

Integrated Environmental Risk Assessment in Construction Management of Offshore Projects: A Framework for Sustainable Marine Development

Arman Haddadi Fishani[1], Eghbal Shakeri[2*]

[1] M.Sc., Department of Construction Management, Amirkabir University of Technology, Tehran, Iran
[2] Associate Professor, Department of Construction Management, Amirkabir University of Technology, Tehran, Iran

*** Corresponding author email address**: eshakeri@aut.ac.ir

Received: 2026-02-01 **Revised:** 2026-06-07 **Accepted:** 2026-06-15 **Initial Publish:** 2026-10-30 **Final Publish:** 2027-03-01

Abstract

The objective of this study was to develop and validate an integrated environmental risk assessment framework for offshore construction project management that supports sustainable marine development through the systematic identification, evaluation, prioritization, and management of environmental risks. This applied mixed-methods study employed a descriptive–analytical design to construct an integrated environmental risk assessment framework for offshore construction projects. The study population consisted of 30 experts from Tehran with professional experience in environmental management, offshore engineering, HSE management, project management, marine engineering, and sustainability assessment. Participants were selected through purposive sampling based on their expertise in offshore projects and environmental risk management. Data collection was conducted through three complementary stages, including a comprehensive review of scientific literature and technical documents, semi-structured expert interviews, and a structured questionnaire developed from the qualitative findings. The questionnaire assessed environmental risks according to probability of occurrence, severity of impact, detectability, controllability, spatial extent, reversibility of damage, and sustainability implications. Qualitative data were analyzed using thematic analysis to identify key environmental risk dimensions and framework components, while quantitative data were analyzed using descriptive statistics and integrated risk prioritization procedures. The final framework was developed through the integration of qualitative and quantitative findings. The results demonstrated significant relationships among the principal components of the proposed framework. Environmental risk identification significantly predicted risk assessment quality ($\beta = 0.79$, $p < 0.001$), while risk assessment quality significantly influenced risk prioritization effectiveness ($\beta = 0.84$, $p < 0.001$). Risk prioritization effectiveness was positively associated with environmental management performance ($\beta = 0.81$, $p < 0.001$), and environmental management performance exhibited the strongest effect on sustainable marine development outcomes ($\beta = 0.88$, $p < 0.001$). Environmental monitoring also significantly contributed to environmental management performance ($\beta = 0.76$, $p < 0.001$), whereas regulatory compliance showed a significant positive relationship with sustainable marine development ($\beta = 0.72$, $p < 0.001$). The integrated prioritization analysis further revealed that major oil spills, toxic chemical discharges, marine habitat destruction, and pipeline leakages represented the highest-priority environmental risks requiring immediate management attention.

Keywords: *Environmental Risk Assessment; Offshore Construction Projects; Sustainable Marine Development; Environmental Management; Marine Ecosystems*

How to cite this article:
Haddadi Fishani, A., & Shakeri, E. (2027). Integrated Environmental Risk Assessment in Construction Management of Offshore Projects: A Framework for Sustainable Marine Development. Management Strategies and Engineering Sciences, 9(3), 1-13.

1. Introduction

The rapid expansion of offshore development projects has transformed marine environments into strategic zones for energy production, transportation infrastructure, resource extraction, carbon storage, and emerging blue economy activities. Offshore construction projects, including offshore oil and gas platforms, subsea pipelines, offshore wind farms,

© 2027 The author(s). Published By: The Research Department of Economics and Management of Tomorrow's Innovators. This is an open access article under the terms of the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License.

marine transportation facilities, and offshore carbon capture and storage systems, have become increasingly important components of national and international development strategies. While these projects contribute substantially to economic growth, energy security, and technological advancement, they simultaneously create significant environmental challenges that require comprehensive assessment and management. Marine ecosystems are among the most sensitive and interconnected ecological systems on Earth, and disturbances generated by offshore construction activities can produce long-lasting impacts on biodiversity, habitat integrity, water quality, ecosystem services, and coastal sustainability. Consequently, environmental risk management has emerged as a central concern in the planning, construction, operation, and decommissioning of offshore infrastructure projects [1-3].

The increasing complexity of marine development has highlighted the limitations of traditional environmental assessment approaches. Conventional risk management models often focus on isolated hazards, individual project components, or regulatory compliance requirements without adequately addressing cumulative ecological impacts, systemic uncertainties, and long-term sustainability implications. Marine ecosystems function through highly interconnected biological, chemical, and physical processes, meaning that environmental disturbances in one area may generate cascading effects across broader ecological networks. Research on cumulative ecosystem impacts has demonstrated that offshore developments can influence marine biodiversity, benthic habitats, species migration routes, sediment dynamics, and food web interactions in ways that extend beyond the immediate footprint of a project [4-6]. As a result, environmental risk assessment frameworks increasingly require integrated approaches capable of evaluating both direct and indirect impacts while incorporating ecological resilience and sustainability considerations into decision-making processes.

Recent developments in offshore renewable energy have further intensified discussions regarding environmental risk management in marine environments. Offshore wind energy projects have experienced substantial growth worldwide as governments pursue decarbonization goals and renewable energy transitions. Although offshore wind developments contribute positively to climate mitigation efforts, they also introduce new environmental concerns related to habitat modification, underwater noise generation, seabed disturbance, bird migration disruption, fisheries interactions, and cumulative ecosystem pressures. Studies examining offshore wind development have emphasized the necessity of ecological risk-based licensing systems, biodiversity-sensitive planning mechanisms, and nature-inclusive infrastructure design to minimize environmental consequences while maximizing socioeconomic benefits [7-9]. Similarly, investigations into renewable energy governance and marine infrastructure regulation have highlighted the importance of integrating environmental risk assessment into broader frameworks of sustainable ocean governance and marine spatial planning [3, 10, 11]. These findings suggest that environmental sustainability cannot be achieved solely through technological innovation but requires comprehensive management systems capable of identifying, evaluating, and mitigating environmental risks throughout the project life cycle.

