted to identify the environmental ramifications of large-scale dredging activities during the construction of artificial islands in the Netherlands. The adequate methods to maintain water quality, less disruption of bottom sediments and dredging effects on plankton, fisheries, and other bottom fauna, and recovery time of the affected marine ecosystem were discussed. The impact on marine species can be reduced by a comprehensive study of the specific area [27]. China created numerous artificial islands over 3 years, from 2013 to 2015, with a total area of about 3000 acres in the Spratly Islands, South China Sea. Through land-reclamation activities, dredging and construction of artificial islands are not new to China, but the rapid development undermined the biodiversity and ecology of the region. Damaging effects on coral reef communities and the health of fisheries in the South China Sea made China's action one of great concern [28].

A detailed study in China was conducted to assess the dispersal and contamination of heavy metals such as cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), arsenic (As), and mercury (Hg) in the sediments of the Longkou Bay and the artificial island of adjacent areas. Heavy-metal accumulation in the sediments resulted from coastal engineering and reclamation activities. As a consequence of the construction of artificial islands offshore, the natural coastline of Longkou experienced significant changes in hydrodynamic conditions. It is anticipated that this might affect the tidal fields and lead to erosion around the bay [20].

In Malaysia, rapid coastal land-reclamation activities commenced in the early 1990s due to rapid urbanization and the higher cost of available land in the urban cities. Many artificial islands have been constructed in different parts of the Malaysian state, such as Johar, Malacca, Labuan, and Panang [29]. These artificial island development projects led to

severe environmental degradation of the marine ecosystem, in which the most prominent species reported, are coral reefs, seagrass meadows, and mudflats. It is anticipated that this might disrupt faunal biomass in the bottom and change the species composition if appropriate measures are not taken for their recovery. Benthic animal communities are usually more prevalent in the shallower water of coastal zones. Alterations in the ocean floors through reclamation activities are a real threat to the survival of benthic organisms. Similarly, disturbance to bottom sediment while dredging activities or marine sediment extraction might remove epifauna [57]. Degraded ecosystems with varied compositions cannot provide a sufficient environment to sustain aquatic life due to the suspension of heavy metals, organics, and other contaminants [58].

A study was conducted in Barcelona, located along the coast of Spain, to explore the influence of artificial island structures on the waves, currents, and mean water level in the surrounding marine habitat using different numerical simulation models [30]. It was revealed through the findings that when an artificial island is developed, it increases the probability of altering the hydrodynamic conditions of the particular area. These changes and modifications may affect the biotic communities [59]. One modification is the change in sediments that might affect the functionality of the coastal area, such as a significant alteration in wave-energy dissipation. However, wave height is one of the major parameters to determine the effects of artificial islands. An adequate decision-making process can address different situations or minimize the long-term effects through the wave-height model. Another study was conducted in Belgium to highlight the environmental implications of waste processing on artificial island development. The study revealed that the construction of said island resulted in noise, bad odor, and aesthetic issues coupled with water pollution. Therefore, it is recommended to reconsider installing a waste-processing plant on the island so the island can be used for other recreational and commercial purposes [31].

From a detailed overview of the Gulf and other world countries' AID literature, these developments must have severe consequences on the environment. There is a need to manage and strategize the environmental implications of said development at national and global levels. Figure 5 and Table 3 represent the geographical distribution of included studies and a comparison of AID environment implications in the Gulf and other world countries.

