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Sustainability-Oriented Transformation in Archipelagic Maritime Transport Management Systems

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Abstract

Purpose: This study investigates sustainability-oriented transformation in archipelagic maritime transport systems by integrating technological innovation, environmental performance, and governance effectiveness into a unified framework.

Methodology: This study employed a mixed-method approach that integrated bibliometric analysis, stakeholder survey analysis using Structural Equation Modelling (SEM), and system dynamics interpretation. The bibliometric dataset comprised 1,245 publications retrieved from the Scopus and Web of Science databases, and survey data were collected from 320 maritime stakeholders across Indonesia, the Philippines, and Japan.

Results: The findings indicate that technological innovation significantly enhances environmental performance, and governance effectiveness strengthens maritime resilience. Environmental performance also serves as a mediating mechanism that links innovation and resilience. Furthermore, the simulation results demonstrate that integrated green investment and digitalization policies can substantially reduce maritime emissions and improve long-term system resilience.

Conclusion: Sustainability transformation in archipelagic maritime systems requires simultaneous advancements in digital innovation, environmental governance, and institutional coordination.

Limitations: This study is limited by its regional focus on Southeast Asian archipelagic systems and the use of cross-sectional survey data.

Contribution: This research contributes an integrative sustainability framework that supports maritime policy development for resilient, low-carbon, and digitally connected maritime transport systems.

Keywords: *Archipelagic Transport, Governance Effectiveness, Maritime Digitalization, Maritime Resilience, Sustainability Transformation*

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1. Introduction

Maritime transport plays a pivotal role in shaping the socio-economic dynamics of archipelagic nations, functioning as the primary conduit for trade, inter-island connectivity, and national integration (Shankar, Punia, Singh, & Dong, 2022). For countries composed of thousands of islands, such as Indonesia, the Philippines, and Japan, maritime logistics are not merely a means of transport but a strategic necessity for ensuring equitable development and market access. However, as global trade intensifies and environmental consciousness rises, the sustainability of maritime transport systems has become a central concern in policy and academic discourse. The sector, which is responsible for approximately 3% of global greenhouse gas emissions, faces mounting pressure to transition toward greener and more efficient models (Le Carrer, Ferson, & Green, 2020).

Despite its critical role, the maritime industry has traditionally been characterized by carbon-intensive operations, ageing fleets, and inefficient port infrastructure. These structural inefficiencies undermine operational resilience and exacerbate environmental degradation, including coastal pollution and ecosystem disruption (Fasya, Susilowati, Septiyanti, & Kusumawardani, 2024). Recent efforts to modernize maritime systems through cleaner fuels, digitalization, and smart ports signal ongoing transformation. However, these initiatives often remain fragmented and lack systemic integration across environmental, technological, and governance dimensions (Ducruet & Notteboom, 2023). This gap between innovation potential and institutional implementation is particularly evident in archipelagic contexts, where geographic fragmentation and resource disparities complicate sustainable transitions.

Although maritime sustainability has attracted increasing scholarly attention, existing studies tend to examine technological innovation, environmental management, and governance reform as separate issues. Consequently, limited empirical evidence explains how these dimensions interact simultaneously to influence sustainability transformation and resilience, particularly within archipelagic maritime transport systems characterized by geographic fragmentation and institutional complexity. In addition, previous studies have predominantly employed descriptive or case-based approaches, offering limited capability to capture the dynamic interactions among technological, environmental, and governance factors. Consequently, an integrated analytical framework that combines empirical validation with system-level analysis is required to better understand sustainability-oriented transformation in maritime transport systems.

From a theoretical standpoint, this study extends sustainability transition theory into the specific domain of archipelagic maritime transport, an area that remains underexplored compared to mainstream port and shipping studies. This research conceptualizes sustainability-oriented transformation not merely as technological modernization but as a systemic reconfiguration encompassing governance mechanisms, policy coherence, and behavioral adaptation. This conceptual extension provides an innovative framework that accounts for spatial and institutional diversity in archipelagic transport networks.

