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# Life Cycle Environmental Impact Modeling in Large Marine Infrastructure Based on Adaptive Management Strategies

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A B S T R A C T

The objective of this study was to develop and validate a comprehensive model of life cycle environmental impacts in large marine infrastructure projects based on adaptive management strategies. This applied study employed a mixed-methods research design integrating qualitative and quantitative approaches. In the qualitative phase, relevant environmental impact dimensions and adaptive management indicators were identified through a comprehensive literature review and semi-structured interviews with 20 experts in marine engineering, environmental management, sustainability assessment, and offshore infrastructure development. Thematic analysis was used to extract the principal constructs and establish the preliminary conceptual framework. In the quantitative phase, data were collected from 384 specialists and professionals working in marine infrastructure, environmental management, and related sectors in Tehran, Iran. A researcher-developed questionnaire was designed based on findings from the qualitative phase and assessed dimensions including life cycle environmental impacts, ecosystem vulnerability assessment, resource utilization efficiency, pollution and emission management, environmental monitoring systems, stakeholder participation, adaptive management strategies, and sustainability performance. Construct validity was examined using exploratory and confirmatory factor analyses, while reliability was assessed through Cronbach's alpha and composite reliability coefficients. Structural equation modeling was conducted using SPSS 28 and AMOS 26 to evaluate the proposed relationships among study variables. The findings demonstrated satisfactory validity and reliability for all measurement constructs, with factor loadings exceeding recommended thresholds and strong internal consistency coefficients. Structural equation modeling revealed that all environmental assessment dimensions significantly and positively influenced adaptive management strategies. Environmental monitoring systems exerted the strongest effect on adaptive management strategies ($\beta = 0.49$, $p < 0.001$), followed by life cycle environmental impacts ($\beta = 0.41$, $p < 0.001$), pollution and emission management ($\beta = 0.36$, $p < 0.001$), ecosystem vulnerability assessment ($\beta = 0.33$, $p < 0.001$), stakeholder participation ($\beta = 0.29$, $p < 0.001$), and resource utilization efficiency ($\beta = 0.27$, $p < 0.001$). Furthermore, adaptive management strategies demonstrated a strong positive effect on sustainability performance ($\beta = 0.68$, $p < 0.001$). The overall structural model exhibited excellent fit indices ($\chi^2/df = 2.14$, CFI = 0.958, TLI = 0.951, IFI = 0.959, GFI = 0.928, RMSEA = 0.054), confirming the adequacy of the proposed framework. The results indicate that adaptive management strategies serve as a critical mechanism linking environmental assessment processes to sustainability outcomes in large marine infrastructure projects.

***Keywords:*** *Life Cycle Assessment; Environmental Impact Modeling; Marine Infrastructure; Adaptive Management; Sustainability Performance.*

## 1. Introduction

Marine infrastructure has become one of the most strategically important sectors supporting global economic development, international trade, energy production, transportation networks, food security, and coastal urbanization. The expansion of offshore wind farms, marine energy systems, ports, aquaculture facilities, floating photovoltaic platforms, subsea transportation systems, and coastal protection structures has accelerated considerably during the last decade as governments and industries seek sustainable pathways to address increasing energy demands, climate change pressures, and resource constraints (Avesani, 2025; Oeishee, 2026). While these developments contribute significantly to economic growth and energy transition objectives, they simultaneously generate complex environmental impacts that affect marine ecosystems, biodiversity, water quality, carbon cycles, and coastal communities. Consequently, understanding the environmental consequences associated with the entire life cycle of large marine infrastructure projects has emerged as a critical challenge for policymakers, engineers, environmental managers, and sustainability researchers (Kabeyi & Olanrewaju, 2023; Portillo et al., 2024). The growing complexity of marine development activities requires comprehensive assessment approaches capable of capturing environmental interactions from project conception and construction through operation, maintenance, and eventual decommissioning. Traditional environmental assessment frameworks often focus on individual project stages and therefore fail to account for cumulative and long-term environmental consequences that emerge across the infrastructure life cycle. This limitation has increased interest in integrated life cycle approaches that provide a more holistic understanding of environmental performance and sustainability outcomes (Bortoli & Agez, 2023; Byles & Mohagheghi, 2023).

Life Cycle Assessment (LCA) has become one of the most widely accepted methodologies for evaluating environmental impacts associated with products, technologies, industrial systems, and infrastructure projects. By systematically quantifying resource consumption, emissions, ecological disturbances, and environmental burdens throughout all stages of a system's existence, LCA enables decision-makers to identify environmental hotspots and opportunities for improvement (Chaurasiya et al., 2026; Portillo et al., 2024). Recent applications of life cycle methodologies in renewable energy systems, marine energy technologies, and large-scale infrastructure planning have demonstrated the importance of considering environmental effects beyond operational phases alone. Research on offshore renewable energy systems has shown that manufacturing processes, material extraction, transportation activities, maintenance operations, and end-of-life management contribute substantially to total environmental impacts and therefore must be incorporated into sustainability assessments (Singh et al., 2024; Zanobetti et al., 2025). Similarly, investigations of floating photovoltaic systems have highlighted the necessity of evaluating environmental trade-offs across the entire project life cycle rather than focusing solely on operational carbon reductions (Oeishee, 2026). Studies of sustainable power grid expansion have further demonstrated that infrastructure planning decisions can have environmental consequences extending across decades, reinforcing the need for comprehensive life cycle environmental modeling approaches (Byles & Mohagheghi, 2023).