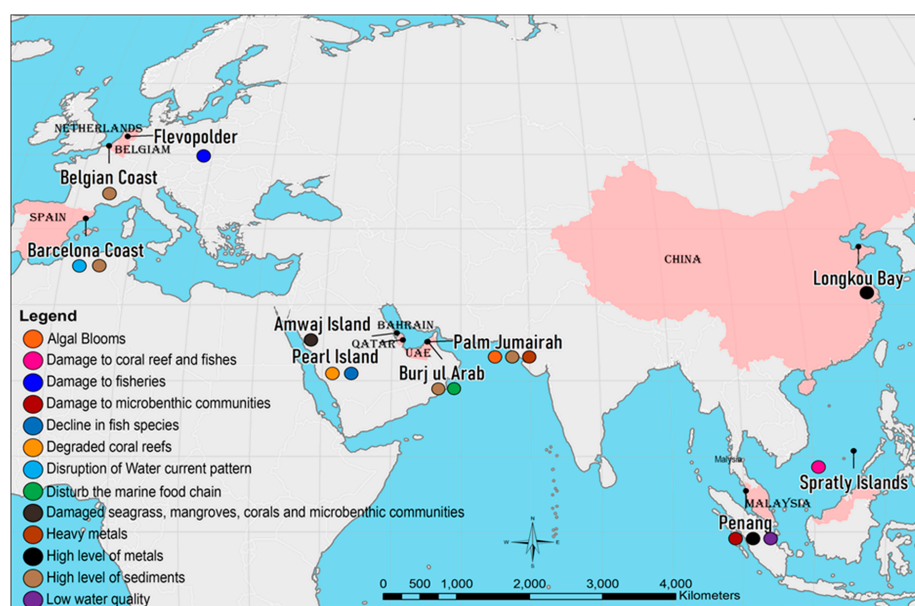


Figure 5. Geographical distribution of included studies and comparison of AID environment implications in the Gulf and other world countries.

Table 3. Geographical distribution comparison with AID environment implications in the Gulf and other world countries.

Country	Artificial Island	Environmental Impact	Reference
Gulf Countries			
Dubai, UAE	Palm Jumeirah Burj ul Arab	Algal blooms, high level of sediments, heavy metals	[18]
		High level of sediments, disturbed marine food chain	[23]
Bahrain	Amwaj Island	Damaged seagrass, mangroves, corals, and microbenthic communities	[25]
Qatar	Pearl Island	Degraded coral reefs, decline in fish species	[26]
Other World Countries			
Netherland	Flevopolder	Damage to fisheries	[20]
China	Spratly Island Longkou Bay	Damage to coral reefs and fishes	[29]
		High level of metals	[29]
Malaysia	Penang	Damage to marine life, high level of metals, poor water quality	[30]
Spain	Barcelona	Disruption of water-current pattern, high level of sediments	[31]
Belgium	Belgian Coast	High level of sediments	[32]

4. Challenges towards Sustainable Development of AID in the Gulf Region

Due to unprecedented environmental impacts from artificial island development, massive amounts of research work and studies have been carried out internationally involving design, general layout, and economic and social benefits without ignoring environmental impacts. In the light of these studies, the following are the major identified barriers.

4.1. Lack of Availability of Basic/Scientific Data

Conventional coastal engineering is equally challenging to extract the basic data of artificial islands related to construction, because it requires massive amounts of fieldwork and research. The lack of availability of basic data adds lots of confusion because construction standards, particularly for artificial islands, are stringent, and without basic information, it becomes a complicated task [60]. Hence, comprehensive studies and surveys are mandatory to obtain adequate information before the commencement of any construction project.

4.2. Least Consideration to the Site Selection of the Artificial Islands

Generally, artificial island construction is limited to the economic gains that lack environmental values. The airport artificial island, the artificial port island, and the auxiliary artificial island are prominent examples. The artificial island mainly focuses on tourism, adequate transportation, and several other factors [60]. The least consideration given is the impact of site selection on the surrounding environment and its species.

4.3. Ineffective Environmental Impact Assessments

Environmental Impact Assessment (EIA) procedures, particularly for coastal development projects, are not followed in true spirit due to broader factors like in many other regions. Another reason is that rapid development does not give adequate time to formulate suitable technical, regulatory, and monitoring capacity to lead this project appropriately [23]. Hence, the desired results cannot be achieved mainly due to the lack of effective national legislative EIA process owners and regulatory bodies.

4.4. Noncompliance with National and International Legislation Related to Artificial Island Development

There are comprehensive guidelines and legislation available to ensure sustainable practices while constructing artificial island development, but it depicts a bleak image when it comes to implementation [23].

4.5. Economic Growth and Environmental Degradation—Highlighting the Importance of the Gulf's Coastal Ecosystems

There is no doubt that the Gulf shares considerable economic values globally, unlike environmental principles. There is still a lack of comprehensive data on potential detrimental environmental impacts on ecosystems due to human-induced coastal and artificial island development [23].

4.6. Lack of Communication and Capacity Building of Public Awareness on Environmental Issues

Public awareness and capacity-building programs play a significant role in sustainable development. It is a prominent platform to gain public participation and support to achieve environmentally friendly goals. Like many other regions, the Gulf also shares a poor environmental understanding of marine ecosystems. Moreover, the lack of interest from governments and authorities encourages others to violate existing regulatory guidelines [36]. Ideally, the government and concerned authorities should encourage public participation and media involvement to minimize detrimental environmental and health impacts through the decision-making process.