In parallel with renewable energy expansion, offshore oil and gas activities continue to play a major role in global energy systems, particularly in developing and energy-dependent economies. Offshore drilling operations, subsea production systems, marine transportation activities, and hydrocarbon infrastructure remain associated with significant environmental risks, including oil spills, chemical discharges, seabed contamination, habitat destruction, greenhouse gas emissions, and accidental releases of hazardous substances. Regulatory scholars and marine risk experts have argued that the increasing complexity of offshore energy systems requires more robust environmental governance mechanisms and more sophisticated risk regulation frameworks capable of addressing technological uncertainties and environmental vulnerabilities simultaneously [12-14]. Public participation and stakeholder engagement have also emerged as critical components of environmental management strategies because local communities, fisheries stakeholders, environmental organizations, and governmental institutions frequently possess valuable knowledge regarding marine environmental conditions and sustainability priorities. Research conducted in offshore oil and gas development regions has demonstrated that incorporating public consultation outcomes into environmental management planning can significantly improve the effectiveness and legitimacy of environmental decision-making processes [15-17].

Another emerging dimension of offshore environmental management relates to the development of marine carbon capture and storage infrastructure. Offshore geological carbon dioxide storage has gained increasing attention as a potential strategy for reducing atmospheric greenhouse gas

concentrations and supporting climate change mitigation objectives. However, the deployment of offshore carbon storage systems introduces additional environmental and operational risks related to geological integrity, leakage potential, ecosystem disturbance, monitoring requirements, and long-term environmental stewardship. Recent reviews have emphasized that successful implementation of offshore carbon storage projects depends on comprehensive risk assessment frameworks capable of addressing environmental uncertainties, technical challenges, and governance requirements throughout the project life cycle [18, 19]. The emergence of such projects further illustrates the growing need for integrated environmental risk assessment methodologies that can accommodate diverse offshore infrastructure types while maintaining a consistent focus on environmental protection and sustainable development objectives.

Environmental sustainability in marine environments is also closely linked to broader principles of ocean governance and blue economy development. The blue economy paradigm promotes the sustainable utilization of marine resources for economic growth, social development, and environmental conservation. However, achieving these objectives requires balancing competing interests among energy development, fisheries, transportation, conservation, tourism, and coastal communities. Studies examining sustainable ocean governance have consistently emphasized that environmental risk management constitutes a foundational requirement for ensuring that marine development activities remain compatible with long-term ecological integrity and socioeconomic resilience [1-3]. Furthermore, emerging research on marine natural capital assessment indicates that significant gaps continue to exist in understanding the cumulative environmental consequences of offshore activities, making comprehensive risk assessment frameworks essential tools for evidence-based decision making [6, 20, 21].

The environmental consequences of offshore construction activities extend beyond ecological concerns and frequently influence social, economic, and governance dimensions of sustainability. Marine pollution incidents, habitat degradation, resource conflicts, and environmental accidents can generate substantial costs for fisheries, tourism industries, coastal communities, and governmental agencies. In addition, the increasing concentration of offshore infrastructure within limited marine spaces has intensified competition among stakeholders and increased the likelihood of environmental and socioeconomic conflicts. Research addressing contested marine spaces and emerging blue economy developments demonstrates that integrated environmental management approaches are necessary for balancing development objectives with ecosystem conservation requirements [16, 17, 22]. Nature-inclusive design approaches, biodiversity-sensitive infrastructure planning, and ecosystem-based management strategies have therefore gained prominence as mechanisms for reducing environmental risks while supporting coexistence among multiple marine users [8, 11, 23].

Risk assessment methodologies themselves have evolved considerably during the past decade. Traditional qualitative and deterministic approaches are increasingly being supplemented by probabilistic models, machine learning applications, multi-criteria decision-making techniques, and integrated sustainability assessment frameworks. Studies focusing on offshore infrastructure risk assessment have demonstrated the value of incorporating probability analysis, uncertainty evaluation, stakeholder perspectives, and sustainability indicators into environmental decision-making processes [7, 24, 25]. Similarly, advances in disaster prevention research have shown that data-driven analytical approaches can improve the identification of emerging risks and enhance proactive environmental management capabilities within marine construction projects [12, 14, 26]. These developments support the argument that environmental risk assessment should be viewed not merely as a compliance exercise but as a strategic management process that informs planning, monitoring, mitigation, and adaptive governance activities.

A further challenge concerns the long-term environmental implications of offshore infrastructure throughout its entire life cycle, including decommissioning and post-operational management. Research examining offshore oil and gas decommissioning options, subsea structure management, and rigs-to-reefs programs demonstrates that environmental impacts continue long after construction and operational phases have ended. Consequently, sustainability-oriented environmental assessment frameworks must incorporate life-cycle perspectives that account for construction impacts, operational risks, cumulative ecosystem effects, and decommissioning outcomes [5, 27, 28]. This life-cycle perspective is particularly important because decisions made during construction management often determine the environmental performance of offshore infrastructure for decades into the future.

Despite substantial advances in marine environmental science, offshore engineering, and sustainability governance, significant gaps remain in the integration of environmental risk assessment within offshore construction management practices. Many existing studies focus on specific environmental hazards, individual industries, or isolated regulatory frameworks rather than developing comprehensive models capable of linking environmental risk identification, assessment, prioritization, monitoring, and management within a unified decision-making structure. Furthermore, growing environmental challenges, including marine pollution, biodiversity loss, climate change, ecosystem degradation, and resource conflicts, underscore the need for integrated frameworks that align project management processes with sustainable marine development objectives [21, 29, 30]. Addressing these challenges requires a holistic approach that incorporates ecological, technical, managerial, regulatory, and sustainability dimensions into a coherent environmental risk management system.

Therefore, the aim of this study was to develop and validate an integrated environmental risk assessment framework for offshore construction project management that supports sustainable marine development through systematic identification, evaluation, prioritization, and management of environmental risks.

