ANTHROPOCENE IMPRINTS ON THE PERSIAN GULF (ARABIAN GULF): A COMPREHENSIVE REVIEW OF POLLUTION AND CONSERVATION CHALLENGES

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Abstract. The Persian Gulf, a shallow semi-enclosed sea bordered by eight nations, faces intensifying ecological degradation under the pressures of the Anthropocene. This review systematically examined pollution types, impacts, and conservation challenges in Persian Gulf from the Scopus database. A bibliometric analysis using VOSviewer identified six major thematic clusters, highlighting evolving research priorities. Chronic oil pollution from extraction, refining, and shipping activities remains a dominant threat, with cumulative impacts on microbial communities, benthic macrofauna, and coral reefs. Heavy metals, including mercury, cadmium, and lead, continue to bioaccumulate in sediments, marine biota, and food webs, posing serious risks to fisheries productivity, food security, and public health. Additionally, thermal pollution and hypersaline effluents from desalination plants are altering salinity-temperature regimes, exacerbating stress on coral reefs and seagrass beds. Rapid coastal development and land reclamation are driving habitat loss, especially for mangroves and mudflats, while microplastic debris is increasingly entangling marine megafauna and contaminating seafood species. The socio-ecological consequences include biodiversity decline, heightened public health threats from seafood contamination and airborne pollutants, economic vulnerabilities in fisheries and tourism sectors, and the cultural erosion of traditional livelihoods such as pearl diving and artisanal fishing. Despite the establishment of Marine Protected Areas and regional initiatives like the Kuwait Action Plan, conservation efforts remain fragmented due to weak governance, geopolitical tensions, and insufficient transboundary cooperation. Critical research gaps persist in cumulative impact assessments, socio-economic valuation, and the integration of climate change stressors into pollution risk models. Safeguarding the Persian Gulf's ecological integrity demands the urgent adoption of ecosystem-based management frameworks, legally binding regional agreements, strengthened science-policy integration, proactive public engagement, and a commitment to embedding planetary health principles into national and regional development strategies.
Keywords: *Persian Gulf, anthropocene, marine pollution, ecosystem-based management, conservation challenges*

Introduction

Covering almost 251,000 square kilometres, the Persian Gulf (PG) is absolutely essential for world energy security, trade, and regional economies. Its coastal countries including Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates, depending mostly on the PG for oil and gas extraction, shipping, fisheries, and freshwater generation by means of desalination (Walgate, 1978; Bryant, 1981).

The same actions that support economic growth, therefore, have also created great environmental loads. The PG, a shallow, semi-enclosed maritime basin with limited exchange via the narrow Strait of Hormuz, is extremely susceptible to the buildup of pollutants (Oostdam, 1980; Bryant, 1981). Driven by operational discharges, offshore extraction, shipping traffic, and aggravated by sporadic disasters like those during the 1991 Gulf War, chronic oil pollution starting as early as the 1970s remains a severe hazard. Modern research still shows significant changes in coral reef, benthic, and microbial ecosystems caused by hydrocarbon pollution.

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Another major stressor is heavy metal pollution, which has been found in sediments and bioaccumulated in marine species including *Bufonaria echinata*, oysters, and fish species confirming their use as biomonitors. While physiological stress reactions in sentinel species like Periophthalmus waltoni show the sub-lethal consequences of pollution in the Hormuz Strait, petroleum contamination has greatly harmed mangrove forests, especially on Qeshm Island and Khamir Port (Ebrahimi-Sirizi and Riyahi-Bakhtiyari, 2013). Reflecting the increasing influence of untreated wastewater discharges and urban expansion, emerging pollutants beyond hydrocarbons and metals such as antibiotics, pharmaceuticals, and microplastics, which are being found more and more in sediments and marine organisms (Kafaei et al., 2018; Gholizadeh et al., 2024). Modelling studies of the northern Persian Gulf show that desalination brine and thermal discharges from large energy infrastructure projects are also changing local salinity and temperature patterns, therefore endangering coral reefs, seagrass meadows, and carbonate sediment structures.

The ecosystems of the Gulf which comprise of coral reefs, seagrass beds, mangroves, mudflats, and saltmarshes, are therefore facing unmatched cumulative pressures from the hallmarks of the Anthropocene: industrialisation, urbanisation, pollution, and climate change (Walgate, 1978; Sinaei et al., 2012; Pourang et al., 2019). Apart from environmental effects, these pressures have serious socio-economic and cultural consequences: biodiversity losses, public health hazards from seafood and air pollution exposure, threats to fisheries production and food security, and the erosion of traditional coastal livelihoods like artisanal fishing and pearl diving (Eagderi et al., 2019; Raeisbahrami and Naderloo, 2023; Kawiyani et al., 2024). Conservation activities stay scattered and undercut by geopolitical conflicts, poor enforcement, and inadequate regional cooperation despite regional efforts like the Kuwait Action Plan and the declaration of Marine Protected Areas (MPA) (Samimi-Namin and Hoeksema, 2023; Dobaradaran, 2024).

This systematic research aimed to thoroughly assess the present condition of marine pollution and conservation issues in the PG. Specifically, it aims to find and combine the main causes of pollution, namely oil spills, heavy metals, desalination discharges, coastal expansion, and plastic debris, and evaluate their combined ecological, public health, socio-economic, and cultural effects. While stressing the obstacles caused by fragmented government and inadequate regional cooperation, the study also questions the efficacy and constraints of current conservation projects like MPA and regional agreements. Moreover, it seeks to highlight important research voids, especially in relation to cumulative pollution evaluations, connections with climate change, socio-economic value of ecosystem services, and public involvement. In the end, the goal is to suggest future paths that support science-driven policymaking, regional cooperation, and ecosystem-based management strategies to protect the delicate marine ecosystems of the PG and the people who rely on them.

Methodology

This study employed a Systematic Literature Review (SLR) methodology based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009), as illustrated in *Figure 1*. The main objective was to systematically analyze and synthesize scholarly literature related to the PG, focusing on

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environmental degradation, pollution dynamics, conservation challenges, and their broader implications for human and ecological systems.

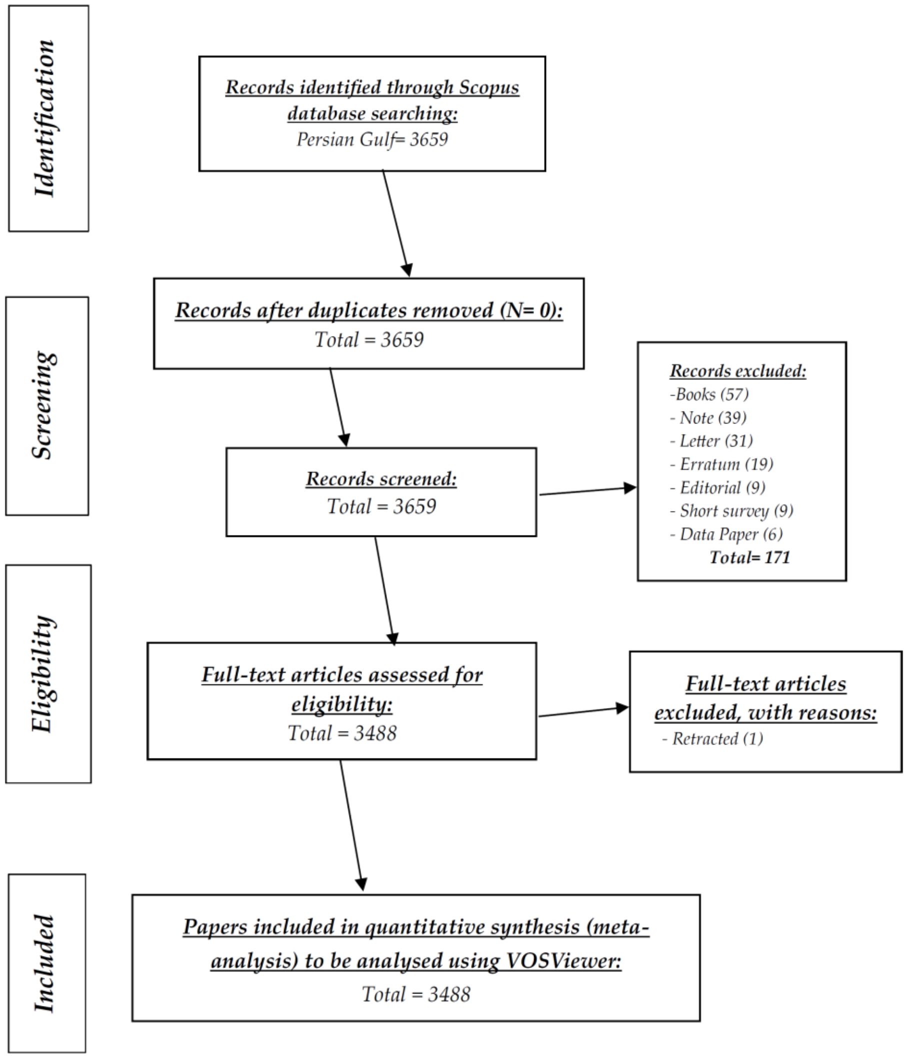

Figure 1. *Flowchart of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (adapted from Moher et al., 2009), used in the present study. Searched on 27 April 2025 Scopus Database*

The bibliographic data came from the Scopus database, chosen for its thorough multidisciplinary coverage and inclusion of high-quality, peer-reviewed research results (Scopus, 2024). Using the phrase "Persian Gulf," a bibliographic search limited to the article title field was done on 27 April 2025 to verify thematic relevance and specificity. Bibliographic data including title, author names, affiliations, abstracts, keywords, source titles, publication years, and DOIs was exported in CSV and RIS formats throughout the database search. Data cleaning techniques were straight away carried out after the export to fix discrepancies in keyword spelling, encoding mistakes, and formatting abnormalities, hence guaranteeing a uniform and high-quality dataset for subsequent study.