5. Strategies to Mitigate Environmental Implications of Aid in the Gulf Region

There are numerous international, regional, and national legislative organizations in the Gulf region to manage the coastal environment and artificial island development. Still, it manifests a bleak picture when it comes to effective governance. Hence, sound policies, strengthening of legislative frameworks, research, considering modern practices, continuous capacity building, encouraging public participation, and rigorous monitoring followed by stringent implementation and engineering advancement are the need of the hour to achieve the milestone of sustainable development [34,61]. Below are the strategies to mitigate the environmental implications of AID in the Gulf countries:

5.1. Strengthening Governance and Legislative Framework of the Gulf's Coastal Environments

In the Gulf countries, detailed policies followed by guidelines that promote sustainable coastal development practices exist, including global policy guidelines to integrate management approaches such as EIA, conservation of vulnerable habitats and species, alternative pollution control technologies, and stakeholder participation.

Other detailed guidelines at the regional level include Abu Dhabi's Urban Planning Council's (UPC) 2007 coastal development guidelines. The fact is that these guidelines have been developed recently and are effective if implemented in true spirit [23]. However, strengthening existing legislative frameworks by the concerned authorities in all mega-developments sprouting along the Gulf coast will further help minimize environmental and economic risks.

5.2. Effective Baseline Data and Monitoring

Baseline studies and accurate data play a significant role in devising strategies to minimize threats due to project activities during the construction phase. Hence, the following guidelines must be considered to overcome the implications due to project activities:

- To formulate a detailed inventory of artificial islands to create a baseline manifesting threats to coastal ecosystems.
- To implement an effective pollution-monitoring program to assess the pollution levels, including environmental status and the chemical and physical parameters of nearby shoreline waters.
- To organize a conference at a regional level, at least on an annual basis, to evaluate the current condition of the Gulf's coastal environments.
- To prevent the environmental degradation, a comprehensive baseline report should be published after every three years to highlight the present condition of the Gulf and the way forward [23].

5.3. Scientific and Technical Capacity Building of Staff

Skilled staff is one of the essential components of any successful project because their role is crucial in minimizing project cost by effectively utilizing resources followed by environmental implications of the project. Therefore, the following guidelines are proposed to enhance the effectiveness of the project:

- Providing research and development opportunities and easy access to technology.
- Ensuring provision of resources for environmental management authorities.
- Lessening bureaucratic pressures and providing adequate opportunities for local and national environmental authorities.
- Qualified staff recruitment, followed by the development of a competent advisory committee having connections with the well-known environmental communities of the world.
- Developing training modules that include all the aspects of coastal and marine monitoring by engaging environmental authorities, research students, and dynamic NGOs [35].

5.4. Enhancing Public Participation in AID Projects

Engagement of the general public in decision-making activity must be a top priority, followed by the independent media to depict the true picture of environmental and health issues [36].

5.5. Effective Environmental Impact-Assessment System for Protecting the Environment

For an ecologically functional ecosystem of coasts and marine life, coastal development that includes dredging and reclamation activities should not disturb the natural habitat. Hence, an effective environmental and ecological impact-assessment study is mandatory to balance development and the environment. However, various additions are required to strengthen the existing EIA process, which includes ecological surveys; project alternatives giving importance to the environmental parameters, unlike economic and political gains; baseline studies; public participation and stakeholders' engagement; compensation; and mitigation strategies, followed by frequent monitoring [24].

5.6. Enforcing Better Fishing Regulations

Methods used for fishing near the artificial islands may pose a severe threat to the natural habitat. Stringent enforcement of rules and regulations will limit overfishing and protect the reefs' population from exploitation. Several methods, such as purse seine, gill-nets, long lining, and pole and line (Figure 6), are considered sustainable while harvesting fish, being used in the South China Sea [28].

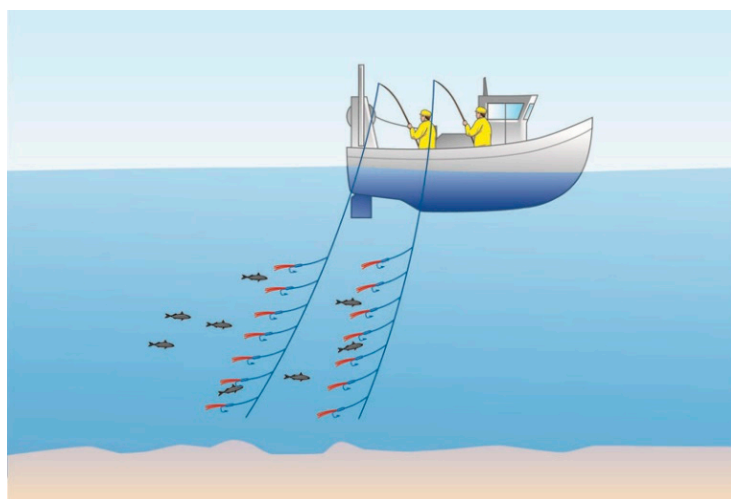


Figure 6. Pole-and-line fishing method (a sustainable fishing strategy) [62].