The environmental significance of marine infrastructure extends beyond energy systems and encompasses a wide range of activities associated with aquaculture, seafood production, marine transportation, and coastal development. Research conducted within the seafood and aquaculture sectors demonstrates that marine-based industries can generate both positive and negative environmental outcomes depending on technological choices, resource management practices, and governance structures (Jones et al., 2022; Laso et al., 2022). Life cycle studies of aquaculture systems have revealed substantial variations in environmental performance across production methods, species, feed systems, and geographic locations (Budhathoki et al., 2025; Li et al., 2024). At the same time, emerging evidence suggests that marine aquaculture may contribute to carbon sequestration, emissions reduction, and ecosystem restoration when implemented using sustainable management principles (Jones et al., 2022; Liu et al., 2024). Similar findings have been reported for seaweed-based production systems and marine bioeconomy initiatives, which demonstrate considerable potential for supporting sustainability transitions while reducing environmental pressures associated with conventional industrial activities (Arantzamendi et al., 2023; Pereira & Cotas, 2024). Life cycle assessment studies of seaweed-based biorefineries further illustrate how circular economy principles can reduce environmental impacts through resource recovery, waste minimization, and sustainable material utilization (Chaurasiya et al., 2026). These findings collectively

indicate that environmental performance in marine systems is highly dependent upon management strategies and decision-making processes operating throughout the project life cycle.

Climate change represents an additional dimension that intensifies the importance of environmental impact modeling in marine infrastructure development. Rising sea levels, increasing ocean temperatures, changing weather patterns, and more frequent extreme events create substantial challenges for the planning, operation, and long-term resilience of marine infrastructure systems (Avesani, 2025; Mihailov et al., 2024). Simultaneously, marine infrastructure projects themselves contribute to climate-related impacts through material production, construction activities, energy consumption, transportation requirements, and waste generation. Recent sustainability assessments have emphasized the necessity of evaluating both direct and indirect climate impacts when designing future marine infrastructure systems (Yuan et al., 2025; Zanobetti et al., 2025). Studies investigating renewable energy transitions have demonstrated that even environmentally beneficial technologies may create unintended ecological consequences if broader life cycle impacts are overlooked (Gallagher, 2025). Research concerning global plant biodiversity has shown that large-scale renewable energy deployment can influence ecosystems through habitat alteration, land-use change, and resource extraction activities (Gallagher, 2025). Similarly, investigations into hydrogen transition pathways have highlighted the importance of integrating environmental sustainability considerations with technological innovation and risk management processes (Yuan et al., 2025). These developments reinforce the need for comprehensive environmental impact models capable of addressing both ecological and socio-environmental dimensions throughout infrastructure life cycles.

The growing adoption of circular economy principles has further transformed perspectives on environmental management within marine infrastructure systems. Rather than focusing exclusively on pollution control and impact mitigation, contemporary sustainability frameworks emphasize resource efficiency, material circularity, waste valorization, and regenerative environmental practices (Chaurasiya et al., 2026; Pandey, 2025). Circular approaches are increasingly recognized as essential mechanisms for reducing environmental burdens while simultaneously enhancing economic performance and system resilience. In marine contexts, circular economy initiatives include sustainable water management, resource recovery technologies, bio-based materials, and environmentally optimized infrastructure designs (Arantzamendi et al., 2023; Pandey, 2025). Research on marine concrete structures has demonstrated that innovative construction approaches can significantly reduce environmental footprints while maintaining structural performance and durability (Minoretti et al., 2025). Likewise, investigations into marine-derived materials and sustainable manufacturing pathways indicate substantial opportunities for improving environmental performance across multiple sectors connected to marine infrastructure development (Pereira & Cotas, 2024). These findings suggest that life cycle environmental assessments must increasingly account for circularity indicators and adaptive resource management strategies in order to capture the full sustainability potential of contemporary infrastructure systems.

Another critical environmental challenge associated with marine infrastructure concerns pollution generation and ecosystem degradation. Marine ecosystems face increasing pressures from plastic pollution, chemical contaminants, habitat fragmentation, and cumulative industrial impacts (Rucevska et al., 2024; Schäli, 2022). The interaction between infrastructure development and marine pollution creates complex environmental dynamics that require integrated assessment approaches. Plastic-related environmental impacts, for example, extend across production, utilization, disposal, and environmental leakage stages, producing long-term consequences for marine biodiversity and ecosystem functioning (Rucevska et al., 2024; Schäli, 2022). Environmental impact assessments that fail to consider these cumulative interactions may underestimate long-term ecological risks and therefore compromise sustainability objectives. Recent studies have emphasized the necessity of incorporating ecosystem vulnerability, biodiversity protection, and environmental resilience considerations into infrastructure planning and management frameworks (Gallagher, 2025; Liu et al., 2024). Consequently, environmental modeling efforts must extend beyond conventional emissions accounting to include broader ecological indicators capable of capturing complex ecosystem responses to infrastructure activities.