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The study moved on to the four systematic PRISMA stages—Identification, Screening, Eligibility, and Included—after data cleaning. A total of 3,659 records were obtained from several document kinds during the Identification step. Records classified as non-research outputs—specifically books (57), notes (39), letters (31), errata (19), editorials (9), brief surveys (9), and data articles (6)—were eliminated in the Screening step. The Eligibility stage produced a final dataset of 3,488 documents for inclusion by verifying the relevance and completeness of the remaining papers, less one retracted article. There were no duplicate records, hence no deduplication processes were required.

Using VOSviewer (version 1.6.20; Van Eck and Waltman, 2009–2023, Leiden University, The Netherlands), quantitative bibliometric analysis (meta-analysis) was applied to these 3,488 texts at the Included stage. Keyword co-occurrence analysis revealed thematic clusters and temporal trends in the cleaned bibliographic dataset comprising titles, abstracts, keywords, and citation metadata. This study adhered to Van Eck and Waltman (2010, 2014, 2017) methodological guidelines. A minimum occurrence criterion of 25 was imposed to guarantee analytical rigour by considering both author-provided and indexed keywords.

Of the 12,794 total retrieved keywords, 242 qualified under the criteria for inclusion. Applying the complete counting technique, every keyword occurrence was given identical weight independent of the number of contributing authors (Van Eck and Waltman, 2010). VOSviewer produced two primary kinds of visualisations: a network map, grouping related keywords into six major colour-coded clusters based on co-occurrence strength, and an overlay visualisation, showing the average publication year linked to each keyword to distinguish between emerging research topics and well-established areas (Van Eck and Waltman, 2014). To grasp the topic progression and knowledge structure inside PG-related study domains, keyword association strengths and cluster structures were mapped (Van Eck and Waltman, 2017).

By means of this methodical and statistical bibliometric technique, the study clarified the main research topics and temporal dynamics in the scientific discourse around the PG, stressing changes from conventional pollution evaluations to modern concerns on climate change consequences, biodiversity preservation, and integrated coastal governance systems.

Results

Overall keyword mapping and visualization

Reflecting the main theme tendencies in PG pollution research, the keyword co-occurrence analysis identified 165 relevant keywords classified into six separate groups (*Figure 2*). With different node sizes reflecting keyword frequencies and line thickness showing co-occurrence intensity, the VOSviewer visualisation reveals a dense network of interrelated nodes. Especially, bigger nodes like "heavy metals," "oil pollution," "microplastics," and "biomonitoring" dominate the network centre, stressing their centrality throughout several research. The closeness and overlapping areas among the clusters show the great multidisciplinary integration in this field of study. Furthermore, the spread of keywords points to a shift from single-pollutant research to a more holistic, ecosystem-based inquiry strategy with time. The visualisation shows how research on environmental contamination in the PG are increasingly targeting cumulative, cross-cutting concerns rather than individual pollutants.

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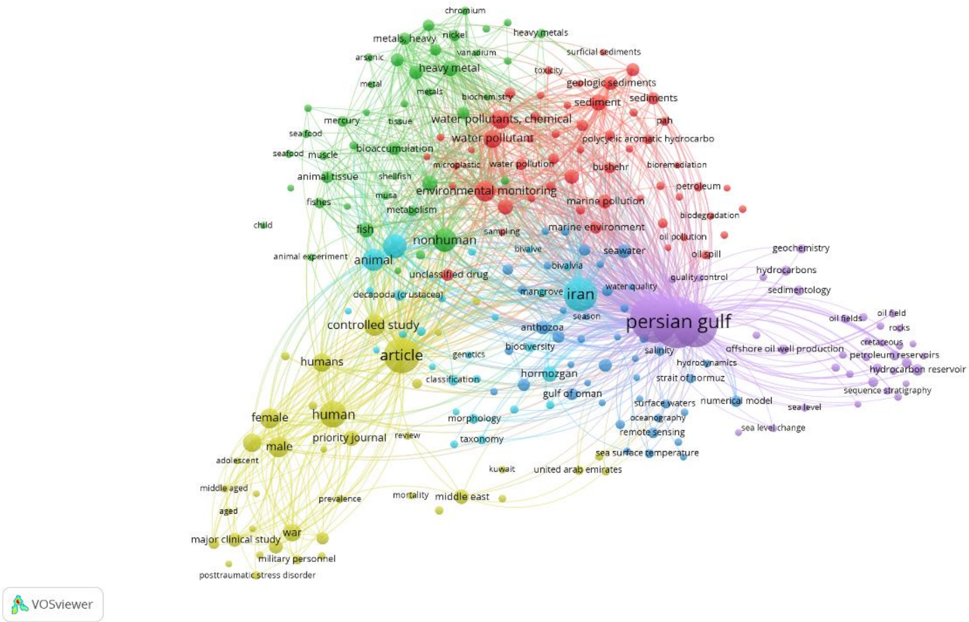

Figure 2. *The bibliographic analysis using Network Visualization in VOSViewer, outputting six major clusters with 242 items meeting the threshold of minimum 25 number of occurrences of a keyword, in which out of 12794 keywords, 242 met the threshold based on 3488 papers searched in Scopus database with keyword 'Persian Gulf' in the article title on 27 April 2025*

Cluster 1: heavy metals contamination

Focusing mostly on heavy metal pollution, a long-standing environmental issue in the PG, Cluster 1 This group is mostly dominated by core terms like "cadmium," "lead," "zinc," "mercury," "bioaccumulation," "risk assessment," and "sediment contamination." Particularly in molluscs like Saccostrea cucullata and fish like Otolithes ruber, several research have looked at metal levels in marine animals, sediment, and seawater. Efforts at biomonitoring have uncovered disturbingly high levels of cadmium (Cd) and mercury (Hg) close to industrial areas such Bandar Abbas and Asaluyeh port. Human health risk studies also show that, particularly for mercury and arsenic, seafood eating presents non-carcinogenic and carcinogenic hazards. Patterns of heavy metal buildup have been connected to anthropogenic activities like oil refining, shipping, desalination discharges, and petrochemical industries, supporting the influence of regional growth in forming pollution footprints. The mapping shows a shift in study from basic concentration reporting to ecological and human risk modelling.

Cluster 2: Hydrocarbon effects and oil pollution

Focussing on "polycyclic aromatic hydrocarbons (PAHs)," "oil spill," "hydrocarbon biodegradation," "sediment quality," and "petroleum hydrocarbons," Cluster 2 centres on hydrocarbon contamination. Originating from chronic leaks, operational discharges, and catastrophic incidents like the 1991 Gulf War oil spill, this cluster highlights the notable body of research on oil-related pollution. Hotspots like Kharg Island, Musa Bay, and the northwest coast are often shown to have higher PAH levels in sediment investigations. Studies have shown detrimental effects on sediment geochemistry, coral reef health, and benthic invertebrate populations. Moreover, more recent research includes hydrodynamic

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modelling to forecast oil diffusion and sedimentation patterns, thereby stressing how winds, currents, and coastal shape affect pollution spread. The obvious persistence of oil-derived pollutants decades after first spills suggests the long-term resilience issues confronting PG ecosystems.

Cluster 3: Emerging pollutants and microplastics

Representing the rapidly expanding study focus on microplastics and other developing pollutants, Cluster 3 "Microplastics," "marine debris," "sediment pollution," "bioaccumulation," and "plastic ingestion" are among the keywords that dominate this cluster. Though more recent investigations have broadened to include microplastic adsorption of heavy metals and organic contaminants, first studies concentrated on recording microplastic prevalence in sediments and molluscs. Studies have revealed extensive microplastic contamination even inside MPA, hence highlighting the ubiquity of plastic pollution. With later consequences for seafood safety, much attention is paid to consumption hazards to fish, bivalves, and sea turtles. The presence of medicines, non-steroidal anti-inflammatory medications, and other new pollutants is also increasingly researched in conjunction with plastics, exposing the complex pollutant cocktails harming the Gulf's biota.