5.7. Disaster Management during Coastal Developments

There is always a risk involved in marine projects, and there is a likelihood of many natural disasters, including climate change, rising sea levels, tsunamis, and flooding. Numerous approaches can be used to overcome these menaces, such as ecological engineering. A hybrid approach creates a natural ecosystem with other valuable habitats such as mangroves to maintain biogenic sediments and wave effects during coastal or artificial island development [37]. Similarly, to maintain the balance that might be disturbed due to dredging and reclamation activities, the geotubes technique is economical to control silt emissions and lower turbidity [39,63].

5.8. Environmental and Climate-Change Modeling

During the design, construction, and operational phases of AID, several statistical models can be used to enhance resilience and sustainability and mitigate detrimental environmental impacts. For example, RUSLE/MUSLE (Revised/Modified Universal Soil Loss Equation) models can estimate yearly soil erosion rates [64,65]. The digital elevation model (DEM) [66] can be implemented jointly with hydrometeorological variables, such as rainfall, which can be retrieved by satellite or measured in situ to analyze soil and water-conservation services. Furthermore, other mathematical and statistical models indicate the areas that are prone to land degradation.

Regional climate-change modeling (RCM) [67], which is tailored for regional specifics at higher resolutions, can be employed to assess future projections of short-term physical phenomena, such as heat waves, floods, cyclones, storms, among others, and long-term effects due to the spatiotemporal variability of hydrometeorological variables, such as temperature, rainfall, humidity, wind speed, among others. Climate-change modeling is an effective tool to develop resilient artificial island design. In addition, the RCM and other climate models can be used to predict future energy demands [68–70].

5.9. Mining Method

Extraction methods for marine sand and gravel play a significant role in determining the implications on the bottom fauna, fisheries, and benthic communities. Hence, extreme care should be taken while mining because if sand is completely removed, it might have an adverse impact on existing life due to disruption of habitat. Similarly, permanent removal of gravel would have detrimental effects on marine habitats. Therefore, a mining method should be selected to limit the impact on the bottom fauna [33].

5.10. Replanting Coral Reefs

Another possible measure to overcome the damages to the natural ecosystem caused due to the development of the artificial island is replanting coral reefs (Figure 7). Coral reefs are a habitat for many marine species such as fishes, and they protect them from coastal erosion. Therefore, they play a huge role in coastal environments. Construction activities for AID can kill the coral reefs, causing habitat degradation. Therefore, it is recommended that coral reefs must be replanted to ensure a healthy marine ecosystem and sustainable island. In addition, sensitive areas should be termed marine protected areas (MPA) to restrict the movement of boats in that particular area to avoid any disruption. The MPA technique has shown significant success in California in protecting habitats and ecosystems of marine species [28].

5.11. Engineering Modifications to Reduce Environmental Impacts

One of the main issues in artificial island development is the high turbidity arising onsite due to construction activities. Similarly, the marine environment is negatively impacted owing to AID. The following case studies elaborate on the usefulness of geotubes, ecological engineering, and deep-insert steel cylinders to overcome the anticipated issues. These are specifically chosen because these structures/techniques can be employed in line to AID to mitigate the harmful effects.



Figure 7. Artificial coral reefs placed in the ocean [71].

5.11.1. Case Study of Bahrain

One prominent example to limit the adverse impacts of dredging (a construction activity necessary for AID) is from geotubes used in Bahrain during the development of Amwaj Island. Contractors used geotubes to tackle the menace of high turbidity instead of a quarry rock-retention dike. The geotubes undoubtedly proved effective in limiting turbidity owing to dredging and reclamation activities. Furthermore, the employment of the geotubes significantly reduced the carbon emissions associated with construction activities [72]. Along with that, turbidity curtains during dredging are also used to control emissions due to silt in the water. Woven polypropylene fabric silt curtains, 3 m in height and 200 m long, were designed to reduce turbidity to their maximum [38]. This innovative technique is quite economical, with numerous environmental benefits, having fewer adverse impacts on the marine ecosystem because less excavation is involved during its installation [39].