Adaptive management has emerged as one of the most promising approaches for addressing environmental uncertainty and complexity in large-scale infrastructure systems. Unlike conventional management frameworks that rely on fixed planning assumptions, adaptive management emphasizes continuous monitoring, learning, stakeholder

engagement, feedback integration, and iterative decision-making processes (Araignous et al., 2023; Migo-Sumagang et al., 2023). This approach is particularly relevant in marine environments where ecological systems exhibit high levels of uncertainty, variability, and interconnectedness. Research examining environmental and social acceptance in ocean energy projects has demonstrated that adaptive management strategies improve environmental performance by facilitating stakeholder participation, enhancing transparency, and enabling timely responses to emerging environmental risks (Araignous et al., 2023). Decision-support models developed for sustainability transitions similarly emphasize the importance of adaptive governance mechanisms for managing uncertainty and optimizing environmental outcomes (Migo-Sumagang et al., 2023). Furthermore, large-scale renewable energy integration studies have shown that system flexibility and adaptive operational strategies can significantly enhance sustainability performance while reducing environmental risks (Halim et al., 2023). These findings indicate that adaptive management principles may provide a valuable framework for improving environmental performance throughout marine infrastructure life cycles.

Despite substantial advances in life cycle assessment methodologies, sustainability evaluation techniques, and adaptive management frameworks, important research gaps remain. Existing studies frequently examine individual technologies, specific environmental indicators, or isolated project phases rather than developing integrated models that capture the dynamic interactions among environmental impacts, management interventions, and sustainability outcomes across entire infrastructure life cycles (Portillo et al., 2024; Singh et al., 2024). Moreover, many environmental assessment frameworks emphasize static evaluations and therefore inadequately address the evolving nature of environmental conditions, stakeholder expectations, technological innovations, and regulatory requirements (Avesani, 2025; Yuan et al., 2025). The increasing scale and complexity of marine infrastructure systems require more sophisticated analytical approaches capable of integrating life cycle thinking with adaptive management principles. Such approaches are necessary for identifying critical environmental hotspots, prioritizing mitigation measures, enhancing resilience, and supporting evidence-based decision-making under conditions of uncertainty. Developing comprehensive models that connect environmental assessment dimensions with adaptive management mechanisms may therefore contribute significantly to both theoretical understanding and practical sustainability management in marine infrastructure development.

Accordingly, the aim of this study was to develop and validate a comprehensive model of life cycle environmental impacts in large marine infrastructure projects based on adaptive management strategies and to examine the relationships among environmental assessment dimensions, adaptive management mechanisms, and sustainability performance outcomes.

## 2. Methods and Materials

This study was conducted using an applied research approach with the objective of developing and validating a comprehensive model for assessing and predicting life cycle environmental impacts in large-scale marine infrastructure projects based on adaptive management strategies. Given the complexity of environmental interactions across the planning, construction, operation, maintenance, and decommissioning phases of marine infrastructure, a mixed-methods research design was adopted. The study integrated qualitative and quantitative approaches to identify critical environmental impact factors, determine adaptive management indicators, and construct a predictive life cycle environmental impact model. The qualitative phase focused on extracting key dimensions and variables from the literature and expert opinions, while the quantitative phase examined the relationships among identified variables and validated the proposed conceptual model through statistical analysis.

The target population consisted of specialists, researchers, project managers, environmental consultants, marine engineers, sustainability experts, and decision-makers involved in marine infrastructure development projects in Tehran, Iran. These individuals possessed substantial experience in environmental assessment, marine engineering, offshore project management, environmental policy, and sustainable infrastructure development. A purposive sampling strategy was employed during the qualitative phase to ensure that participants possessed relevant expertise and practical knowledge regarding environmental impact assessment and adaptive management practices in marine environments. Twenty experts participated in the qualitative interviews, which continued until theoretical saturation was achieved and no new themes emerged.

For the quantitative phase, a sample of 384 participants was selected from professionals working in governmental organizations, consulting firms, engineering companies, environmental agencies, academic institutions, and marine project management organizations located in Tehran. The sample size was determined using Cochran's formula for large populations and was considered sufficient for structural equation modeling and multivariate statistical analyses. Inclusion criteria included a minimum of five years of professional experience in marine infrastructure projects, environmental management, sustainability assessment, or related disciplines. Participation was voluntary, and informed consent was obtained from all respondents before data collection commenced. Confidentiality and anonymity of participant information were maintained throughout the study.

Data collection was performed using a combination of literature review, semi-structured expert interviews, and a researcher-developed questionnaire. In the initial stage, an extensive review of scientific articles, environmental impact assessment reports, sustainability frameworks, life cycle assessment studies, marine infrastructure management guidelines, and adaptive management literature was conducted to identify the principal environmental impact categories and adaptive management components relevant to large marine infrastructure projects. The review covered international standards and frameworks associated with environmental sustainability, life cycle thinking, ecosystem protection, resource management, and marine environmental governance.

Semi-structured interviews were subsequently conducted with experts to explore perceptions regarding the most significant environmental impacts occurring throughout the life cycle of marine infrastructure systems and the adaptive management mechanisms capable of mitigating these impacts. The interview protocol included open-ended questions concerning environmental risks, ecosystem disturbances, resource consumption, pollution pathways, biodiversity conservation, monitoring practices, stakeholder engagement, and adaptive decision-making processes. Interviews were recorded with participant consent, transcribed verbatim, and subjected to qualitative analysis to extract recurring themes and indicators.