Cluster 4: Biomonitoring techniques and bioindicators

Cluster 4 includes research using biological reactions to track environmental effects. Bioindicators are key organisms include mudskippers (*Boleophthalmus dussumieri*), oysters (*Saccostrea cucullata*), foraminifera, macroalgae, and coral species. Often measured are biomarkers such as glutathione S-transferase activity, superoxide dismutase levels, histopathological changes, and assemblage diversity indexes. Studies indicate that heavy metals, hydrocarbons, and microplastic exposure greatly influence these biological markers. Multivariate analysis of benthic community structures has also produced early-warning indicators of environmental deterioration long before chemical thresholds are crossed. The growing use of integrated biomonitoring techniques shows a move towards proactive environmental assessment tools that can direct mitigation before irreversible ecosystem losses take place.

Cluster 5: Issues of biodiversity and conservation

Cluster 5 emphasises the increasing alarm over habitat destruction and loss of biodiversity. Key words are "coral bleaching," "mangroves," "seagrass loss," "hawksbill turtle conservation," and "biodiversity hotspots." Researches show that pollution pressures along with coastal development and climate change are hastening habitat loss in the PG. Among the main conservation issues mentioned are coral reef deterioration brought on by oil pollution, mangrove deforestation connected to industrial growth, and lower sea turtle hatching rates. Though maritime protected zones (MPAs) exist, research question their low spatial coverage, poor enforcement, and inadequate ecological representativeness. Research in conservation biology advocates quick habitat restoration projects, growth of MPAs, and pollution reduction included into more general marine spatial planning systems.

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Cluster 6: Socio-economic consequences and human health risks

Cluster 6 deals with the human aspects of pollution. Prominent are words like "public health," "seafood contamination," "risk assessment," "tourism influence," and "economic vulnerability." Health risk studies show that seafood eaters are exposed to inappropriate amounts of microplastic pollutants, PAHs, and mercury, which causes worries about long-term health effects including cancer, developmental abnormalities, and endocrine disruption. Environmental quality decline also affects coastal populations reliant on fishing, tourism, and maritime businesses in increasing economic hazards. Studies show a feedback loop whereby environmental deterioration lowers ecosystem services, which then aggravates socio-economic inequalities, especially in less economically resilient Gulf nations. These results show that marine pollution is a major public health and socio-economic catastrophe in the area as well as not only an environmental one.

Temporal trends derived from timeline analysis

The timeline visualisation based on publication years reveals obvious trends in the development of PG pollution investigations (*Figure 3*). Largely motivated by significant environmental catastrophes like the Gulf War oil spills, research mostly concentrated on oil spills and hydrocarbon pollution in the early decades (1970s–1980s). Reflecting increasing industrialisation in coastal areas, the emphasis during the 1990s and early 2000s was on heavy metal pollution in sediments and marine life. Studies addressing new contaminants including microplastics and medicines show a clear rise from 2010 forward. The 2020s reveal even more growth into integrative subjects including ecological health evaluations, human health risk modelling, and conservation planning. Especially, the current timeline patterns show more use of sophisticated techniques including biomarker testing, multivariate risk analysis, and remote sensing for pollution surveillance. The chronological study shows, generally speaking, a definite movement from pollutant identification towards integrated environmental and societal effect evaluation.

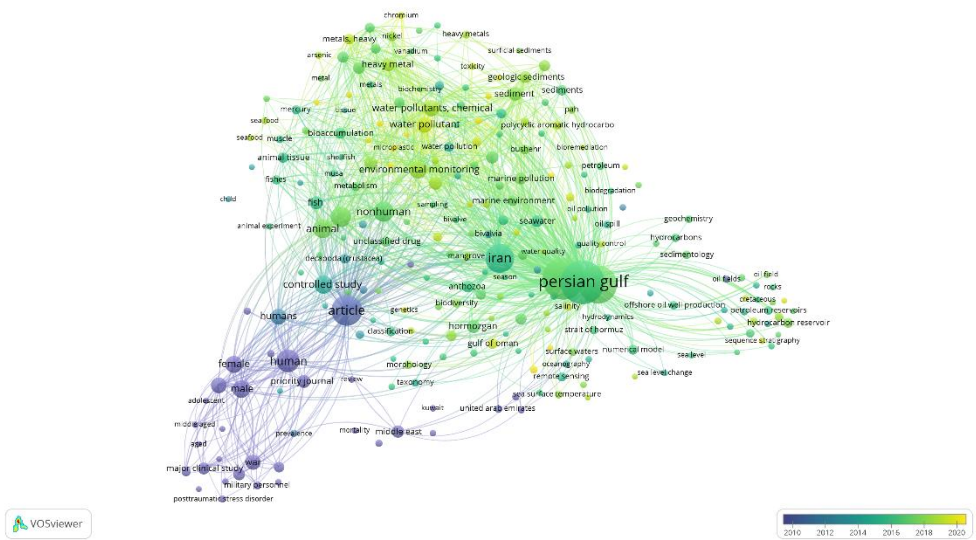

Figure 3. *The bibliographic analysis using Overlay Visualization in VOSViewer, outputting the trends of research themes from 1868 to 2025. Note: The output consists of six major clusters with 242 items meeting the threshold of minimum 25 number of occurrences of a keyword, in which out of 12794 keywords, 242 met the threshold based on 3488 papers searched in Scopus database with keyword 'Persian Gulf' in the article title on 27 April 2025*

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Discussion

Pollution threats in the Persian Gulf

Figure 4 shows the overall pollution threats in the PG.

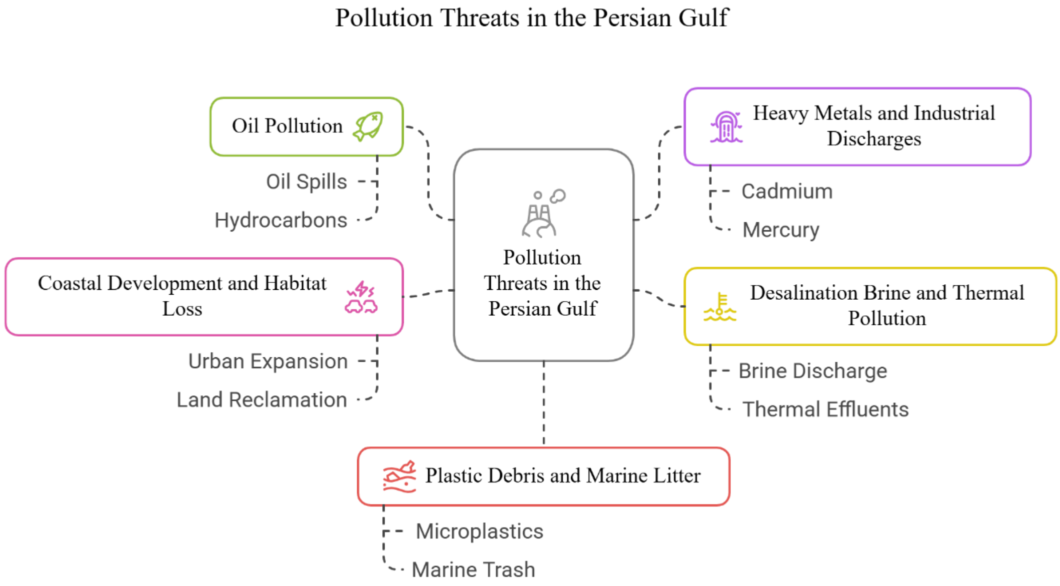

Figure 4. *The overall pollution threats in the Persian Gulf*

Oil pollution

Oil-related operations still rule the pollution scene of the PG, and this was particularly clear in the clustering study (Cluster 1). Oil spills from extraction, refining, and shipping activities emit hydrocarbons into the marine environment, affecting fish stocks, coral reefs, and seabird populations (Heydari et al., 2024). Keyword co-occurrence maps and publication timeline patterns both showed this predominance of oil pollution, with words like oil spill, hydrocarbons, Kharg Island, and chronic exposure front and centre.

As hydrocarbons are still found decades later (Mirvakili et al., 2013; Albano et al., 2016), the legacy of past events like the 1991 Gulf War oil leak remains clear. Cluster studies verified a clear clustering around biota responses and oil spill aftermaths. Chronic oil exposure, aggravated by episodic spills, drastically changes microbial community structures along the pollution continuum in the PG, Rezaei Somee et al. (2021). Likewise, Heydari et al. (2024) found that oil pollution in Jafari Creek caused observable changes in benthic macroinvertebrate populations, suggesting long-lasting ecological stress consistent with the oil pollution cluster patterns.

Furthermore, simulation studies by Faghihifard and Badri (2016) modelled the transport and diffusion of oil pollution near the Assaluyeh oil terminal, revealing persistent localised contamination risks influenced by current systems for matching the cluster's link between hydrodynamics and pollutant dispersion. Results from satellite observations (Evtushenko et al., 2019) and remote sensing approaches (Mohammadi et al., 2021) further supported the cluster's thematic concentrate on spatial oil contamination detection.

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The VOSviewer timeline showed that, overall, oil pollution is still a constantly growing topic, particularly along shipping routes and oil facilities. The results of clustering provide solid evidence that oil-related effects represent a constant and growing danger to coastal livelihoods and environmental resilience in the PG.