Moreover, the functioning of the geotube involves the filling of material and dewatering by capturing 99% of solids, and then captured solid materials can be landfilled, as shown in Figure 8.



Figure 8. Mechanism of the geotube sediment filling, dewatering, and consolidation [73].

5.11.2. Case Study of Malaysia

Ecological engineering, also termed ecoengineering, is an emerging field that integrates engineering and ecological perspectives to bring sustainable urban environments. The

ecosystem model is most suitable for those areas where enough space is available between the coastline and urban zones [74] to house or facilitate the formation of natural ecosystems such as reefs, seagrass beds, mangroves, saltmarshes, and others to weaken the effects of waves [37], and is effective at maintaining the balance of biogenic sediments. In summary, ecological engineering helps preserve the marine environment during AID and ensures its sustainable development.

The building of Penang Island of Malaysia is a conspicuous example of ecological engineering works where a hybrid approach was used to create an ecosystem of shellfish reefs in association with other useful habitats such as mangroves to restore the services and functions of the ecosystem on the coast and new artificial islands. Figure 9 represents a conceptual diagram comparing an artificial island without and with ecoengineering as an ecological management solution for artificial island development [29].

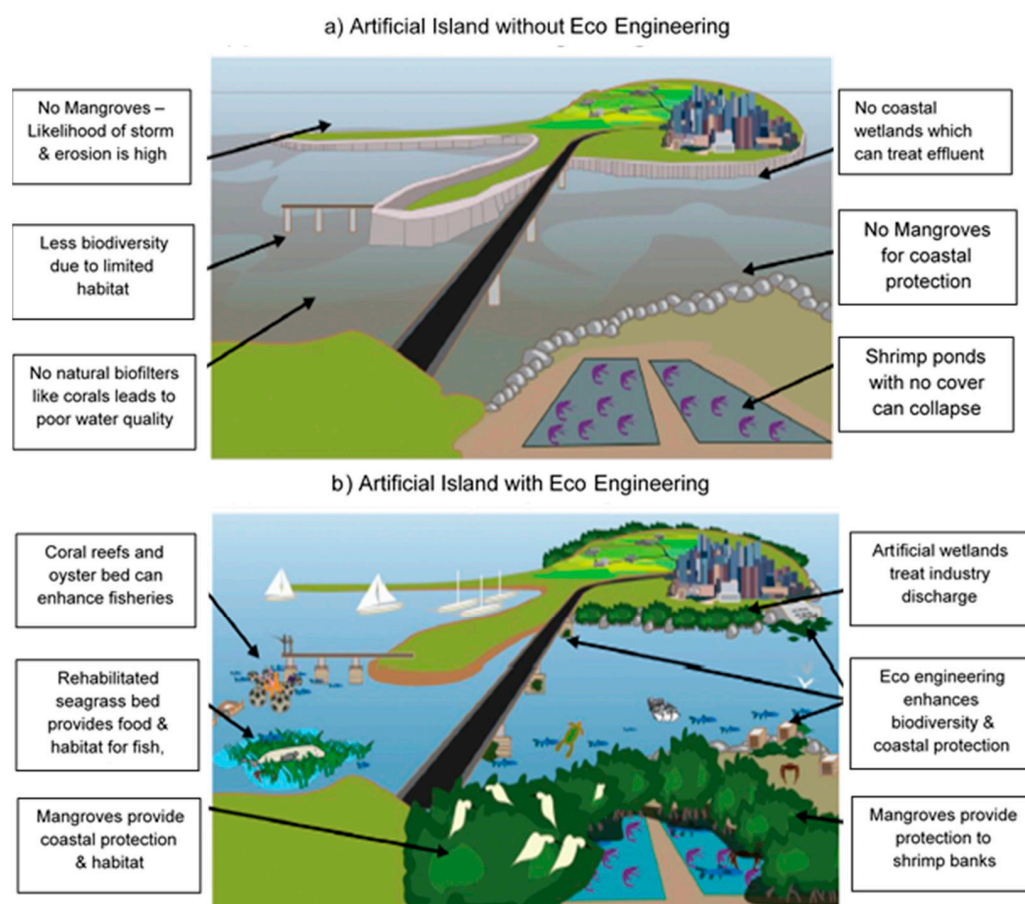


Figure 9. (a) Artificial island without ecoengineering, and (b) with ecoengineering as a management solution [29].