2. Methodology

The present study was designed as an applied, descriptive–analytical, and mixed-methods study with the purpose of developing an integrated framework for environmental risk assessment in the construction management of offshore projects. The study adopted a problem-oriented approach because environmental risks in offshore construction projects are multidimensional and cannot be evaluated adequately through a single technical, managerial, or ecological perspective. Accordingly, the research process combined qualitative identification of environmental risk factors with quantitative assessment and prioritization of those risks. The qualitative phase was used to identify the main sources of environmental risk, the relevant assessment indicators, and the possible environmental consequences associated with offshore construction activities. The quantitative phase was then used to evaluate the relative importance, probability, severity, detectability, and management priority of the identified risks in order to construct an integrated assessment framework applicable to sustainable marine development. The statistical population consisted of specialists and professionals working in Tehran who had direct academic, managerial, consulting, or executive experience in offshore construction projects, environmental management, HSE management, marine engineering, project risk management, oil and gas infrastructure, or sustainable development planning. A total of 30 experts from Tehran participated in the study. Participants were selected through purposive sampling because the research required expert judgment rather than general public opinion. The inclusion criteria were having at least five years of relevant professional or academic experience, familiarity with environmental aspects of offshore projects, and willingness to participate in the research process. The final group included environmental experts, HSE managers, offshore project managers, construction management specialists, marine engineers, risk assessment consultants, and university faculty members whose expertise was related to environmental risk, project management, or marine sustainability. Participation was voluntary, and all participants were informed about the purpose of the study, the confidentiality of their responses, and the academic use of the collected data.

Data were collected using a combination of documentary review, semi-structured expert interviews, and a structured expert questionnaire. In the first stage, relevant scientific literature, technical reports, offshore construction guidelines, environmental management documents, HSE standards, and project risk management frameworks were reviewed in order to extract an initial list of environmental risk sources and assessment indicators. This review focused on the environmental dimensions of offshore construction activities, including seabed disturbance, marine pollution, waste generation, accidental spills, underwater noise, emissions from construction equipment and vessels, disruption of marine habitats, biodiversity loss, sediment dispersion, coastal ecosystem degradation, and cumulative environmental impacts. The documentary review provided the preliminary conceptual basis for the development of the interview guide and the initial risk assessment framework. In the second stage, semi-structured interviews were conducted with selected experts to refine the extracted indicators and identify context-specific risks relevant to offshore construction management. The interview questions addressed the main environmental hazards in offshore construction projects, the managerial factors that intensify or reduce these risks, the adequacy of existing environmental control measures, and the indicators that should be included

in an integrated environmental risk assessment framework. The interviews allowed participants to explain their professional experiences and to identify risks that may not be fully reflected in formal documents or conventional risk assessment models. The interview guide was reviewed by three academic and professional specialists before use to ensure content relevance, clarity, and alignment with the objectives of the study.

In the quantitative stage, a structured questionnaire was developed based on the findings of the documentary review and expert interviews. The questionnaire consisted of items related to environmental risk sources, environmental consequences, managerial control capacity, and sustainable development implications of offshore construction projects. The experts evaluated each identified risk according to several criteria, including probability of occurrence, severity of environmental impact, detectability, controllability, spatial extent of impact, reversibility of damage, and relevance to sustainable marine development. The questionnaire used a five-point Likert scale to capture expert judgments in a standardized manner. Higher scores indicated greater risk significance, greater environmental severity, lower controllability, or stronger priority for managerial intervention, depending on the specific criterion. The content validity of the questionnaire was assessed by a panel of specialists in environmental management, offshore engineering, and project risk assessment. Their comments were used to revise ambiguous items, remove overlapping indicators, and improve the conceptual clarity of the instrument. The reliability of the questionnaire was examined using internal consistency analysis, and the instrument was considered acceptable after confirming that the reliability coefficient was within an appropriate range for expert-based research. The final questionnaire was distributed among the 30 Tehran-based experts, and the completed responses formed the basis for the quantitative prioritization of environmental risks.

Data analysis was conducted in two complementary phases. In the qualitative phase, the data obtained from documentary review and semi-structured interviews were analyzed through thematic analysis. The interview texts and extracted documentary evidence were reviewed repeatedly in order to identify meaningful units related to environmental risk sources, risk consequences, control mechanisms, and sustainability requirements. Similar codes were grouped into broader categories, and these categories were organized into the main dimensions of the proposed framework. This process led to the classification of environmental risks into several integrated domains, including physical and ecological risks, pollution-related risks, construction and operational risks, managerial and regulatory risks, emergency and accident-related risks, and sustainability-oriented risks. The qualitative analysis helped clarify the relationships among risk sources, environmental consequences, and management responses. It also ensured that the final framework was not limited to technical risk indicators but also included managerial, institutional, and sustainability-related dimensions. To strengthen the credibility of the qualitative findings, expert feedback was used during the refinement of categories and indicators, and only the risk factors that were conceptually relevant and repeatedly emphasized by experts were retained for the quantitative phase.

In the quantitative phase, the questionnaire data were analyzed using descriptive and inferential statistical procedures as well as environmental risk prioritization logic. Descriptive statistics, including mean, standard deviation, frequency, and relative importance scores, were used to summarize expert judgments regarding each risk indicator. The significance and priority of risks were then determined by combining expert scores related to probability, severity, detectability, controllability, and environmental sustainability impact. The integrated risk score was calculated in a way that reflected both the likelihood of risk occurrence and the seriousness of its environmental consequences. Risks with higher probability, higher severity, lower detectability, lower controllability, broader spatial impact, and lower reversibility were assigned higher priority in the final framework. This approach made it possible to distinguish between ordinary construction-related environmental risks and critical risks that require immediate managerial intervention in offshore projects. The quantitative results were also used to rank the identified risks and determine which risk domains had the greatest implications for sustainable marine development.

The final stage of analysis involved integrating the qualitative and quantitative findings into a coherent environmental risk assessment framework for offshore construction management. The qualitative findings provided the conceptual structure of the framework, while the quantitative results determined the relative priority and management urgency of each risk factor. The integrated framework was developed to show how environmental risk identification, risk assessment, risk prioritization, control planning, monitoring, and sustainability feedback can be connected within the construction management process of

offshore projects. The framework emphasizes that environmental risk assessment should not be treated as a separate technical activity conducted after project design, but as a continuous management process embedded in planning, procurement, construction, monitoring, and corrective action. Therefore, the proposed model links environmental risk assessment with sustainable marine development by incorporating ecological protection, pollution prevention, regulatory compliance, stakeholder accountability, adaptive monitoring, and continuous improvement into the decision-making process of offshore construction projects.