Based on findings from the literature review and qualitative interviews, a researcher-developed questionnaire was designed to measure the identified constructs. The instrument consisted of several dimensions including environmental impact assessment across life cycle stages, ecosystem vulnerability, emissions and pollution management, marine biodiversity conservation, resource utilization efficiency, environmental monitoring systems, stakeholder participation, organizational learning, adaptive decision-making capacity, risk mitigation effectiveness, and sustainability performance outcomes. Questionnaire items were assessed using a five-point Likert scale ranging from strongly disagree to strongly agree. Content validity was evaluated by a panel of environmental management and marine engineering experts who reviewed the questionnaire for relevance, clarity, comprehensiveness, and representativeness. Their feedback was incorporated into the final version of the instrument. Construct validity was examined through exploratory and confirmatory factor analyses, while reliability was assessed using Cronbach's alpha coefficients and composite reliability measures. The obtained reliability values exceeded accepted thresholds, confirming the internal consistency and stability of the measurement instrument.

Qualitative data obtained from expert interviews were analyzed using thematic analysis. Interview transcripts were repeatedly reviewed to identify meaningful units of information, which were subsequently coded and categorized into broader themes representing environmental impact dimensions and adaptive management strategies. Through iterative coding and comparison procedures, conceptual relationships among themes were established and integrated into a preliminary conceptual framework.

Quantitative data analysis was performed using SPSS version 28 and AMOS version 26. Initially, descriptive statistics were calculated to summarize participant characteristics and variable distributions. Normality assumptions were assessed through skewness and kurtosis indices. Exploratory factor analysis was conducted to identify the underlying factor structure of the questionnaire and verify the dimensionality of the constructs. Confirmatory factor analysis was subsequently employed to evaluate measurement model adequacy and establish convergent and discriminant validity.

Structural equation modeling was used to test the proposed relationships among life cycle environmental impact variables, adaptive management components, and sustainability performance outcomes. Model fit was evaluated using multiple goodness-of-fit indices, including the chi-square to degrees of freedom ratio, Comparative Fit Index, Tucker–Lewis Index, Incremental Fit Index, Goodness-of-Fit Index, and Root Mean Square Error of Approximation. Direct, indirect, and total effects among

latent variables were estimated to determine the magnitude and significance of relationships within the model. In addition, bootstrapping procedures were applied to assess mediation effects and improve the robustness of parameter estimates. Statistical significance was evaluated at the 0.05 level, and the final model was interpreted as a comprehensive framework for understanding and managing environmental impacts throughout the life cycle of large marine infrastructure projects through adaptive management strategies.

## 3. Findings and Results

A total of 384 valid questionnaires were collected and included in the final analysis. Among the respondents, 71.1% were male and 28.9% were female. The mean age of participants was 42.67 years (SD = 8.94), with ages ranging from 29 to 63 years. Regarding educational attainment, 18.0% held bachelor's degrees, 56.8% held master's degrees, and 25.2% possessed doctoral qualifications. Participants represented a diverse range of professional backgrounds, including marine engineering (31.5%), environmental management (24.7%), offshore project management (18.5%), sustainability and environmental consulting (15.1%), and academic or governmental environmental policy positions (10.2%). The average professional experience was 13.84 years (SD = 6.12), indicating that the sample consisted primarily of highly experienced specialists familiar with large-scale marine infrastructure projects and environmental assessment practices. This distribution suggests that the respondents possessed the technical expertise and practical knowledge required to evaluate environmental impacts and adaptive management mechanisms throughout the life cycle of marine infrastructure systems.

**Table 1**

*Descriptive Statistics of the Main Study Variables*

| Variable | Mean | SD | Minimum | Maximum | Skewness | Kurtosis |
|---|---|---|---|---|---|---|
| Life Cycle Environmental Impacts | 3.87 | 0.61 | 1.84 | 4.95 | -0.42 | -0.36 |
| Ecosystem Vulnerability Assessment | 3.74 | 0.67 | 1.56 | 4.89 | -0.38 | -0.44 |
| Resource Utilization Efficiency | 3.69 | 0.72 | 1.71 | 4.92 | -0.31 | -0.51 |
| Pollution and Emission Management | 3.81 | 0.64 | 1.62 | 4.97 | -0.47 | -0.28 |
| Environmental Monitoring Systems | 3.94 | 0.58 | 2.03 | 5.00 | -0.53 | -0.17 |
| Stakeholder Participation | 3.62 | 0.75 | 1.47 | 4.91 | -0.26 | -0.59 |
| Adaptive Management Strategies | 4.01 | 0.55 | 2.18 | 5.00 | -0.61 | -0.12 |
| Sustainability Performance | 3.89 | 0.60 | 1.95 | 4.98 | -0.45 | -0.34 |

Table 1 presents the descriptive statistics for the principal constructs included in the study. The results indicate that Adaptive Management Strategies obtained the highest mean score (M = 4.01, SD = 0.55), suggesting that respondents perceived adaptive management mechanisms as highly important and widely applicable for managing environmental impacts throughout marine infrastructure life cycles. Environmental Monitoring Systems also demonstrated a relatively high mean score (M = 3.94, SD = 0.58), reflecting the critical role of continuous monitoring and feedback processes in adaptive environmental governance. Sustainability Performance (M = 3.89, SD = 0.60) and Life Cycle Environmental Impacts (M = 3.87, SD = 0.61) were evaluated positively by respondents, indicating strong recognition of the relationship between environmental management practices and sustainable project outcomes. Furthermore, all skewness and kurtosis values fell within acceptable ranges, confirming the approximate normality of data distribution and supporting the use of multivariate statistical techniques, including structural equation modeling. The relatively low standard deviations across variables also suggest substantial agreement among experts regarding the importance of environmental impact assessment and adaptive management strategies in large marine infrastructure projects.