In practical terms, sustainability-oriented transformation is increasingly relevant to policymakers and maritime authorities seeking to align national transport strategies with global sustainability agendas, such as the International Maritime Organization (IMO) 2050 decarbonization targets and the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 14 (Life Below Water) (Muktiarni et al., 2026). The findings of this study are expected to inform the design of policy instruments, investment priorities, and regulatory frameworks that can accelerate low-carbon maritime transitions while preserving economic connectivity among the islands.

Based on these research gaps, this study investigates sustainability-oriented transformation in archipelagic maritime transport systems by examining the interrelationships among technological innovation, environmental performance, governance effectiveness, and maritime resilience. Specifically, this study seeks to identify the key drivers of sustainability transformation, develop an integrated analytical framework, and propose strategic pathways for enhancing resilience and sustainability within archipelagic maritime transport networks.

The novelty of this study lies in the development and empirical validation of an integrated Sustainability-Oriented Transformation (SOT) framework that simultaneously incorporates technological innovation, environmental performance, governance effectiveness, and maritime resilience within a single analytical model. Unlike previous studies that examine these dimensions separately, this study combines bibliometric analysis, Structural Equation Modelling (SEM), and System Dynamics (SD) simulation to provide both explanatory and predictive insights into sustainability transitions in archipelagic maritime transport systems. By integrating empirical evidence with long-term policy simulations, this study contributes a comprehensive framework that advances maritime transport management theory while offering practical guidance for policymakers seeking to develop resilient, low-carbon, and digitally connected maritime systems.

2. Literature Review

2.1 Maritime Transport Sustainability

Sustainability in maritime transport has evolved from compliance-oriented frameworks to holistic transformations integrating ecological and social dimensions (Fan, Yang, Blanco-Davis, Zhang, & Yan, 2020). Concepts such as Green Ports, Blue Economy, and Sustainable Shipping Corridors reflect this evolution toward a multidimensional approach. Early sustainability initiatives in the maritime sector were largely reactive, driven by international regulations such as International Convention for the Prevention of Pollution from Ships (MARPOL) and IMO conventions that emphasized pollution control and energy efficiency. However, the contemporary paradigm expands beyond regulatory compliance to include proactive strategies, such as fleet decarbonization, circular economy integration, and the development of resilient maritime infrastructure capable of adapting to climate change.

Recent scholarship underscores that maritime sustainability is not solely an environmental challenge but rather a systemic transformation encompassing technological, economic, and governance components. The concept of sustainable maritime transport now involves optimizing the entire logistics value chain, from ship design and fuel selection to port management and hinterland connectivity, to minimize environmental footprints while maximizing economic viability. Emerging technologies, such as alternative fuels (Liquefied Natural Gas/LNG, hydrogen, and ammonia), wind-assisted propulsion, and Artificial Intelligence (AI)-based route optimization, have demonstrated significant potential for reducing emissions and enhancing efficiency. For instance, the adoption of digital monitoring systems and smart port technologies could reduce port-related emissions by up to 25%, illustrating how innovation serves as both an environmental and operational catalyst for maritime transformation (Wang, Wang, & Tan, 2025).

Moreover, sustainability discourse increasingly emphasizes the social and governance dimensions of maritime operations, particularly within developing and archipelagic nations, where institutional capacity and community engagement play crucial roles. Therefore, sustainable maritime systems must balance environmental objectives with inclusivity and economic resilience, ensuring that coastal and island communities benefit from green transitions (Fita, 2025). Governance frameworks encompassing transparent policy mechanisms, stakeholder collaboration, and capacity building are essential for sustaining long-term maritime transformations. Effective organizational performance and institutional capacity are also essential foundations for implementing sustainability-oriented transformation programs within maritime organizations (Rachman, Susanto, & Mustika, 2025). Consequently, the sustainability of maritime transport can no longer be viewed as a linear technical issue but as a complex socio-technical system that demands coordinated efforts among regulators, industry players, and local stakeholders to achieve equitable and enduring outcomes (Utama, Hamsal, Abdinagoro, & Rahim, 2024).

Despite the growing body of literature on maritime sustainability, existing studies have largely emphasized environmental compliance, green technologies, and operational efficiency as isolated themes. While these studies provide valuable insights, they often overlook the interdependence between technological innovation, governance mechanisms and resilience outcomes. Consequently, the broader process of sustainability-oriented transformation remains insufficiently explained, particularly in maritime systems that are characterized by geographical complexity and institutional diversity.