5.11.3. Case Study of Hong Kong

Hong Kong–Zhuhai–Macao Bridge (HZMB) Island-Tunnel Project mainly consists of two artificial islands, and the designated site had the Chinese White Dolphin National Natural Conservation Zone. Hence, a novel construction method was brought into practice to protect the conservation zone. Through the deep-insert steel-cylinder piling with auxiliary cells method, two artificial islands, each with a land area of around 100,000 m², were formed in 6 months instead of 3 years in the light of the originally proposed method. Due to the speedy construction of island walls using said method, the construction activities increased tremendously. Similarly, marine work duration was significantly shortened by deploying extensive prefabricated structures.

Furthermore, the use of this method in this context minimized the dredging volume required for the artificial island foundations. It greatly reduced sedimentation and turbidity levels, lessened ship-collision risks during construction activities, and reduced the project's impacts on the environment, for example, effects on the Chinese white dolphin habitat. However, this method is most applicable to soft soil [32].

The discussed strategies to mitigate the environmental implications of AID are consolidated in Table 4.

Table 4. Summary of reviewed literature on strategies to mitigate environmental implications of AID.

Strategy	Remarks	Reference
Legislative framework	Strengthening the existing legislative framework by enforcing AID laws implementation effectively	[23]
Baseline data and monitoring	Effective ecological baseline and meteorological data and pollution-monitoring programs aid in artificial island protection	[23]
Scientific and technical-capacity building of staff	Technical-capacity building of staff that consider the environment as a priority in development projects	[35]
Public participation	Engagement of the public in the decision-making activity in AID projects	[36]
EIA system	Effective environmental and ecological impact-assessment study is mandatory to keep the balance maintained between development and the environment	[24]
Fishing regulations	Ensuring better fishing regulations, such as pole and line, are considered to be sustainable in order to conserve fisheries near artificial islands	[28]
Mining method	Extreme care should be taken while mining because if sand is completely removed, it might have an adverse impact on existing life	[33]
Artificial coral reef	Replanting artificial coral reefs near AID projects to promote biodiversity	[28]
Geotube	Installation of the geotube near Amwaj Island to reduce sediment/turbidity and carbon emissions	[38]
Ecoengineering	Application of ecoengineering such as artificial coral reefs, oyster beds, mangroves near artificial islands for coastal protection and richness of biodiversity as a management solution	[29]
Environmental modeling	Several environmental models can be utilized to improve resilience and sustainability, as well as mitigate the negative environmental impacts, during the design, construction, and operation phases of AID.	
Climate-change modeling	Climate-change modeling is a useful technique for creating robust artificial islands. The RCM, as well as other climate models, can be used to forecast future energy demands.	
Deep-insert steel-cylinder piling with the auxiliary cells' construction technique	Deep-insert steel-cylinder piling with auxiliary cells method reduced the marine work duration and minimized the dredging volume, resulting in a reduction in increased sedimentation and turbidity levels, lessening ship-collision risks, and reducing the project's environmental impacts	[32]

6. Conclusions and Outlook

The coastal and marine environment has been a major focus in the Gulf regarding social and economic aspects like many other countries, and unlike environmental aspects. There is no denying the fact that AID brings unprecedented and continuous degradation of the marine environment and various natural ecosystems. A high level of turbidity owing to massive dredging has witnessed a noticeable loss of many fish species, coral reefs, shells, and oyster beds. Sedimentation and heavy metals in the marine waters have contributed to salinity and temperature extremes, which accelerate the destruction of microbenthic communities and disrupt natural water-current patterns. To mitigate unsustainable practices to protect marine ecosystems from further degradation, scientific data, passable site selection, effective environmental assessment, and compliance with national and inter-

national legislation are vital to ensure sustainable development. Given the importance of economic and social aspects, there is a dire need to prioritize environmental aspects to achieve the milestone of sustainable development. Therefore, this study intends to focus policymakers and governmental and environmental organizations on environmental aspects during AID by manifesting established environmental implications to create an ecologically balanced environment. Several environmental issues related to AID have been presented and discussed in the literature survey. Furthermore, the recommendations such as the development of the legislative framework, data monitoring, use of statistical and climate-change modeling, implementation of environmental impact assessment, employment of the geotubes, and the application of ecoengineering, have been made as mitigation measures for environmental implications related to the AID.

Future Research

This review highlights the following research gaps that can be used for future research:

- Baseline and scientific data play an essential role in determining a suitable strategy for a particular location. Hence, research on the effective environmental assessment process before executing any artificial island or coastal development project is essential.
- Research in monitoring the effectiveness of engineering strategies to mitigate environmental impacts of AID in Gulf countries.

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