**Table 2**

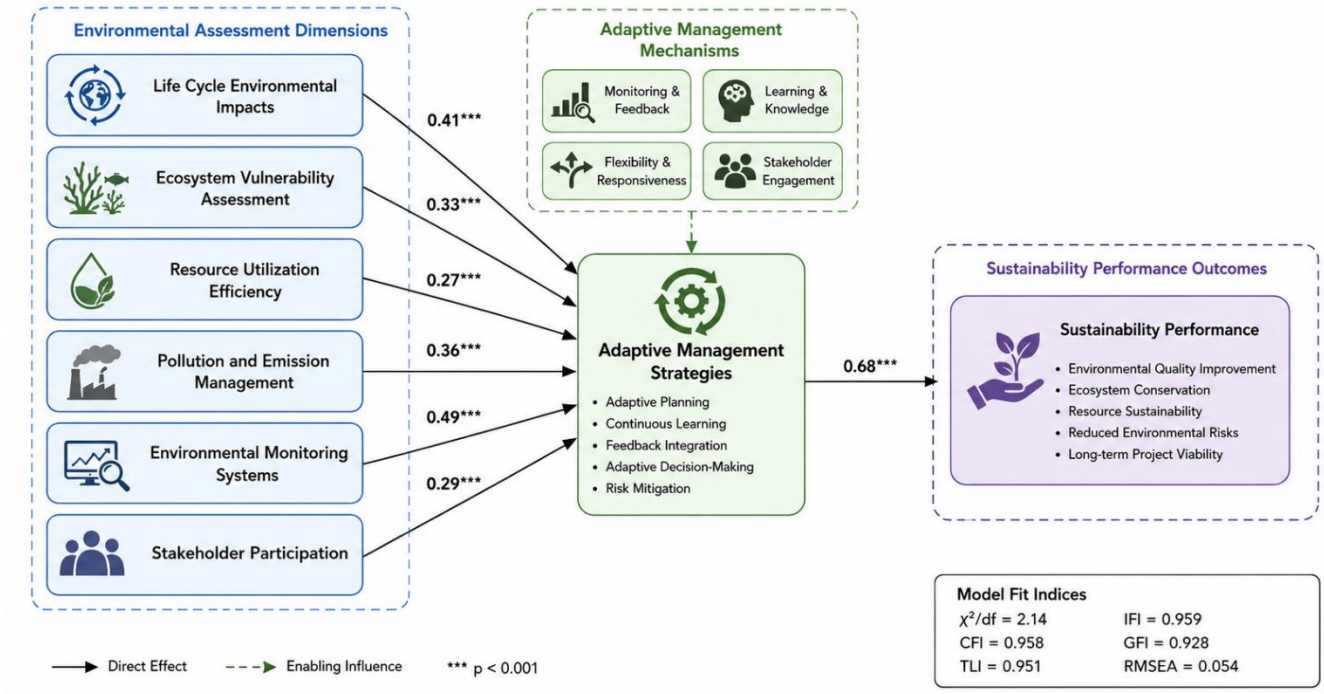
*Confirmatory Factor Analysis and Measurement Model Assessment*

| Construct | Factor Loading Range | AVE | Composite Reliability | Cronbach's Alpha |
|---|---|---|---|---|
| Life Cycle Environmental Impacts | 0.72–0.89 | 0.68 | 0.91 | 0.89 |
| Ecosystem Vulnerability Assessment | 0.70–0.87 | 0.65 | 0.90 | 0.88 |
| Resource Utilization Efficiency | 0.73–0.88 | 0.67 | 0.91 | 0.89 |
| Pollution and Emission Management | 0.75–0.90 | 0.71 | 0.93 | 0.91 |
| Environmental Monitoring Systems | 0.76–0.91 | 0.72 | 0.93 | 0.92 |
| Stakeholder Participation | 0.69–0.86 | 0.63 | 0.89 | 0.87 |
| Adaptive Management Strategies | 0.77–0.92 | 0.73 | 0.94 | 0.92 |
| Sustainability Performance | 0.74–0.90 | 0.70 | 0.92 | 0.90 |

The confirmatory factor analysis results demonstrated strong psychometric properties for all latent constructs included in the model. Factor loadings ranged from 0.69 to 0.92, substantially exceeding the minimum acceptable threshold of 0.50 and indicating that observed indicators adequately represented their underlying latent variables. Average Variance Extracted values ranged from 0.63 to 0.73, confirming satisfactory convergent validity because all values exceeded the recommended threshold of 0.50. Similarly, Composite Reliability coefficients ranged from 0.89 to 0.94, while Cronbach's alpha coefficients ranged from 0.87 to 0.92, demonstrating excellent internal consistency and reliability across all scales. These findings indicate that the measurement model successfully captured the multidimensional nature of environmental impacts, adaptive management practices, and sustainability outcomes. Overall, the measurement model exhibited strong validity and reliability, providing a robust foundation for testing the hypothesized structural relationships among the study variables.