3. Findings and Results

A total of 30 experts participated in the study. Among them, 21 participants (70.0%) were male and 9 participants (30.0%) were female. Regarding educational attainment, 8 participants (26.7%) held a master's degree, 19 participants (63.3%) held a doctoral degree, and 3 participants (10.0%) had postdoctoral qualifications. In terms of professional specialization, 7 experts (23.3%) were environmental management specialists, 6 (20.0%) were offshore engineering professionals, 5 (16.7%) were HSE managers, 4 (13.3%) were project management specialists, 4 (13.3%) were marine engineering experts, and 4 (13.3%) were sustainability and risk assessment consultants. The average professional experience of the participants was 14.8 years (SD = 4.9), ranging from 6 to 27 years. This composition ensured that the study benefited from extensive multidisciplinary expertise and provided a comprehensive perspective on environmental risks associated with offshore construction projects.

Table 1. Descriptive Statistics of the Main Environmental Risk Dimensions in Offshore Construction Projects

Environmental Risk Dimension	Mean	Standard Deviation	Relative Importance (%)	Rank
Marine Pollution Risks	4.68	0.39	93.6	1
Biodiversity and Habitat Degradation Risks	4.53	0.44	90.6	2
Emergency and Accidental Event Risks	4.41	0.48	88.2	3
Waste Generation and Disposal Risks	4.29	0.52	85.8	4
Regulatory and Environmental Compliance Risks	4.17	0.55	83.4	5
Construction Equipment Emission Risks	4.08	0.61	81.6	6
Sediment Dispersion and Seabed Disturbance Risks	3.96	0.63	79.2	7
Underwater Noise and Vibration Risks	3.82	0.66	76.4	8

The results presented in Table 1 indicate that marine pollution risks were perceived as the most significant environmental challenge in offshore construction projects, obtaining the highest mean score (M = 4.68). This finding suggests that experts considered oil spills, chemical leakage, fuel discharge, and contamination of marine waters as the most critical threats to sustainable marine development. Biodiversity and habitat degradation risks ranked second (M = 4.53), highlighting the importance of protecting marine ecosystems, coral habitats, spawning grounds, and aquatic species during construction activities. Emergency and accidental event risks achieved the third highest score (M = 4.41), indicating the substantial concern associated with unexpected incidents such as platform failures, pipeline ruptures, and hazardous material releases. In contrast, underwater noise and vibration risks received the lowest mean score among the identified dimensions, although the average remained relatively high (M = 3.82), demonstrating that experts still regarded this category as environmentally significant. Overall, all dimensions scored above the midpoint of the scale, confirming the multidimensional nature of environmental risks in offshore projects and emphasizing the need for an integrated assessment framework capable of addressing ecological, technical, managerial, and regulatory challenges simultaneously.

Table 2. Integrated Environmental Risk Prioritization Based on Probability, Severity, Detectability, and Sustainability Impact

Risk Factor	Probability	Severity	Detectability	Sustainability Impact	Integrated Risk Score	Priority Level
Major Oil Spill Events	4.70	4.93	4.65	4.95	4.81	Very High
Toxic Chemical Discharge	4.52	4.88	4.49	4.84	4.68	Very High

Marine Habitat Destruction	4.39	4.81	4.35	4.91	4.62	Very High
Pipeline Leakage	4.44	4.67	4.31	4.58	4.50	Very High
Improper Waste Disposal	4.18	4.36	4.07	4.32	4.23	High
Excessive Sediment Dispersion	4.01	4.14	3.98	4.21	4.09	High
Air Emissions from Construction Vessels	3.96	4.08	3.84	4.03	3.98	Moderate
Underwater Noise Pollution	3.84	3.92	3.75	3.89	3.85	Moderate

The integrated prioritization analysis revealed substantial differences among specific environmental risk factors. Major oil spill events achieved the highest integrated risk score (4.81), reflecting their combination of severe environmental consequences, extensive spatial impacts, long-term ecological recovery requirements, and significant implications for sustainable marine development. Toxic chemical discharge and marine habitat destruction also demonstrated extremely high risk levels, indicating that environmental management strategies should prioritize preventive measures targeting these areas. Pipeline leakage ranked fourth, emphasizing the importance of monitoring infrastructure integrity throughout the construction phase. Risks related to waste disposal and sediment dispersion were classified as high-priority issues, suggesting that improved operational controls and environmental monitoring systems are required to minimize cumulative ecosystem impacts. Although air emissions and underwater noise pollution received comparatively lower scores, their classification as moderate risks indicates that they remain important contributors to environmental degradation and should not be overlooked during project planning and implementation. The overall pattern demonstrates that experts attributed the greatest significance to risks capable of generating irreversible ecological damage and long-term sustainability consequences rather than risks associated only with short-term operational disturbances.