Heavy metals and industrial discharges

In the VOSviewer study, industrial discharges and heavy metals were clearly shown as a second main cluster (Cluster 2). Industrial effluents comprising cadmium, mercury, lead, arsenic, vanadium, and nickel infiltrate sediments and bioaccumulate in marine animals, providing notable ecological and human health hazards (Shirneshan et al., 2012; Elsagh et al., 2021). Core nodes of this group were keywords like cadmium, lead, mercury, bioaccumulation, and environmental danger, underlining the intense study concentration on metal-related pollution.

Both in the literature and visibly in the network mapping, elevated concentrations near important urban and industrial centres such as Kuwait City, Abu Dhabi, Bandar Abbas, and Asaluyeh were confirmed (Elsagh et al., 2021; Akbarzadeh-Chomachaei et al., 2023). Ecological risk at Dayer Port was evaluated by Allami et al. (2024), where the sediments indicated extremely high heavy metal concentrations matching locations marked as "hotspots" of pollution in the clustering. The results of Bibak et al. (2020) using macro-algae as bio-monitors and Parsaian et al. (2018) utilising benthic foraminifera mirrored the establishment of a robust secondary cluster node including bioindicators. Emphasising the change in research towards biological early-warning systems, this subcluster was graphically linked to the main heavy metals cluster.

Furthermore, underlined by nematode assemblage changes (Sahraean et al., 2017) and lower echinoderm diversity (Soltani et al., 2024) is the more general ecological deterioration brought on by cumulative contamination as link the cluster clearly described between species decline and metal pollution. Chaharlang et al. (2012) and Hosseini et al. (2016) provided more shellfish data, hence supporting the public health alerts shown in the risk-oriented subclusters. The clustering findings not only support the broad, multi-dimensional hazards ranging from environmental harm to seafood safety and human health issues but also help to explain them greatly.

Desalination brine and thermal pollution

More than half of the world's desalination capacity is located in the PG, and this characteristic clearly created a distinctive cluster in the VOSviewer study of Cluster 3. The discharge of heated effluents and hypersaline brine from desalination plants drastically affects local salinity and temperature regimes, endangering coral reefs, seagrass beds, and more general marine biodiversity (Abbaspour et al., 2006). Prominent mapping of these pressures in the clustering statistics showed close interconnection of keywords like desalination, thermal pollution, brine discharge, and ecosystem danger.

As Dehghan and Lak (2014) noted, thermal discharges aggravate localised seawater temperature rises, hence harming carbonate sediment formations. Their results support the group linking thermal effluents to carbonate deterioration, implying that the Gulf's particular sedimentary characteristics are under grave danger. The timeline trend analysis, in which thermal pollution studies rose dramatically post-2015, highlighted this theme area particularly.

Furthermore, modelling studies by Mehrfar et al. (2023) revealed that coastal currents and mesoscale eddies greatly affect the spatial distribution of brine and heat-altered

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plumes, hence extending pollution effects beyond point sources. The co-occurrence network effectively captured this connectivity with hydrodynamics, connecting oceanographic modelling straight with pollution risk evaluations.

Moreover, studies by Abbaspour et al. (2006) underlined that thermal pollution from coastal industries including power plants and petrochemical facilities which can pose significant environmental and economic hazards in the northern Gulf. Recent studies by Mardani et al. (2022) revealed fresh issues indicating that the total impact of radiation, thermal, and noise pollution from large platforms like South Pars increases environmental stress even more. The clustering emphasised the linked and compounding character of stressors throughout Gulf ecosystems by confirming a study trend towards evaluating multi-modal pollution instead of considering desalination effects in isolation.

Coastal development and habitat loss

Dominant human causes of habitat loss in the PG have been rapid urban expansion, port building, land reclamation, and dredging (as supported in Cluster 4). Drastic changes in natural sedimentation patterns have caused more erosion, turbidity, and loss of vital habitats like mangroves, mudflats, and coral reefs (Akbarzadeh-Chomachaei et al., 2023).

Pejman et al. (2014) found through heavy metal studies that urban development activities, especially in the northwest PG, have upset sediment layers, moving legacy pollutants and increasing environmental hazards. In line with the connections between land reclamation, sediment pollution, and ecological collapse, Zare et al. (2025) also found notable buildup of possibly hazardous components in regions undergoing fast coastal transition. As underlined by Akbarzadeh-Chomachaei et al. (2023), the problem is most severe in heavily developed areas like Bandar Abbas, Qeshm Island, and Hormuz-Lark. In some areas, sediment contamination patterns reflect urbanisation footprints, a finding backed by clustering proximity between urbanisation and pollution hotspots. Khajehpour et al. (2017)'s policy modelling research underlined that without proactive, system-based environmental governance frameworks, coastal development will continue to promote pollution escalation and habitat destruction.

Furthermore, clustering analysis identified a developing trend surrounding the decline of ecosystem services, implying that unregulated building could worsen the effects of climate change like sea-level rise and storm surges by removing natural coastal barriers. The temporal trend indicated further that, post-2018, scientific focus was turning more and more towards include coastal preservation into urban design even if policy translation had little success. Therefore, published studies and clustering obviously support the idea that coastal expansion is among the most important and pressing dangers to the ecological and socio-economic sustainability of the PG.

Plastic debris and marine litter

Particularly plastics, marine debris has become a major pollution vector along the shores and bottom habitats of the PG. The Cluster 5 revealed substantial representation of this topic as a separate group. Emphasising the increasing scientific and managerial concern, the clustering obviously connected microplastics, marine trash, environmental hazards, and sediment contamination.

Plastic accumulation affects marine megafauna like sea turtles, dugongs, and seabirds by means of consumption and entanglement, hence contributing to biodiversity loss (Darijani et al., 2022). Particularly after 2017, a significant increase in microplastic-related research was noted in the timeline study, which reflected this issue. Gholizadeh et

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al. (2024) investigated several sources and kinds of microplastic pollution in Bushehr Province's coastal waters and sediments, showing how urban runoff, industrial discharge, and maritime activities let plastics into the marine system.

Moreover, research by Darijani et al. (2022) underlined that dust-borne contaminants, including microplastic fibres, are not limited to marine habitats but also land on coastal roadways and adjacent terrestrial areas, hence contributing to the total load of marine debris. Clustering overlaps between coastal pollution, roadway dust, and sediment contamination demonstrated this cross-ecosystem transmission of microplastics, hence highlighting the ubiquitous character of plastic litter.

Zamani-Ahmadmahmoodi et al. (2010) emphasised the relationship between plastic debris and other contaminants by linking pollution hotspots defined by high plastic trash to higher mercury levels in coastal wetland bird species, suggesting complicated pollutant synergies. This corresponds to the more general pattern observed in the VOSviewer clustering, where multi-pollutant interactions for example, microplastics and heavy metals which were more often co-cited.

Ecological risk assessments by Rezaei et al. (2021) and Janadeleh et al. (2018) further revealed that marine trash aggravates ecosystem vulnerabilities when paired with heavy metal contamination, hence stressing benthic and pelagic communities. Doust et al. (2024)'s integrated hydrodynamic models showed even more how marine currents and eddies move floating and submerged trash, hence complicating site selection for conservation actions like artificial reefs. Emphasised in Cluster 5, this dynamic distribution of debris calls for adaptive, mobility-informed conservation design and renders static management strategies insufficient.

When considered together, the clustering findings and current research emphasise that plastic pollution in the PG is not only a localised problem but rather part of a larger, linked pollution matrix influencing water quality, sediment integrity, biota health, and ecosystem resilience. Dealing with it need for regional coordinated monitoring, better waste management systems, and cross-sectoral policy integration.

Ecological and socio-economic impacts

Figure 5 shows the overall environmental socio-economic impacts of pollution in the PG.

Biodiversity decline

Particularly close to urbanised coastal centres, desalination plants, and oil extraction sites, pollution in the PG has caused significant and quickening biodiversity losses. Keywords including biodiversity loss, coral reefs, seagrass deterioration, and habitat fragmentation were closely linked in Cluster 1, which significantly emphasised this issue. Linked not just to rising sea surface temperatures but also to chronic oil spills, heavy metal deposition, and eutrophication pressures, coral bleaching episodes have becoming more common (Evtushenko et al., 2019; Mohammadi et al., 2021).

Sediment pollution and hypersaline effluents from desalination facilities are progressively destroying seagrass beds, which are essential habitats for young fish, crabs, and dugongs (Bibak et al., 2021; Sharifinia et al., 2022). The declining health of seagrass habitats shown in the clustering data emphasises even more the cascade consequences on related food webs. Long-term ecotoxicological studies show physiological stress in bioindicator species like the mudskipper *Boleophthalmus dussumieri*, which displays

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enzymatic changes including alterations in glutathione S-transferase activity, all are in reaction to PAH and metal exposure (Sinaei et al., 2012; Sinaei and Rahmanpour, 2013).