**Figure 1**

*Final Structural Model of Life Cycle Environmental Impact Assessment and Adaptive Management Strategies in Large Marine Infrastructure Projects*




The structural model presented in Figure 1 illustrates the integrated relationships among environmental impact dimensions, adaptive management mechanisms, and sustainability performance outcomes. The model

demonstrates that adaptive management functions as a central mediating mechanism linking environmental assessment processes with long-term sustainability achievements. Environmental monitoring, stakeholder engagement, ecosystem vulnerability assessment, and pollution management collectively contribute to the development of adaptive decision-making capabilities, which subsequently improve sustainability performance. The visual representation of the model highlights the interconnected nature of environmental governance processes and emphasizes the importance of continuous learning, feedback incorporation, and strategic adaptation throughout the infrastructure life cycle. The figure also demonstrates that environmental management effectiveness depends not only on technical assessment procedures but also on institutional responsiveness and organizational flexibility, thereby supporting the theoretical foundations of adaptive environmental management.

**Table 3**

*Structural Equation Modeling Results*

| Hypothesized Path | Standardized β | t-value | p-value |
|---|---|---|---|
| Life Cycle Environmental Impacts → Adaptive Management Strategies | 0.41 | 7.92 | <0.001 |
| Ecosystem Vulnerability Assessment → Adaptive Management Strategies | 0.33 | 6.44 | <0.001 |
| Resource Utilization Efficiency → Adaptive Management Strategies | 0.27 | 5.61 | <0.001 |
| Pollution and Emission Management → Adaptive Management Strategies | 0.36 | 7.18 | <0.001 |
| Environmental Monitoring Systems → Adaptive Management Strategies | 0.49 | 9.73 | <0.001 |
| Stakeholder Participation → Adaptive Management Strategies | 0.29 | 5.87 | <0.001 |
| Adaptive Management Strategies → Sustainability Performance | 0.68 | 12.85 | <0.001 |

The structural equation modeling results revealed statistically significant relationships among all hypothesized pathways. Environmental Monitoring Systems exerted the strongest influence on Adaptive Management Strategies ($\beta = 0.49$, $p < 0.001$), indicating that continuous monitoring, environmental surveillance, and real-time feedback mechanisms are essential drivers of adaptive decision-making processes in marine infrastructure projects. Life Cycle Environmental Impacts also demonstrated a substantial positive effect on Adaptive Management Strategies ($\beta = 0.41$, $p < 0.001$), suggesting that comprehensive assessment of environmental consequences across project phases enhances organizational capacity for adaptive responses. Pollution and Emission Management exhibited a significant positive effect ($\beta = 0.36$, $p < 0.001$), followed by Ecosystem Vulnerability Assessment ($\beta = 0.33$, $p < 0.001$), Stakeholder Participation ($\beta = 0.29$, $p < 0.001$), and Resource Utilization Efficiency ($\beta = 0.27$, $p < 0.001$). Most importantly, Adaptive Management Strategies demonstrated a strong and highly significant effect on Sustainability Performance ($\beta = 0.68$, $p < 0.001$), confirming its pivotal role in achieving sustainable environmental outcomes.

The overall structural model exhibited excellent fit to the observed data. The goodness-of-fit indices indicated satisfactory model adequacy ($\chi^2/df = 2.14$, CFI = 0.958, TLI = 0.951, IFI = 0.959, GFI = 0.928, RMSEA = 0.054). All indices met or exceeded recommended thresholds, supporting the validity of the proposed conceptual framework. The findings collectively demonstrate that environmental monitoring, ecosystem assessment, pollution control, resource efficiency, and stakeholder engagement contribute significantly to adaptive management capabilities, which in turn enhance sustainability performance throughout the life cycle of large marine infrastructure projects. These results provide strong empirical support for the proposed adaptive management framework and highlight the importance of integrating continuous environmental assessment and adaptive governance mechanisms into marine infrastructure planning, construction, operation, and decommissioning activities.

## 4. Discussion and Conclusion

The purpose of this study was to develop and validate a comprehensive model for evaluating life cycle environmental impacts in large marine infrastructure projects based on adaptive management strategies. The findings demonstrated that all environmental assessment dimensions, including life cycle environmental impacts, ecosystem vulnerability assessment, resource utilization efficiency, pollution and emission management, environmental monitoring systems, and stakeholder participation, exerted significant positive effects on adaptive management strategies. Furthermore, adaptive management strategies exhibited a strong positive influence on

sustainability performance. The overall model demonstrated excellent goodness-of-fit indices, confirming the adequacy of the proposed framework for explaining relationships among environmental assessment variables, adaptive management mechanisms, and sustainability outcomes in marine infrastructure projects.

One of the most important findings of this study was that environmental monitoring systems represented the strongest predictor of adaptive management strategies. This result suggests that continuous environmental observation, data collection, performance tracking, and feedback mechanisms play a central role in enabling adaptive decision-making throughout the life cycle of marine infrastructure systems. Adaptive management relies fundamentally on the availability of timely and reliable environmental information, allowing managers to respond effectively to emerging risks, changing ecological conditions, and unforeseen project impacts. This finding is consistent with studies emphasizing the importance of monitoring and iterative learning processes in complex environmental systems. Research on environmental and social acceptance in ocean energy projects demonstrated that continuous monitoring and stakeholder-informed feedback significantly improve environmental management outcomes and project sustainability (Araignous et al., 2023). Similarly, decision-support frameworks developed for sustainability transitions highlight the critical role of information feedback loops and adaptive learning in reducing uncertainty and enhancing environmental performance (Migo-Sumagang et al., 2023). The current finding therefore reinforces the notion that effective environmental governance in marine infrastructure projects requires dynamic monitoring systems capable of supporting evidence-based adaptive responses.