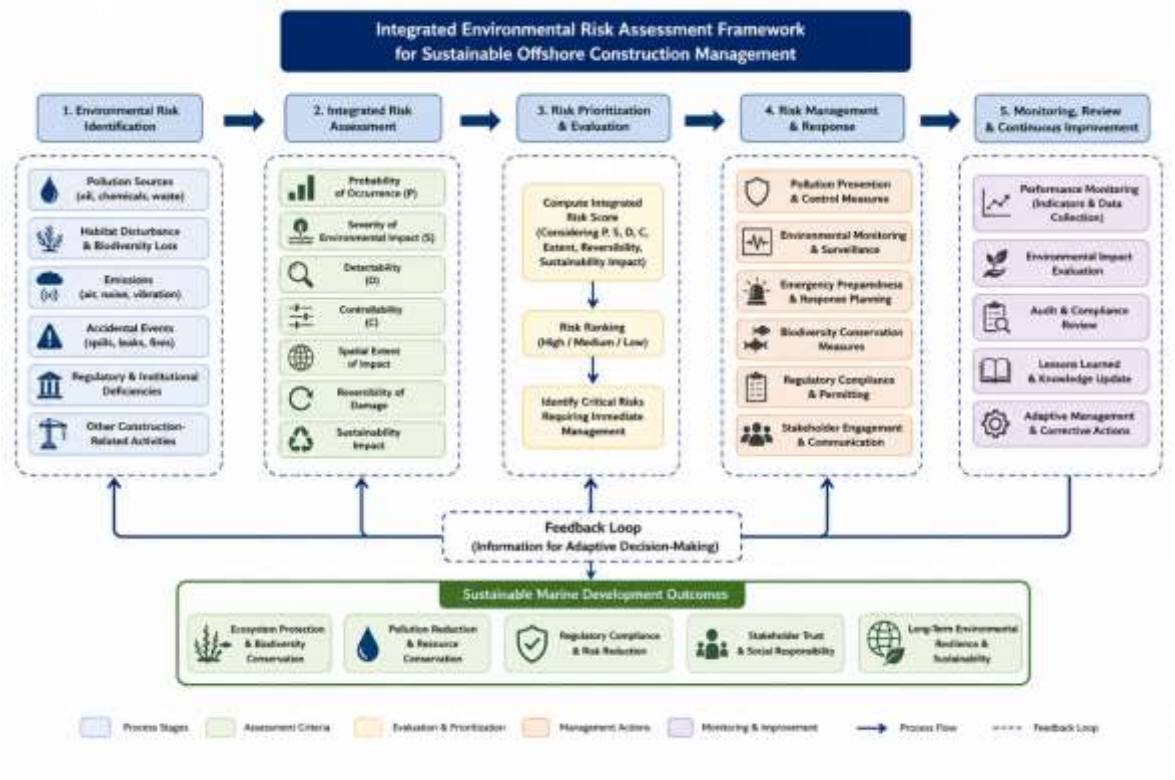


Figure 1. Integrated Environmental Risk Assessment Framework for Sustainable Offshore Construction Management

The conceptual framework presented in Figure 1 illustrates the dynamic relationship between environmental risk sources, assessment mechanisms, management interventions, and sustainable development outcomes. The model begins with environmental risk identification, including pollution sources, habitat disturbances, waste generation, emissions, accidental events, and regulatory deficiencies. These risks are subsequently evaluated through an integrated assessment process incorporating probability, severity, detectability, controllability, and sustainability

impact criteria. Based on the assessment results, risks are prioritized and linked to specific management responses such as environmental monitoring, emergency preparedness planning, pollution prevention programs, biodiversity conservation measures, regulatory compliance mechanisms, stakeholder engagement initiatives, and continuous improvement strategies. The framework further demonstrates the existence of a feedback loop in which monitoring results inform future decision-making and contribute to adaptive environmental management. This structure reflects the principle that environmental risk assessment should function as a continuous and proactive management process rather than a one-time evaluation activity. The figure therefore provides a comprehensive representation of how environmental protection objectives can be systematically integrated into offshore construction management to support sustainable marine development.

Table 3. Structural Relationships Among the Main Components of the Proposed Framework

Relationship Path	Standardized Coefficient (β)	t-value	Significance Level
Environmental Risk Identification → Risk Assessment Quality	0.79	8.92	<0.001
Risk Assessment Quality → Risk Prioritization Effectiveness	0.84	10.37	<0.001
Risk Prioritization Effectiveness → Environmental Management Performance	0.81	9.74	<0.001
Environmental Management Performance → Sustainable Marine Development	0.88	11.21	<0.001
Environmental Monitoring → Environmental Management Performance	0.76	8.45	<0.001
Regulatory Compliance → Sustainable Marine Development	0.72	7.93	<0.001

The findings reported in Table 3 demonstrate strong and statistically significant relationships among the principal components of the proposed framework. The strongest association was observed between environmental management performance and sustainable marine development ($\beta = 0.88$, $p < 0.001$), indicating that effective environmental management practices play a central role in achieving sustainability objectives in offshore projects. Risk assessment quality showed a substantial positive influence on risk prioritization effectiveness ($\beta = 0.84$, $p < 0.001$), suggesting that more accurate and comprehensive assessments lead to better allocation of managerial resources and more efficient mitigation strategies. Similarly, environmental risk identification strongly predicted assessment quality ($\beta = 0.79$, $p < 0.001$), highlighting the importance of comprehensive hazard recognition during the early stages of project planning. Environmental monitoring and regulatory compliance also exhibited significant contributions to environmental management performance and sustainable development outcomes. Collectively, these results support the theoretical assumptions underlying the proposed framework and indicate that sustainability in offshore construction projects is best achieved through an integrated sequence of risk identification, assessment, prioritization, monitoring, and management activities. The consistency of the relationships across all framework components further confirms the validity of adopting a holistic environmental risk management approach in offshore construction settings.

4. Discussion and Conclusion

The present study aimed to develop and validate an integrated environmental risk assessment framework for offshore construction project management in support of sustainable marine development. The findings demonstrated that marine pollution risks, biodiversity and habitat degradation risks, emergency and accidental event risks, and waste management risks were perceived by experts as the most critical environmental challenges associated with offshore construction projects. Furthermore, the integrated prioritization analysis revealed that major oil spills, toxic chemical discharges, marine habitat destruction, and pipeline leakages represented the highest-priority environmental risks. The structural analysis also confirmed that environmental risk identification, assessment quality, risk prioritization effectiveness, environmental management performance, monitoring systems, and regulatory compliance were significantly associated with sustainable marine development outcomes. Collectively, these findings support the proposition that environmental sustainability in offshore construction projects depends on the implementation of a comprehensive risk management framework that integrates ecological, managerial, technical, and governance dimensions throughout the project lifecycle.