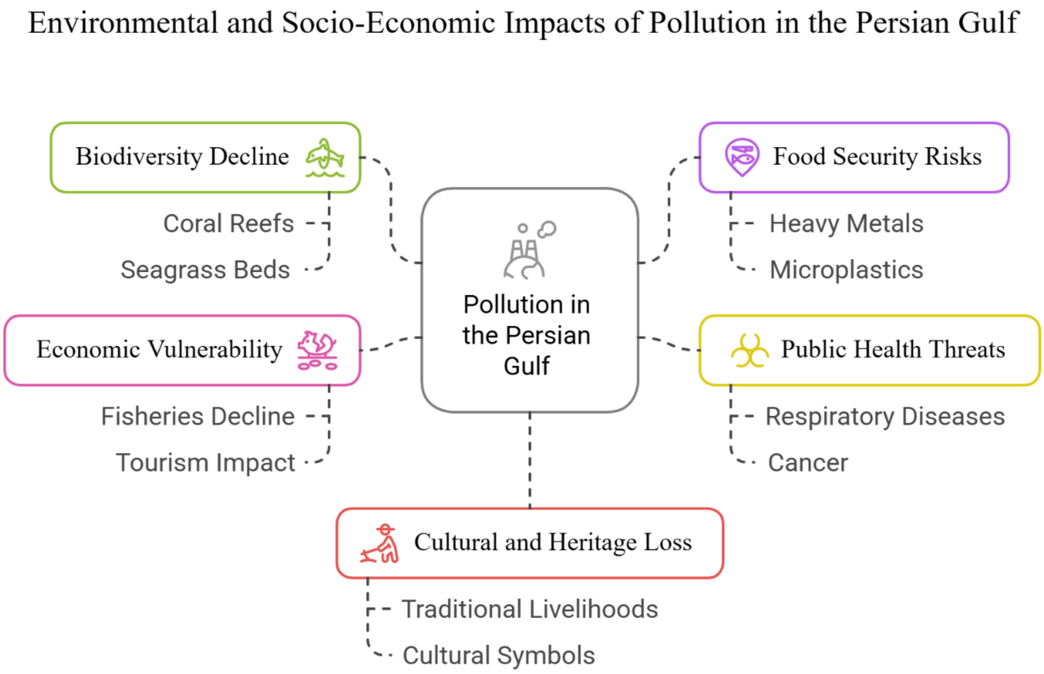

Figure 5. *The overall environmental socio-economic impacts of pollution in the Persian Gulf*

Moreover, the loss of coral reefs and mangrove habitats has led to decreases in related biodiversity including commercially vital fish and mangrove crabs (Savari et al., 2013; Eagderi et al., 2019; Raeisbahrami and Naderloo, 2023). Emphasising the critical conservation needs for these coastal habitats, Cluster 1 also connected mangrove degradation with a fall in species diversity. The results on environmental magnetic fingerprints (Kardel et al., 2023) and radioactive contamination episodes (Reza Abdi et al., 2008) also highlight how pollution is widespread not only in biota but also in abiotic components such sediments and surface waters. These cumulative stresses weaken the resilience of PG marine ecosystems to climate change when combined with habitat fragmentation and thermal pollution stress (emphasised in Cluster 2), therefore threatening biodiversity persistence across trophic levels.

The timeline graphic backed up these worries by indicating growing academic attention from 2016 forward on the combined effects of oil pollution, heat discharge, and microplastic deposition on biodiversity losses in the Gulf.

Food security risks

For coastal populations reliant on seafood supplies, pollution's damage to fisheries poses a significant food security concern. Linking terms like heavy metals, bioaccumulation, fish contamination, and health risk assessment, this topic fit Cluster 3 in the VOSviewer grouping. Oysters (Saccostrea cucullata), sea cucumbers, commercial fish species, and macro-algae (Shirneshan et al., 2012; Haghshenas et al., 2020; Bibak et al., 2021; Rezaei et al., 2021) have consistently shown heavy metals like mercury,

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cadmium, nickel, and lead at bioaccumulative levels. Spatial studies of pollution levels throughout other Gulf areas mirrored these results.

Research by Dadashi et al. (2018) and Tarighat et al. (2024) underlined that eating tainted seafood could increase the likelihood of chronic diseases like cancer, renal impairment, and neurological diseases. Advanced nanocomposite techniques for identifying trace metal contamination in seafood samples (Tarighat et al., 2024) have especially highlighted the demand for more sensitive and proactive monitoring systems.

Furthermore, growing microplastic pollution in sediments and molluscs has generated worries regarding human secondary consumption of plastic-bound poisons (Nabizadeh et al., 2019; Kor and Mehdinia, 2020). Results from Cluster 5, where microplastics and food security concerns were thematically connected, highlighted this problem. Microplastics increase the toxicity to seafood eaters by acting as carriers for hydrophobic contaminants including phthalates, PCBs, and hydrocarbons (Beitgader et al., 2025).

Given that PG nations depend mostly on local fisheries for their food supply, these dangers are especially concerning; any change in seafood quality might greatly affect food prices, nutritional security, and public confidence in seafood safety. Maintaining the health of coastal ecosystems is therefore vital not only for biodiversity conservation but also for preserving livelihoods and socio-economic stability throughout the Gulf area, as underlined in several ecological risk assessments (Janadeleh et al., 2018; Gholizadeh et al., 2024).

Public health threats

Marine pollution in the PG has effects on human health that go far beyond the tainting of the food chain. Keywords including cancer, respiratory sickness, heavy metals, and microplastics were front and centre in Cluster 3 (Food Security, Human Health, and Contamination) and Cluster 4 (Pollution Exposure and Health Risks) of the VOSviewer analysis, reflecting this worry powerfully. A wide spectrum of diseases, from different cancers to respiratory, cardiovascular, and neurological disorders, has been directly linked to waterborne and airborne pollutants including mercury, arsenic, hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and microplastics (Shirani et al., 2012; Sinaei and Rahmanpour, 2013; Kardel et al., 2023).

Lelieveld et al. (2009) strongly underlined that major ozone air pollution events in the Gulf region increase respiratory disease frequency, particularly among vulnerable groups including children, the elderly, and outdoor workers. Public health concerns are also greatly increased by hydrocarbon pollution, a constant topic noted in the timeline patterns from 2010. Research by Hassanshahian et al. (2020) and Sinaei et al. (2012) shown that ongoing exposure to hydrocarbons, both via seafood consumption and environmental exposure that can increase the likelihood of genotoxicity, immune system suppression, and endocrine disruption.

Another layer of danger comes from microplastics, now acknowledged as ubiquitous transporters of adsorbed toxic chemicals (Nabizadeh et al., 2019; Kor and Mehdinia, 2020). Fish and shellfish easily eat these particles, which can accumulate in human consumers thereby increasing exposure to hydrophobic contaminants like phthalates and PCBs. Moreover, social-economic inequality increases total health load. Often without access to regular health checkups, clean water alternatives, or varied income sources, marginalised coastal and fishing communities suffer unequal exposure and more susceptibility to pollution-related illnesses.

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Institutional obstacles make the problem even more acute. Poor pollution control rule enforcement, inadequate monitoring initiatives, and fragmented government structures (Tavakolian et al., 2024) cause delayed reactions to developing contamination incidents, hence aggravating long-term health effects. These results highlight the pressing need for integrated public health surveillance systems combining human health outcome tracking with marine environmental monitoring across PG countries.

Economic vulnerability

Ecosystem deterioration brought on by pollution directly translates into notable financial weaknesses for coastal states of the PG. The VOSviewer map's Cluster 6 drew attention to economic loss, tourist impact, and GDP decline as related keywords. Driven by oil spills, heavy metal contamination, and habitat destruction, fisheries declines diminish the availability of commercially valuable species like prawns, groupers, and sardines, which increases operating costs for conventional fishers and aquaculture businesses (Haghshenas et al., 2020; Rezaei et al., 2021).

The time series study also reveals that post-2015 research more and more tackles the financial consequences of marine pollution. Vital for water security in arid Gulf countries, desalination equipment suffers extra operational expenses from biofouling and corrosion of intake systems polluted by marine contaminants including hydrocarbons, microplastics, and heavy metals (Sharifinia et al., 2022). Upgrades to maintenance and filtration to handle poor water quality increase millions in unexpected yearly costs.

Visible coastal deterioration is also more and more threatening travel once a thriving industry especially in places like Kish Island, Qeshm Island, and the UAE's coastal resorts. Marine trash, oil tar balls, coral reef loss, and coastal erosion turn off tourist investments and lower visitor numbers (Doust et al., 2024; Kawiyani et al., 2024). Once fundamental to Gulf tourism branding, clean beaches and dynamic marine ecosystems are now gravely endangered.

Restoration efforts are made more difficult by emerging pollutants include antibiotics (Kafaei et al., 2018) and microplastics (Kor and Mehdinia, 2020), which further increase the cost and technical difficulty of environmental cleanup initiatives. Economic modelling studies in line with Tavakolian et al. (2024) show that if thorough pollution reduction policies are not followed, coastal GDP contributions might drop by as much as 15–20% by 2030, especially impacting smaller Gulf states with strong dependence on fisheries and tourism industries.