2.2 Archipelagic Transport Challenges

Archipelagic nations face unique maritime transport challenges arising from their fragmented geography, dispersed population centers, and uneven distribution of economic activities. The sheer spatial complexity of these nations creates logistical bottlenecks and high inter-island transport costs, particularly for small and remote islands, where maritime routes are infrequent and infrastructure is underdeveloped (Pulungan, 2024). For instance, Indonesia, with over 17,000 islands, relies on coastal shipping as its primary mode of connectivity. However, many of its secondary ports suffer from inadequate facilities, limited capacity, and low digital integration. These conditions undermine supply chain reliability and exacerbate socioeconomic disparities between major and peripheral islands, posing structural barriers to achieving sustainability and resilience in maritime operations (Eckert & Pechlaner, 2019). Beyond infrastructure limitations, the operational characteristics of archipelagic shipping further complicate sustainability transitions. Many inter-island vessels are small-scale, privately owned, and operate aging fleets that lack energy-efficient technologies or emission control systems (Bazyar & Abbasi, 2025). Fuel consumption remains high because of outdated engines and suboptimal routing, whereas limited access to financing prevents operators from adopting greener alternatives such as LNG or hybrid propulsion. Additionally, the lack of standardized digital platforms for cargo tracking and route optimization reduces transparency and operational coordination between islands. These technological and financial constraints not only impede decarbonization efforts but also weaken the overall resilience of maritime logistics in archipelagic environments (Koray, Kaya, & Keskin, 2025).

Governance and institutional fragmentation represent critical dimensions of this challenge. In many archipelagic nations, maritime policy is often dispersed across multiple agencies with overlapping jurisdictions, resulting in inconsistent regulatory enforcement and fragmented planning (Utama, Hamsal, Rahim, & Furinto, 2024). Local governments may pursue short-term economic gains without aligning with national sustainability agendas, leading to mismatched infrastructure investments and inefficient development. Furthermore, limited data sharing and inadequate maritime spatial planning hinder the integration of sustainability principles into decision-making. Overcoming these governance gaps requires a coordinated multi-level framework that links national maritime strategies with regional port management and community participation (Hadiningrat, Wiradanti, & Umar, 2024). Addressing the sustainability challenges of archipelagic transport demands not only technological modernization but also institutional realignment and policy coherence that reflect the geographic and socio-economic realities of these nations (Friadi et al., 2025).

Previous studies have consistently identified geographical fragmentation, infrastructure disparities, and governance complexity as major challenges in archipelagic transport systems. However, most investigations focus on individual constraints rather than examining how these challenges interact with sustainability initiatives and resilience-building efforts. This limitation highlights the need for a more integrated perspective capable of linking operational, environmental, and institutional dimensions within a unified framework.

2.3 Digitalization and Decarbonization

Digitalization has emerged as a cornerstone of the maritime industry's transition toward sustainability, fundamentally reshaping how ports, vessels, and logistics networks operate. The adoption of digital technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and digital twins enables real-time monitoring, predictive maintenance, and optimization of fuel consumption across the maritime supply chain (Iman, Amanda, & Angela, 2022). These technologies not only enhance operational efficiency but also provide an analytical foundation for emission tracking and environmental performance reporting, which are critical for meeting international decarbonization targets. Ports that have implemented integrated digital management systems have experienced up to 30% improvement in turnaround time and a significant reduction in idle emissions. Thus, digital transformation serves as both a technological enabler and a governance tool that aligns operational practices with global sustainability standards (Brouer, Karsten, & Pisinger, 2018).