One of the most important findings of this study was the identification of marine pollution risks as the highest-priority environmental concern. This finding is consistent with growing international concerns regarding the

vulnerability of marine ecosystems to pollution generated by offshore industrial activities. Marine pollution can arise from oil spills, drilling discharges, chemical releases, waste disposal practices, vessel operations, and accidental construction incidents. Such contamination may affect water quality, marine biodiversity, fisheries productivity, ecosystem services, and coastal economies for extended periods. Previous studies have similarly emphasized that marine pollution remains one of the most persistent challenges facing sustainable ocean governance and blue economy development. Research focusing on marine environmental sustainability has shown that effective pollution prevention strategies are fundamental to preserving ecosystem integrity and supporting long-term sustainable development objectives [1, 2, 21]. Furthermore, studies investigating environmental management strategies in offshore oil and gas developments have demonstrated that proactive stakeholder engagement, environmental monitoring, and preventive planning can significantly reduce pollution-related risks and improve environmental performance [13, 15]. Therefore, the prominence of pollution-related risks in the present study reflects both the ecological sensitivity of marine environments and the potentially irreversible consequences associated with environmental contamination.

The second major finding concerned the high ranking of biodiversity and habitat degradation risks. Experts consistently emphasized that offshore construction activities have the potential to alter marine habitats, disturb ecological processes, and threaten biodiversity through seabed disturbance, sediment dispersion, underwater noise generation, and physical habitat modification. This result aligns closely with previous research highlighting the cumulative ecological impacts of offshore infrastructure development. Investigations conducted in relation to offshore wind energy projects and marine ecosystem management have documented substantial concerns regarding habitat fragmentation, species displacement, disruption of migration routes, and ecological degradation resulting from marine construction activities [4, 7, 8]. Similarly, biodiversity conservation guidelines for energy infrastructure development emphasize that environmental planning must prioritize habitat protection, ecological monitoring, and ecosystem-based management approaches to reduce biodiversity losses and promote coexistence between infrastructure development and environmental conservation objectives [11, 23]. The current findings reinforce these arguments by demonstrating that biodiversity-related risks remain among the most significant environmental considerations in offshore construction management.

The findings also revealed that accidental events, including oil spills, pipeline leakages, equipment failures, and hazardous material releases, were perceived as highly significant risks. These results are understandable given the complexity of offshore construction environments and the substantial environmental consequences that can arise from operational failures. Previous studies examining offshore drilling operations and marine project management have similarly reported that emergency incidents often represent low-frequency but high-consequence events requiring comprehensive preparedness measures and robust risk regulation systems [12, 14]. Research addressing disaster prevention in marine construction projects has further demonstrated that insufficient planning, inadequate monitoring systems, and weak organizational coordination can increase the likelihood and severity of environmental accidents [26]. Consequently, the current findings highlight the importance of integrating emergency preparedness, contingency planning, real-time environmental monitoring, and adaptive management strategies into offshore construction management frameworks.

Another important outcome of the study was the identification of major oil spills and toxic chemical discharges as the highest-ranked individual environmental risks. This result is consistent with extensive evidence indicating that hydrocarbon contamination and chemical pollution can produce widespread ecological damage, including mortality of marine organisms, degradation of habitats, contamination of fisheries resources, and disruption of ecosystem functions. The high prioritization of these risks reflects not only their immediate environmental consequences but also their long-term implications for ecological recovery and sustainable development. Studies examining offshore energy developments and marine environmental governance have consistently emphasized the necessity of implementing precautionary approaches, rigorous environmental regulations, and continuous monitoring systems to reduce the likelihood of catastrophic pollution events [3, 10, 30]. Moreover, the precautionary principle has increasingly become a cornerstone of sustainable marine governance because environmental uncertainties and ecological complexities often limit the ability of decision-makers to predict the full consequences of marine development activities. The findings of the present study strongly support the incorporation of precautionary

risk management principles within offshore construction projects.

The study further demonstrated that environmental risk assessment quality significantly influences risk prioritization effectiveness, which subsequently affects environmental management performance and sustainable development outcomes. This finding is particularly important because it provides empirical support for the conceptual structure of the proposed framework. Effective environmental management begins with accurate identification and assessment of environmental hazards. If risks are underestimated, overlooked, or inadequately characterized, mitigation strategies may fail to address critical environmental threats. Previous research on environmental risk assessment methodologies has similarly shown that integrated assessment frameworks capable of incorporating probability, severity, uncertainty, and sustainability considerations can substantially improve environmental decision-making quality [7, 24, 25]. The present findings therefore suggest that organizations should invest significant resources in improving environmental assessment processes because such investments directly contribute to more effective risk management and sustainability performance.

The strong relationship observed between environmental management performance and sustainable marine development represents another notable finding of this study. Sustainable development in marine environments requires more than compliance with environmental regulations; it requires proactive management systems capable of balancing ecological protection, economic development, and social responsibility. Research on blue economy governance has repeatedly emphasized that environmental sustainability depends upon the successful integration of environmental objectives into organizational decision-making processes [1, 2]. Furthermore, studies examining marine governance challenges have highlighted the importance of transparency, stakeholder participation, institutional coordination, and adaptive management in achieving sustainable development outcomes [16, 17]. The present results support these perspectives by demonstrating that effective environmental management functions as a critical mechanism through which environmental risks are translated into sustainable development outcomes.

The significance of environmental monitoring identified in the proposed framework also deserves attention. Continuous monitoring was found to contribute substantially to environmental management effectiveness, highlighting its role as a feedback mechanism for adaptive decision-making. This finding is supported by contemporary environmental management literature, which increasingly advocates for dynamic and adaptive approaches to environmental governance. Climate change, ecosystem variability, technological innovation, and emerging environmental threats create conditions of uncertainty that cannot be effectively addressed through static management approaches. Studies examining climate-smart marine management and marine environmental monitoring have emphasized that continuous data collection, environmental surveillance, and adaptive governance structures are essential for responding to changing environmental conditions and improving management effectiveness over time [6, 21]. Consequently, monitoring systems should be viewed not merely as regulatory requirements but as strategic tools for sustainability management.