Thus, the interrelated socio-economic and environmental vulnerabilities call for the implementation of ecosystem-based management, integrated maritime spatial planning, and transboundary collaboration to safeguard natural capital as well as economic resilience in the PG.

Cultural and heritage loss

The environmental deterioration of the PG is not only an ecological or financial problem; it is also a deep cultural tragedy. Strong keyword connections between habitat loss, traditional livelihoods, and coastal communities in Cluster 2 from the clustering analysis underlined the interdependence of ecological and cultural deterioration. Once flourishing on traditional livelihoods including artisanal fishing, pearl diving, seasonal mangrove harvesting, and dhow-building, coastal communities are today seeing the fast collapse of their centuries-old way of life (Ghaemi et al., 2024; Kawiyani et al., 2024).

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Pollution-driven deterioration of coral reefs, mangroves, and seagrass beds has directly upset the natural cycles that have sustained conventional economic activities. Due to habitat degradation, changed salinity levels, and rising sea temperatures aggravated by coastal pollution, seasonal fish migrations that were once predictable and vital to artisanal fishing societies are now more irregular (Savari et al., 2013; Raeisbahrami and Naderloo, 2023). As newer generations have less chance to interact with the maritime environment in culturally relevant ways, traditional ecological knowledge handed orally between generations and closely linked to local marine ecosystems is being lost.

The destruction of iconic habitats such as coral reefs and mangrove forests once considered not only as ecological treasures but also as potent cultural symbols of resilience and prosperity. They represent a real loss of collective identity among PG peoples (Mehraban and Esmaeili, 2018; Eagderi et al., 2019). Now accelerating because of compounded stressors including oil pollution, thermal discharges, and microplastics, coral reef deterioration directly undermines cultural activities like subsistence reef fishing, artisanal shellcrafting, and seasonal community celebrations linked to marine abundance.

Not only biologically but also culturally historical environmental catastrophes like the 1991 Kuwaiti oil fires have left a lasting mark. As recorded in satellite-based studies by Jalali et al. (2000), pollution-driven plant loss especially in coastal deserts and mangrove stands. It has exacerbated the degradation of natural heritage areas. Once entwined into the folklore, art, and oral histories of Gulf people, these places today confront physical oblivion under the weight of unrelenting industrialisation and environmental neglect. Recent research underlines how frequently cultural losses are ignored in policy reactions concentrating only on ecological restoration. But there is an increasing danger of cutting the deep-rooted cultural linkages between Gulf civilisations and their maritime environment if intentional measures to preserve the linked natural and cultural legacy of the PG are not made. Intangible cultural losses, such as the declining knowledge of traditional navigation routes, pearl diving songs, and coastal resource stewardship practices which are irreplaceable qualities of PG identity that no remedial effort can completely restore, as Kawiyani et al. (2024) and Ghaemi et al. (2024) underlined.

Protecting the cultural legacy of the PG therefore calls for comprehensive approaches going beyond pollution reduction. Active recording of traditional practices, community-led conservation initiatives, and acknowledgement of cultural landscapes as essential elements of maritime protection activities all call for active documentation. Neglecting to do so will not only weaken ecological resilience but also undermine the historical memory and group identity of the PG's coastal people.

Conservation initiatives and governance challenges

Figure 6 shows the conservation challenges in the PG.

Regional agreements and initiatives

Mainly driven by the formation of the Regional Organisation for the Protection of the Marine Environment (ROPME) and the Kuwait Action Plan (KAP), efforts to preserve the delicate marine ecosystems of the PG have a long history. These systems have tried to improve PG countries' cooperation on topics such pollution monitoring, oil spill response, and sustainable coastal management (Kawiyani et al., 2024). The timeline analysis and cluster synthesis, especially Cluster 5 shows that despite the presence of such

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cooperation agreements, the area nonetheless suffers chronic and increasing environmental deterioration.

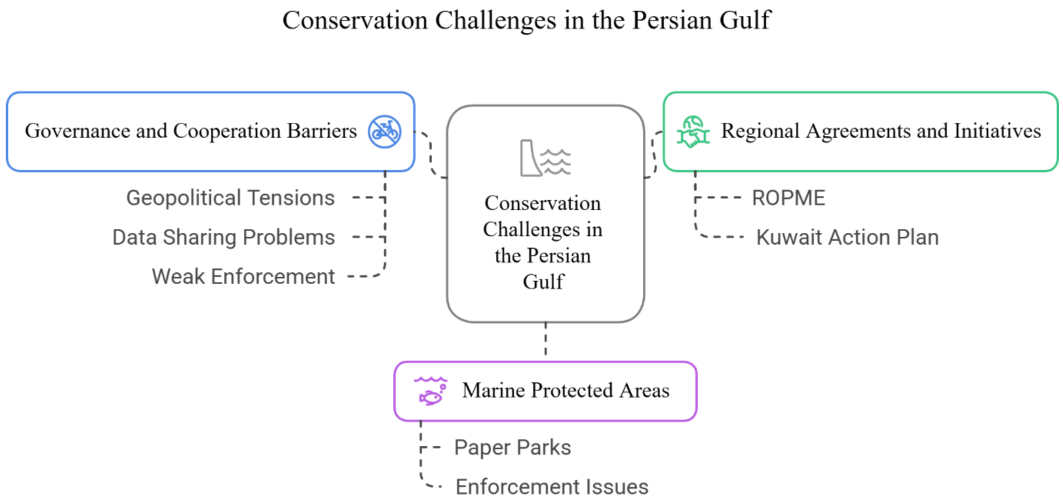

Figure 6. *The conservation challenges in the Persian Gulf*

Many of these projects' major flaws are their reactive character. Often, national conservation policies have been created in reaction to significant environmental catastrophes like oil spills rather than with proactive, ecosystem-based management techniques with chronic, cumulative pollution stressors in mind (Raeisbahrami and Naderloo, 2023). Although some nations have formalised oil spill contingency plans, Samimi-Namin and Hoeksema (2023) report that the real on-ground efficacy of these plans varies greatly due to a lack of emergency infrastructure, divided jurisdictional responsibilities, and low technical standards harmonisation throughout the PG.

Moreover, new environmental studies have highlighted important weaknesses in biodiversity hotspots still under inadequate protection or bad management. Oil pollution, heavy metals, desalination brine, and marine debris are compounding threats to important habitats including coral reefs, mangrove forests, and seagrass beds (Nasiri et al., 2023; Kawiyani et al., 2024; Ghaemi et al., 2024). These results underline the pressing need for a change from incident-based reactions to integrated, science-driven marine conservation systems. Fortunately, citizen science projects like beach clean-up programs assessed by Dobaradaran (2024) have shown significant promise to raise public environmental awareness and close monitoring gaps. Such projects, meanwhile, are still underused and more institutional backing is needed to expand these grassroots movements into official conservation plans. Though the groundwork for regional cooperation is there, significant governance obstacles such as divided political priorities, restricted cross-border environmental data sharing, and uneven enforcement can still impede the PG's capacity to attain significant, long-term marine conservation.

Marine protected areas (MPAs)

MPAs spread throughout the PG constitute a fundamental element of regional conservation activities. Among the most remarkable are Iran's MPA, the UAE's Marawah MPA, and Qatar's Al Shaheen MPA (Kawiyani et al., 2024). Analysis from Cluster 5 and results from subsequent research, however, show a troubling pattern: many MPAs operate

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more as "paper parks" than as efficient conservation areas, usually lacking enforcement, ecological representation, and functional management capacity (Samimi-Namin and Hoeksema, 2023).

Often located outside officially designated MPA borders or poorly safeguarded from nearby industrial operations, critical ecosystems under severe threat including coral reefs suffering from hydrocarbon contamination (Oladi and Shokri, 2021), mangrove forests undergoing sedimentation and pollution stress (Raeisbahrami and Naderloo, 2023), and sea turtle nesting sites exposed to habitat disturbance (Nasiri et al., 2023). Albano et al. (2016) and Naji et al. (2017) proved even more that intensive oil and gas production persists near MPAs, frequently without adequate environmental protections, hence compromising the core goals of these protected areas.

Enforcement capability is severely hampered even where MPAs exist on paper by insufficient surveillance technologies (e.g., satellite monitoring, drone-based patrolling), low budget, and bureaucratic fragmentation among environmental, fisheries, and energy authorities. Emerging and evolving threats as well including microplastic proliferation (Naji et al., 2018; Jahedi et al., 2025) and the infiltration of pharmaceutical pollutants like nonsteroidal anti-inflammatory drugs (Beitgader et al., 2025) in which also highlight the demand for dynamic and adaptive MPA management strategies.

The absence of transboundary cooperation among PG countries is another important concern. Though conservation projects are mostly nationally motivated, their impact is constrained since pollution and marine species movement patterns cross national borders. The timeline analysis reveals that, despite more than twenty years of awareness, a binding transboundary maritime spatial planning system has not appeared, therefore endangering vital natural corridors.