The results also revealed a significant positive relationship between life cycle environmental impacts and adaptive management strategies. This finding indicates that comprehensive evaluation of environmental consequences across planning, construction, operation, maintenance, and decommissioning stages enhances the capacity of organizations to implement adaptive management practices. The result supports the fundamental assumptions of life cycle assessment, which emphasize the importance of understanding cumulative and long-term environmental consequences rather than focusing exclusively on individual project phases. Previous studies have similarly highlighted the value of life cycle approaches for identifying environmental hotspots and informing strategic management decisions. Research examining renewable energy systems concluded that life cycle assessments provide essential information for optimizing sustainability performance and reducing environmental burdens throughout infrastructure life cycles (Portillo et al., 2024). Investigations of wave energy technologies further demonstrated that environmental impacts vary substantially across different life cycle stages, making comprehensive assessment essential for effective environmental management (Singh et al., 2024). Comparable conclusions have been reported in studies of floating photovoltaic systems and sustainable power grid expansion, where life cycle thinking was identified as a prerequisite for achieving long-term environmental sustainability (Byles & Mohagheghi, 2023; Oeishee, 2026). Consequently, the present findings confirm that life cycle environmental assessment serves as a critical foundation for adaptive environmental governance in marine infrastructure projects.

Another significant finding concerned the positive influence of pollution and emission management on adaptive management strategies. Marine infrastructure projects often generate environmental pressures through material extraction, construction activities, transportation operations, waste generation, and energy consumption. Effective pollution management therefore becomes essential for maintaining environmental quality and minimizing ecological degradation. The results suggest that organizations with stronger pollution control capabilities are better positioned to adopt adaptive environmental management practices because they possess greater awareness of environmental risks and mitigation opportunities. This finding aligns with previous studies emphasizing the importance of emissions reduction and environmental impact mitigation in sustainable marine development. Research on e-fuels for maritime transportation demonstrated that proactive environmental management significantly improves sustainability outcomes by reducing emissions and environmental burdens throughout operational life cycles (Zanobetti et al., 2025). Similar conclusions have been reported regarding environmental impacts associated with energy resources and renewable energy systems, where pollution prevention strategies contributed substantially to environmental performance improvements (Kabeyi & Olanrewaju, 2023; Portillo et al., 2024). Moreover, investigations concerning plastics and marine pollution have highlighted the necessity of integrated management approaches capable of addressing complex environmental interactions and cumulative ecological impacts (Rucevska et al., 2024; Schäli, 2022).

The current findings therefore support the growing consensus that pollution management constitutes a central component of adaptive environmental governance.

The study additionally found that ecosystem vulnerability assessment significantly influences adaptive management strategies. Marine ecosystems are characterized by high levels of ecological complexity, biodiversity richness, and environmental sensitivity. Infrastructure development can affect ecosystem functioning through habitat modification, biodiversity loss, hydrological changes, and cumulative ecological disturbances. Assessing ecosystem vulnerability allows managers to anticipate potential environmental consequences and implement preventive measures before significant ecological damage occurs. This finding is supported by previous research highlighting the importance of biodiversity conservation and ecosystem protection within sustainability frameworks. Studies examining ecological benefits associated with mariculture demonstrated that ecosystem-oriented management strategies can generate positive environmental outcomes while supporting economic development objectives (Liu et al., 2024). Likewise, reviews investigating renewable energy transitions and global plant diversity emphasized the necessity of accounting for ecosystem vulnerability when planning large-scale infrastructure developments (Gallagher, 2025). Research concerning climate mitigation pathways involving seaweed systems also highlighted the importance of preserving ecosystem integrity while pursuing sustainability goals (Burg et al., 2023). The current results therefore reinforce the argument that ecosystem vulnerability assessment should be integrated into all stages of marine infrastructure planning and management.

Resource utilization efficiency also emerged as a significant determinant of adaptive management strategies. Efficient use of materials, energy, water, and other resources contributes directly to environmental sustainability by reducing waste generation, minimizing resource depletion, and lowering environmental impacts. The positive association observed in this study suggests that organizations emphasizing resource efficiency are more likely to embrace adaptive management practices because both concepts share common objectives related to sustainability optimization and environmental stewardship. This finding corresponds closely with contemporary circular economy literature emphasizing resource recovery, waste minimization, and sustainable production systems. Research on integrated technologies for sustainable water management demonstrated that resource efficiency and circular resource recovery substantially improve environmental performance and resilience (Pandey, 2025). Similar findings have been reported in studies of seaweed-based biorefineries, sustainable aquaculture systems, and bio-based marine materials, all of which emphasize efficient resource utilization as a critical pathway toward sustainability (Arantzamendi et al., 2023; Chaurasiya et al., 2026; Pereira & Cotas, 2024). These studies support the present findings by illustrating how resource optimization contributes to both environmental protection and adaptive organizational capacity.