The findings additionally support the importance of regulatory compliance and governance mechanisms in environmental risk management. Marine environments are characterized by multiple overlapping jurisdictions, competing stakeholder interests, and complex regulatory requirements. Effective governance frameworks help establish environmental standards, clarify responsibilities, and ensure accountability among project developers and operators. Previous studies examining marine environmental governance, offshore infrastructure regulation, and sustainable ocean management have consistently emphasized the importance of strong legal frameworks in reducing environmental risks and promoting sustainable development objectives [3, 10, 30]. Therefore, the strong association between regulatory compliance and sustainable marine development observed in this study reinforces the necessity of integrating governance considerations into environmental risk assessment frameworks.

The relevance of the present findings extends beyond conventional offshore construction projects and applies to emerging forms of marine infrastructure development. Recent advances in offshore carbon storage systems, renewable energy infrastructure, and decommissioning initiatives have introduced new environmental challenges requiring comprehensive risk management approaches. Studies examining offshore carbon dioxide storage projects have highlighted the importance of environmental monitoring, risk assessment, and long-term stewardship in ensuring environmental safety and sustainability [18, 19]. Likewise, investigations into offshore infrastructure decommissioning have demonstrated that environmental considerations remain important throughout the entire

infrastructure lifecycle, including post-operational phases [5, 27, 28]. These studies support the broader applicability of the integrated framework developed in the present research.

Finally, the findings of this study should be interpreted within the broader context of emerging marine environmental challenges. Increasing pressures from climate change, expanding offshore infrastructure, fisheries sustainability concerns, marine pollution events, and ecosystem degradation continue to create complex environmental management demands. Emerging environmental issues, including ecosystem resilience, marine resource competition, and environmental uncertainty, require management frameworks that are comprehensive, adaptive, and sustainability-oriented [9, 20, 29]. The integrated environmental risk assessment framework proposed in this study responds to these challenges by linking environmental risk identification, assessment, prioritization, management, monitoring, and sustainability outcomes within a unified decision-making structure capable of supporting long-term marine environmental stewardship.

Several limitations should be acknowledged when interpreting the findings of this study. First, the study relied on expert judgments obtained from a relatively limited sample of specialists located in Tehran, which may restrict the generalizability of the findings to other geographical contexts and offshore sectors. Second, the framework was developed using cross-sectional data and therefore does not capture temporal changes in environmental risks or management effectiveness over time. Third, although the study incorporated experts from multiple professional backgrounds, some stakeholder groups such as coastal communities, fisheries representatives, and environmental non-governmental organizations were not directly included in the assessment process. Finally, the proposed framework was evaluated conceptually rather than through implementation in an actual offshore construction project, which may limit conclusions regarding its operational effectiveness under real-world conditions.

Future studies should evaluate the proposed framework through application in actual offshore construction projects to examine its effectiveness under operational conditions. Longitudinal research designs could be employed to investigate how environmental risks evolve throughout project lifecycles and how adaptive management strategies influence sustainability outcomes over time. Comparative studies involving different countries, marine environments, and offshore industries would also help identify context-specific risk factors and improve the external validity of the framework. Additionally, future research could integrate advanced technologies such as artificial intelligence, remote sensing systems, predictive analytics, and digital environmental monitoring platforms to enhance environmental risk assessment capabilities and improve decision-making processes.

Project developers, environmental managers, and regulatory authorities should adopt integrated environmental risk assessment approaches during the earliest stages of offshore project planning. Environmental monitoring systems should be strengthened through continuous data collection, real-time reporting mechanisms, and adaptive management protocols. Organizations should prioritize biodiversity conservation, pollution prevention, emergency preparedness, and stakeholder engagement as core elements of environmental management strategies. Training programs should be developed to improve environmental risk awareness among project personnel, contractors, and decision-makers. Finally, environmental sustainability objectives should be embedded within project governance structures so that environmental protection becomes an integral component of offshore construction management rather than a separate compliance activity.

Authors' Contributions

Authors equally contributed to this article.

Acknowledgments

Authors thank all participants who participate in this study.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

References

[1] M. Huang, M. Voyer, D. Benzaken, and A. Watanabe, "Blue Economy and Blue Finance: Toward Sustainable Development and Ocean Governance," 2022, doi: 10.56506/hdlz1912.

[2] J. Su, "Global Ocean Governance and Ecological Civilization: Building a Sustainable Ocean Economy for China," pp. 117-154, 2022, doi: 10.1007/978-981-16-4799-4_3.

[3] Y. C. Chang, "Editorial: Rule of Law in the Governance of New Frontiers of the Marine Environment," *Frontiers in Marine Science,* vol. 10, 2023, doi: 10.3389/fmars.2023.1277409.

[4] G. J. Piet, J. E. Tamis, J. T. v. d. Wal, and R. H. Jongbloed, "Cumulative Impacts of Wind Farms on the North Sea Ecosystem," 2021, doi: 10.18174/556024.

[5] J. Melbourne-Thomas *et al.*, "Decommissioning Research Needs for Offshore Oil and Gas Infrastructure in Australia," *Frontiers in Marine Science,* vol. 8, 2021, doi: 10.3389/fmars.2021.711151.

[6] A. Fairbrass, K. Fradera, R. Shucksmith, L. Greenhill, T. Acott, and P. Ekins, "Revealing Gaps in Marine Evidence With a Natural Capital Lens," *Philosophical Transactions of the Royal Society B Biological Sciences,* vol. 380, no. 1917, 2025, doi: 10.1098/rstb.2023.0214.

[7] S. G. Bolam, "Developing an Ecological Risk-based Approach to Facilitate Licensing Offshore Wind Development," *Ecosphere,* vol. 17, no. 1, 2026, doi: 10.1002/ecs2.70520.

[8] M. Avesani, "The Mediterranean Offshore Wind Turn: Lessons, Risks, and Regional Reflections," *Open Research Europe,* vol. 5, p. 66, 2025, doi: 10.12688/openreseurope.19339.3.

[9] G. Song, "Understanding Taiwan's Offshore Wind Industry," *Open Access Government,* vol. 40, no. 1, pp. 478-479, 2023, doi: 10.56367/oag-040-10532.