All things considered, the present administration and structure of MPAs in the PG do not meet their stated conservation objectives. Future plans ought to provide well-enforced, biologically consistent, and adaptively managed MPAs that include new pollution concerns and promote more robust regional collaboration top priority if they are to solve growing biodiversity losses and habitat degradation.

Governance and cooperation barriers

The extremely fragmented and politically sensitive governance scene is one of the main barriers to good marine conservation in the PG. Efforts to create a comprehensive and consistent framework for transboundary environmental management have been greatly hampered by geopolitical tensions especially between Iran and various Gulf Cooperation Council (GCC) nations (Kawiyani et al., 2024). Though the marine ecosystems of the PG cross political boundaries, national sovereignty concerns generally overshadow ecological continuity. Despite great awareness of transboundary ecological interdependence, Cluster 6 findings draws attention to the lack of a legally binding marine spatial planning system enabling Gulf states to jointly control shared resources (Raeisbahrami and Naderloo, 2023).

Lacking a regional maritime spatial planning system, conservation efforts have been haphazard, with projects scattered across national authority boundaries instead than guided by biological values. As a result, localised, country-specific programs without cross-border coordination frequently handle issues including oil pollution, heavy metal contamination, habitat destruction, and plastic trash accumulation. This strategy not only allows for duplication efforts, poor resource usage, and important conservation gaps but also fails to control ecosystem-wide risks.

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Another significant obstacle in governance is data sharing. Often hampered by national security issues and political sensitivities, cooperative environmental monitoring across the PG is erratic and very irregular (Samimi-Namin and Hoeksema, 2023). Consequently, vital data on ecological risk factors, species population dynamics, pollution trends, and habitat conditions stays segregated inside national agencies. The absence of open and easily available environmental databases compromises science-driven decision-making and hinders the early identification of regional environmental disasters (Pourkerman et al., 2017; Ghaemi et al., 2024). Recent research, for example, found hotspots of mercury and heavy metal pollution (Shirneshan et al., 2012; Keshavarzi et al., 2018; Hosseini et al., 2021), but these results have not yet been methodically included into a thorough Gulf-wide environmental risk assessment system.

Environmental rules are notoriously weakly enforced all around the region. Responses have usually been ad hoc and reactive, aimed at short-term cleanups rather than systematic prevention methods, even in situations where documented extensive pollution of sediments and marine biota exists such as at Asaluyeh Port and along the northern PG shoreline. Many times, regulatory systems have no significant fines for noncompliance, which offers no inducement for businesses to follow pollution control policies. Moreover, inadequate institutional capability for environmental monitoring combined with administrative fragmentation between environmental and industrial ministries greatly undermines enforcement efficacy.

Though appearing in certain locations, citizen involvement and community-based conservation projects are still lacking when compared to world best practices. Documented by Dobaradaran (2024), initiatives such citizen science monitoring and beach cleanups show that people participation can improve environmental awareness and produce useful data to augment official monitoring systems. Institutional backing for such projects, meanwhile, is scant; more general public involvement is still pushed aside in policy-making and enforcement activities.

The aim of sustainable marine conservation across the PG will stay elusive without improved regional cooperation mechanisms based on mutual trust, data transparency, and shared ecological goals. Urgently required are the development of clear, scientifically-based enforcement policies, the expansion of public-private conservation partnerships, and the inclusion of citizen involvement into national environmental plans. The only sensible way to guarantee the future health and resilience of the marine ecosystems of the PG is to build confidence and institutionalise collaboration beyond political disputes.

Research gaps and future directions

Figure 7 shows the overall research gaps and future directions in PG conservation.

Evaluations of cumulative impact

A huge study vacuum remains in evaluating the cumulative and synergistic effects of several co-occurring stressors even with the abundance of studies on particular pollution sources in the PG. Most current studies concentrate on isolated pollutants such as hydrocarbons from oil spills (Aagh et al., 2016), heavy metals like cadmium and mercury (Abdollahi et al., 2013; Hosseini et al., 2016; Mirza et al., 2019; Cheraghi and Almasieh, 2024), or microplastics (Naji et al., 2018). Though these dynamics are not well understood, as shown in Cluster 2 and Cluster 4, the overlapping presence of oil residues, heavy metals, PAHs, and plastic debris produces intricate chemical combinations that can synergistically magnify toxicological effects.

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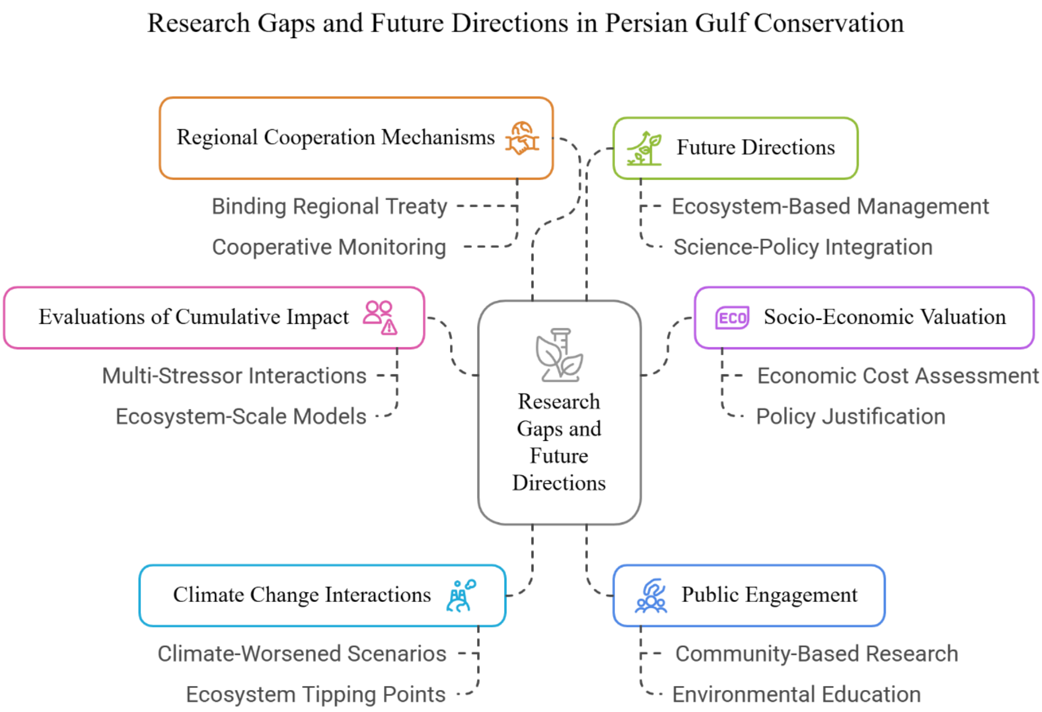

Figure 7. *The overall research gaps and future directions in Persian Gulf conservation*

Though studies have recorded the bioaccumulation of mercury in fish species (Hosseini et al., 2016) and evaluated heavy metal contamination in sediments across several coastal areas (Kazemi et al., 2012; Asl et al., 2022), few models consider how co-exposure to PAHs and metals might magnify sublethal stress effects on marine biota. Research on PAH contamination resulting from oil pollution (Chaharlang et al., 2012; Aagh et al., 2016) similarly neglects simultaneous pressures from sediment-bound heavy metals or plastic-related toxins, hence underestimating overall ecosystem risk.

Future studies should give priority to creating whole, ecosystem-scale cumulative impact models able to mimic multi-stressor interactions under real-world situations. Such models should include hydrodynamic dispersion of contaminants, species-specific sensitivity thresholds, trophic bioaccumulation pathways, and sediment quality among other factors. Embracing cumulative assessments would help academics and politicians to better find ecosystem tipping points and establish pollution limits that reflect ecological reality instead of simplified, single-contaminant criteria.

Moreover, spatially explicit risk mapping combining oil spill diffusion models (Faghihifard and Badri, 2016), heavy metal distribution analyses (Delshab et al., 2017), and plastic debris accumulation patterns (Gholizadeh et al., 2024) which can be useful tools to guide marine spatial planning and give conservation actions top priority in very affected areas of the PG.

Socio-economic valuation

Another important area of expertise is the conversion of ecological deterioration into socio-economic language that could affect resource allocation and policy choices. Although significant work has been done to assess environmental contamination using ecological risk indices (Dehghan Madiseh et al., 2009; Davari et al., 2010), relatively few

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studies have actually calculated the direct and indirect economic costs linked to ecosystem damage. Cluster 5 points out that the absence of economic value undermines the political need for strong conservation actions.

For example, seafood contamination by bioaccumulated metals including cadmium, lead, and mercury (Chaharlang et al., 2012; Hosseini et al., 2016; Cunningham et al., 2019) poses serious threats to food security in Gulf countries largely reliant on local fisheries. There is, however, a lack of empirical research estimating the economic cost of dwindling fish stocks, higher healthcare responsibilities from tainted seafood intake, or the decline of market confidence in PG fishery exports.