Stakeholder participation was also found to significantly enhance adaptive management strategies. Marine infrastructure projects affect multiple stakeholder groups, including governmental agencies, local communities, environmental organizations, industry representatives, and scientific institutions. Effective stakeholder engagement facilitates information exchange, increases social acceptance, improves transparency, and supports collaborative problem-solving. The significant relationship observed in this study indicates that stakeholder participation contributes directly to organizational adaptability by broadening knowledge bases and improving responsiveness to environmental concerns. This finding is highly consistent with previous studies emphasizing the role of stakeholder engagement in environmental governance. Research investigating environmental and social acceptance modules for ocean energy projects found that stakeholder involvement significantly improves environmental performance and sustainability outcomes (Araignous et al., 2023). Likewise, sustainability initiatives within the seafood sector have demonstrated that collaboration among stakeholders enhances environmental management effectiveness and supports sustainable development objectives (Laso et al., 2022). Therefore, the present results further validate stakeholder participation as a fundamental component of adaptive environmental management.

The most influential relationship identified in the study was the strong positive effect of adaptive management strategies on sustainability performance. This finding confirms the central proposition of the proposed model and demonstrates that adaptive management functions as a critical mechanism linking environmental assessment activities with sustainability outcomes. Organizations capable of learning from environmental feedback, adjusting management practices, integrating stakeholder perspectives, and responding proactively to environmental changes achieve superior sustainability performance. This result

aligns closely with previous studies emphasizing adaptive governance and sustainability-oriented decision-making. Research examining hydrogen transition strategies demonstrated that adaptive and flexible governance frameworks enhance sustainability performance under conditions of technological and environmental uncertainty (Yuan et al., 2025). Similar conclusions have been reported in studies of renewable energy integration, climate mitigation technologies, and sustainable infrastructure systems, where adaptive approaches were associated with improved environmental outcomes and resilience (Halim et al., 2023; Migo-Sumagang et al., 2023). Furthermore, investigations into marine concrete structures, climate-resilient naval systems, and offshore wind development have emphasized that adaptive management enhances both environmental sustainability and long-term infrastructure resilience (Avesani, 2025; Mihailov et al., 2024; Minoretti et al., 2025). Collectively, these findings provide strong support for the theoretical assumption that adaptive management represents a critical pathway through which environmental assessments translate into meaningful sustainability improvements.

The findings also have broader implications for sustainability transitions occurring across marine and coastal sectors. Studies involving deep-sea mining, sustainable healthcare manufacturing using marine resources, climate-friendly seafood production, and aquaculture carbon footprint reduction all demonstrate the growing need for integrated environmental management frameworks capable of balancing economic development with ecological protection (Ali et al., 2026; Jones et al., 2022; Li et al., 2024; Pereira & Cotas, 2024). The proposed model contributes to this objective by providing a structured framework that integrates environmental assessment, adaptive management, and sustainability performance within a single analytical system. Such integration is particularly important given the increasing complexity of marine infrastructure projects and the escalating environmental challenges associated with climate change, biodiversity loss, pollution, and resource scarcity. The strong model fit observed in the present study further suggests that adaptive management can serve as an effective organizing principle for environmental governance across diverse marine infrastructure contexts.

Several limitations should be acknowledged when interpreting the findings of this study. First, the research relied primarily on self-reported perceptions of experts and professionals, which may introduce response bias despite the participants' extensive experience. Second, the study employed a cross-sectional design that captured relationships among variables at a single point in time, limiting the ability to establish causal relationships conclusively. Third, participants were recruited from organizations located in Tehran, which may affect the generalizability of the findings to other geographical regions or institutional contexts. Fourth, although the proposed model incorporated major environmental and adaptive management dimensions, other potentially influential factors such as regulatory pressures, financial constraints, organizational culture, and technological maturity were not included. Finally, the study focused on a generalized marine infrastructure framework and did not differentiate among specific project types such as offshore wind farms, ports, marine energy facilities, or aquaculture systems.

Future studies should examine the proposed framework using longitudinal research designs to investigate how adaptive management strategies evolve throughout different phases of infrastructure life cycles. Researchers may also compare environmental impact pathways across various categories of marine infrastructure projects to determine whether sector-specific differences exist. Additional studies could incorporate economic, social, technological, and governance variables to develop more comprehensive sustainability models. Comparative international investigations would be valuable for identifying contextual factors that influence environmental management effectiveness across different regulatory and cultural environments. Future research may further employ advanced simulation techniques, system dynamics modeling, machine learning approaches, and scenario analysis methods to improve predictive capabilities and support strategic environmental planning under conditions of uncertainty.

Organizations responsible for planning, constructing, and operating marine infrastructure projects should establish comprehensive environmental monitoring systems that provide continuous feedback throughout project life cycles. Environmental assessments should be expanded beyond regulatory compliance requirements to include long-term ecosystem vulnerability, resource efficiency, and sustainability considerations. Project managers should institutionalize adaptive management practices through regular review processes, performance evaluation mechanisms, and evidence-based decision-making procedures. Stakeholder engagement should be incorporated into all stages of project development to improve transparency, environmental accountability, and social acceptance. Investment in digital monitoring technologies,

environmental data management platforms, and sustainability analytics can further strengthen adaptive management capabilities. Finally, policymakers should encourage the integration of life cycle assessment methodologies and adaptive management principles within environmental regulations and infrastructure planning frameworks to support sustainable marine development and long-term ecological resilience.

## Authors' Contributions

Authors contributed equally to this article.

## Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

## Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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## Declaration of Interest

The authors report no conflict of interest.

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## Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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