[10] O. Woolley, "Renewable Energy and the Law of the Sea," pp. 35-62, 2022, doi: 10.1017/9781009042178.003.

[11] A. Christine *et al.*, "Coexistence and Nature-Inclusive Design in Nordic Offshore Windfarms," 2023, doi: 10.6027/ner2023-01.

[12] Y. Yang, "Advancing the Robustness of Risk Regulation for Offshore Drilling Operations in China," *Frontiers in Marine Science,* vol. 10, 2023, doi: 10.3389/fmars.2023.1125092.

[13] O. O. Sofoluwe, O. J. Ochulor, A. Ukato, and D. D. Jambol, "Promoting High Health, Safety, and Environmental Standards During Subsea Operations," *World Journal of Biology Pharmacy and Health Sciences,* vol. 18, no. 2, pp. 192-203, 2024, doi: 10.30574/wjbphs.2024.18.2.0248.

[14] A. D. Sackey *et al.*, "An Assessment of Sociotechnical Transition in Marine Warranty Survey Practice: Case of West Africa's Marine and Cargo Project Management Against Risk," 2023, doi: 10.21203/rs.3.rs-3449097/v1.

[15] M. W. C. Sinambela, "Formulating Environmental Management Strategies From Public Consultation Inputs Using Importance–performance Analysis for Oil and Gas Development in the North Natuna Sea," *Iop Conference Series Earth and Environmental Science,* vol. 1618, no. 1, p. 012006, 2026, doi: 10.1088/1755-1315/1618/1/012006.

[16] R. Fofack-Garcia *et al.*, "Socio-Political Acceptability of Floating Offshore Wind Farms in France: Challenges and Perspectives for Marine Governance Towards Sustainability," *Ocean & Coastal Management,* vol. 236, p. 106513, 2023, doi: 10.1016/j.ocecoaman.2023.106513.

[17] S. A. Ebbin and N. Trumbull, "Contested Spaces in the New Blue Economy: Competing for Connecticut's Thames River Working Waterfront," *Geographical Journal,* vol. 189, no. 2, pp. 217-230, 2021, doi: 10.1111/geoj.12409.

[18] S. Zendehboudi, M. Seyyedattar, N. M. C. Saady, O. Mohammadzadeh, A. Mamudu, and D. Heagle, "Exploring the Potential of Offshore Geological CO₂ Storage in Canada: A Comprehensive Review and Future Outlook," *Energy & Fuels,* vol. 39, no. 13, pp. 5987-6025, 2025, doi: 10.1021/acs.energyfuels.4c04939.

[19] T. Zhang *et al.*, "Insights and Guidance for China's Offshore CO2 Storage Development: Evidence From Global Experience," *Energies,* vol. 17, no. 12, p. 2983, 2024, doi: 10.3390/en17122983.

[20] D. Murray, V. Campón-Linares, C. M. O'Brien, R. B. Thorpe, R. P. Vieira, and F. Gilmour, "Emerging Issues in Fisheries Science by Fisheries Scientists," *Journal of Fish Biology,* vol. 105, no. 2, pp. 557-563, 2024, doi: 10.1111/jfb.15683.

[21] M. Lange *et al.*, "Climate-Smart Socially Innovative Tools and Approaches for Marine Pollution Science in Support of Sustainable Development," *Cambridge Prisms Coastal Futures,* vol. 1, 2023, doi: 10.1017/cft.2023.11.

[22] G. K. Sarangi, "Offshore Wind Energy as an Emergent Ocean Infrastructure in India: Mapping of the Social and Environmental Impacts," *SSRN Electronic Journal,* 2022, doi: 10.2139/ssrn.4204155.

[23] L. Bennun *et al.*, "Mitigating Biodiversity Impacts Associated With Solar and Wind Energy Development: Guidelines for Project Developers," 2021, doi: 10.2305/iucn.ch.2021.04.en.

[24] Q. Mao, M. Guo, J. Lv, J. Chen, P. Xie, and M. Li, "A Risk Assessment Framework of Hybrid Offshore Wind–Solar PV Power Plants Under a Probabilistic Linguistic Environment," *Sustainability,* vol. 14, no. 7, p. 4197, 2022, doi: 10.3390/su14074197.

[25] B. Liu, M. Gong, X. Wu, and X. Liu, "A Comprehensive Model of Vessel Anchoring Pressure Based on Machine Learning to Support the Sustainable Management of the Marine Environments of Coastal Cities," *Sustainable Cities and Society,* vol. 72, p. 103011, 2021, doi: 10.1016/j.scs.2021.103011.

[26] Y. Junjia, A. H. Alias, N. A. Haron, and N. A. Bakar, "Trend Analysis of Marine Construction Disaster Prevention Based on Text Mining: Evidence From China," *Sustainable Marine Structures,* vol. 6, no. 1, pp. 20-32, 2024, doi: 10.36956/sms.v6i1.1026.

[27] J. P. Nicolette *et al.*, "A Framework for a Net Environmental Benefit Analysis Based Comparative Assessment of Decommissioning Options for Anthropogenic Subsea Structures: A North Sea Case Study," *Frontiers in Marine Science,* vol. 9, 2023, doi: 10.3389/fmars.2022.1020334.

[28] E. G. Pereira, O. Omotuyi, A. Koenck, P. Obani, M. Gopaulsingh, and S. Mohammed, "Decommissioning Offshore Oil and Gas Platforms: Is the Rigs-to-Reefs Program a More Sustainable Alternative?," *Journal of Sustainable Development Law and Policy (The),* vol. 14, no. 1, pp. 1-26, 2023, doi: 10.4314/jsdlp.v14i1.2s.

[29] H. Julia *et al.*, "Holopelagic Sargassum Beachings in the Western Atlantic Ocean: A Scoping Review Ranging From Causes to Management," *Environmental Research Letters,* 2026, doi: 10.1088/1748-9326/ae4d60.

[30] C. Xiao-lin, "Review of National Laws and Regulations in China in Relation to the Precautionary Approach to Fisheries Management," *Fisheries Management and Ecology,* 2025, doi: 10.1111/fme.70017.