Likewise, deterioration of coastal ecosystems like mangroves and coral reefs has negative consequences for industries like coastal protection and tourism; however, only a small number of studies have tried to measure these losses in financial terms (Mehraban and Esmaeili, 2018; Sharifinia et al., 2022). Urgently required are thorough socio-economic studies that using ecosystem service value models like cost-benefit analyses, replacement cost techniques, or willingness-to-pay surveys in order to reveal the actual extent of economic danger environmental deterioration causes.

Including socio-economic valuation into environmental evaluations could help legislators to justify more strongly investments in pollution reduction, habitat restoration initiatives, and MPA extensions. Simultaneously, scenario modelling linking pollutant paths with expected economic losses (Tavakolian et al., 2024) could provide PG states a strong financial incentive to give ecosystem-based management and pollution control techniques top priority.

To match conservation efforts with national development goals, therefore, it is essential to close the gap between environmental science and economic value. This guarantees that safeguarding the PG's marine ecosystems is seen not only as an ecological need but also as a socio-economic need for regional stability and prosperity.

Climate change interactions

One major flaw in the pollution studies of the PG is the neglect of how pollution stressors interact with climate change causes. Though empirical research on these compound impacts is limited, rising sea surface temperatures, changing salinity, and ocean acidification are predicted to magnify the harmful effects of pollutants including hydrocarbons, heavy metals, and plastics (Abdollahi et al., 2013; Saadatmand et al., 2022).

Pollution hotspots in the PG frequently coincide with areas quite susceptible to climate stress, such coral reefs and shallow seagrass beds, as shown by the clustering results in Cluster 3 and Cluster 6. There are few longitudinal studies evaluating how pollution aggravates climate-driven deterioration in spite of this overlap. Coral reefs already vulnerable to oil pollution, PAHs, and thermal discharges have increased bleaching hazards under rising ocean temperatures, for example (Delshab et al., 2017). Still missing, though, is thorough monitoring connecting pollutant exposure to thermal stress reactions throughout several reef sites.

Similarly, as lower pH raises metal desorption from sediments, sediment-bound metals like mercury and cadmium may become more accessible under acidified circumstances (Parvaneh, 1979; Cheraghi and Almasieh, 2024). This change not only increases environmental toxicity but also raises bioaccumulation concerns in commercial species like oysters (Shirneshan et al., 2012), hence increasing food safety problems.

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Pollution risk models have to be quickly included by future studies including climate factors including temperature changes, salinity stress, and acidification trends. Predicting ecosystem tipping points under realistic, climate-worsened pollution scenarios calls for multidisciplinary research integrating oceanic surveillance, toxicological, and climate modelling. Gulf countries can only create robust adaptation plans that safeguard human well-being under evolving environmental conditions by knowing these interactions.

Public engagement

Equally important is the absence of efficient public involvement in tackling marine pollution issues. Though scientific research has shown the health hazards of tainted seafood (Raissy, 2016; Cunningham et al., 2019) and polluted sediments affecting coastal communities (Abdollahi et al., 2013; Delshab et al., 2017), public awareness campaigns and participatory projects stay few and scattered.

Citizen-driven initiatives such coastline cleanup projects (Dobaradaran, 2024) are irregular and usually lack official incorporation into national conservation plans, as indicated in Cluster 5. Rarely included in monitoring initiatives or decision-making processes, local fishers of both pollution victims and key stakeholders can create a gap between scientific results and grassroots activity.

Furthermore, low environmental knowledge among coastal communities limits behavioural change, hence aggravating land-based pollution from sources including industrial runoff, untreated wastewater, and plastics. Sustainable effect depends on strengthening environmental stewardship via community-based participatory research (CBPR), citizen science initiatives, and school-based marine conservation education.

Programs that actively include communities in pollution reporting, biodiversity studies, and water quality monitoring can foster public ownership of conservation activities. This grassroots mobilisation in turn can push politicians to implement more stringent environmental rules and raise industry compliance rates.

Empowering local communities especially marginalised fishers and indigenous coastal groups in the setting of the PG's socio-political scene can be a strong motivator for bottom-up environmental governance. Future studies should investigate creative communication techniques, participatory government systems, and culturally appropriate environmental education projects to close the ongoing divide between scientific understanding and public involvement.

Regional cooperation mechanisms

Though more and more localised research shows pollution levels all around the PG (Dehghan Madiseh et al., 2009; Davari et al., 2010; Mirza et al., 2019), the area still lacks a unified, binding transboundary governance system able to handle major environmental hazards. Many environmental problems especially oil spills, heavy metal dissemination, and marine debris accumulation in which to transcend national lines, as emphasised by the clustering results. Current initiatives, such as the Kuwait Action Plan (KAP), on the other hand, are mostly voluntary and have little enforcement power (Saadatmand et al., 2022).

Pollution incidents like significant oil spills or the drift of microplastics (as seen in Cluster 2 and Cluster 5) reveal that without coordinated and enforceable regional action, mitigation remains fragmented and ineffectual. National-only policies insufficiently safeguard even scientifically important areas like Nayband Bay or Khouran Straits, therefore neglecting ecological interconnectedness across borders (Asl et al., 2022). It is

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now urgently required that Gulf countries create a legally binding, science-driven regional environmental treaty supported by robust compliance systems, cooperative monitoring initiatives, shared pollution databases, and coordinated restoration efforts.

Regional cooperation should also include heavy metals, plastics, thermal effluents, and climate resilience in addition to oil pollution management. Success will rely not just on political will but also on enhancing technical capabilities via regional centres of excellence, cross-border scientific partnerships, and consistent cooperative environmental reporting. Without such group governance creative ideas, future conservation and pollution control in the PG would be erratic, underfunded, and biologically inadequate.

Future directions

Looking ahead, conservation and management of the PG's vulnerable ecosystems have to completely adopt ecosystem-based management (EBM) ideas, therefore addressing the marine environment as an interconnected whole instead of a series of separate locations. As indicated across the six clusters in the Results section, EBM strategies have to take into account the cumulative effects of oil pollution, heavy metals, plastics, climatic stressors, and habitat fragmentation.

Strengthening science-policy integration will be crucial since it will guarantee that innovative ecological and toxicological studies are properly converted into legislative action. Policy choices have to be evidence-based, open, and guided by cumulative ecosystem health evaluations rather than only piecemeal pollutant monitoring. Moreover, especially in a politically sensitive area like the PG, regional trust-building will be very crucial. Shared environmental objectives such as fisheries sustainability, coastal resilience, and food security, which can provide entry points for developing cooperative connections even among more general geopolitical difficulties.

Empowerment of local communities will also be vital. Coastal communities should be active participants in environmental governance as well as beneficiaries, not only. Expanding participatory monitoring initiatives, encouraging indigenous knowledge systems, and integrating environmental education into coastal communities would help to foster a culture of stewardship absolutely necessary for long-term conservation success. Research agendas have to give cumulative impact modelling that combines several stressors, economic assessment of ecosystem services lost to degradation, and the creation of long-term, climate-resilient monitoring programs first priority. This also entails looking at nature-based restoration alternatives including green coastal infrastructure, coral reef gardening, and mangrove rehabilitation.

Ultimately, the environmental future of the PG can only be protected by means of cooperative, multidisciplinary, inclusive approaches grounded on robust science, democratic governance, and sincere regional cooperation. The urgency is obvious: delay or fragmented action runs the risk of breaching ecological tipping points beyond recovery, so endangering not just biodiversity but also human well-being and regional stability for decades to come.

Conclusion

A sad example of a semi-enclosed marine ecosystem under severe Anthropocene stress is the PG. Chronic oil pollution, heavy metal and industrial discharges, desalination brine and thermal effects, habitat destruction, and rising plastic trash have all combined to

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produce a cumulative environmental calamity. Now more apparent across the PG's fragile coastal and marine ecosystems are biodiversity losses, public health concerns, food security challenges, economic weaknesses, and cultural losses. Although national conservation initiatives and regional accords exist, their efficacy is compromised by fragmented government, poor enforcement, and little public involvement. Though designated, MPA frequently lack sufficient administration; the lack of binding transboundary collaboration creates important gaps in shared environmental care. Furthermore, pollution research has mostly ignored cumulative effects and interactions with climate change, hence impeding adaptive and comprehensive control approaches even further.

The sustainability of the PG going ahead depends on a paradigm change towards ecosystem-based management centred in science-policy integration, cumulative risk assessments, socio-economic valuing of ecosystem services, and climate-resilient conservation planning. Essential actions are to strengthen regional trust, enable community involvement, and create legally enforceable cooperative systems. In the end, protecting the PG is a cultural and humanitarian need as much as it is an ecological or economic one. Preserving the unique biodiversity of this essential marine area, maintaining the ecological stability of one of the most geopolitically important regions, and ensuring the well-being of millions who rely on its resources all depend on protecting it. To guarantee the Gulf's resilience for future generations, audacious, coordinated, and forward-looking initiatives are absolutely required.

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