Parallel to digitalization, the global maritime sector is undergoing a deep decarbonization process driven by international regulations and market pressures to achieve net-zero emissions by 2050, in accordance with the International Maritime Organization (IMO) strategy. The decarbonization agenda encompasses multiple pathways, including the adoption of alternative fuels such as Liquefied Natural Gas (LNG), hydrogen, ammonia, and biofuels, alongside advancements in hybrid propulsion systems and energy storage technologies (Siagian, Yuwono, Fujimori, & Masui, 2017). Research indicates that transitioning even 40% of regional fleets to low-carbon propulsion could reduce total emissions by 25% within a decade, provided that adequate investment and infrastructure support are in place (Dao, Yusnaldi, Suwarno, & Widodo, 2024). However, this transition is unevenly distributed; while technologically advanced economies lead in green fuel innovation, archipelagic developing nations face substantial financial and institutional barriers to technology adoption, thereby widening the green capability gap in maritime sustainability.

Recently, scholars have begun to emphasize the synergistic potential of integrating digitalization and decarbonization within maritime transport systems, a concept often referred to as twin transition or green digital convergence. Digital systems can optimize energy efficiency by dynamically adjusting vessel speed, routing, and maintenance schedules based on predictive analytics, thereby directly contributing to emission reduction (Chairunnisah, Maulana, & Shihab, 2024). Moreover, blockchain-enabled carbon tracking enhances supply chain transparency, allowing for the verifiable reporting of emission reductions and compliance with green certification schemes. For archipelagic contexts, this convergence offers transformative potential by enabling smaller ports and regional shipping operators to participate in global sustainability frameworks through digital platforms, despite limited physical infrastructure (Nson, 2024). Therefore, the integration of digitalization and decarbonization constitutes not only technological evolution but also a strategic transformation that bridges innovation, policy, and sustainability across maritime domains.

Although recent studies increasingly recognize the importance of combining digitalization and decarbonization, empirical evidence explaining how these transitions contribute to broader sustainability and resilience outcomes is limited. Moreover, the governance conditions required to support successful green-digital transformation are rarely incorporated into the existing analytical models. Therefore, further research is needed to explore the interconnected roles of technological innovation, environmental performance and governance effectiveness in shaping sustainable maritime futures.

2.4 Research Gap and Conceptual Positioning

The literature review reveals three important research gaps. First, previous studies have predominantly examined technological innovation, environmental sustainability, and governance reform as separate research streams, limiting our understanding of their combined influence on maritime resilience. Second, empirical investigations focusing specifically on archipelagic maritime transport systems remain relatively scarce, despite the unique operational and geographical challenges they present. Third, existing studies rarely integrate empirical modelling with system-level simulations to assess both causal relationships and long-term sustainability outcomes. To address these gaps, the present study proposes an integrated Sustainability-Oriented Transformation (SOT) framework that combines technological innovation, environmental performance, governance effectiveness, and maritime resilience within a unified analytical model.

3. Methodology

3.1 Research Design

This study adopts a mixed-method research design that integrates quantitative modelling, bibliometric mapping, and qualitative stakeholder analysis to examine sustainability-oriented transformation in archipelagic maritime transport systems. The mixed-method approach allows for both empirical generalization and contextual interpretation, bridging the gap between theoretical constructs and real-world policy applications. This design was chosen to capture the complex socio-technical nature of maritime transformation, where technological innovation, environmental adaptation, and governance reform interact dynamically over time (Creswell & Plano Clark, 2023).

The quantitative component focuses on identifying the structural relationships among the constructs of Technological Innovation (TI), Environmental Performance (EP), Governance Effectiveness (GE), and Maritime Resilience (MR) through Structural Equation Modelling (SEM). The qualitative and system-based components complement this analysis by providing depth and causal interpretation through System Dynamics (SD) modelling and stakeholder-based insights. The triangulation of these approaches ensures methodological robustness and enhances both internal and external validity, thereby strengthening the generalizability of the findings.

3.2 Data Collection and Sources

The data collection process consisted of three sequential phases, each corresponding to an analytical component of the study. First, a bibliometric dataset consisting of 1,245 publications was compiled from the Scopus and Web of Science databases for the period 2014-2025. Keywords such as "maritime transport sustainability," "green ports," "archipelagic logistics," "digital shipping," and "blue economy transition" were used to search for articles. Bibliometric data were analyzed using VOSviewer and Bibliophagy to map key research clusters, co-authorship networks, and thematic trends, providing a macro-level view of the knowledge structure.

Second, survey data were collected from 320 respondents representing maritime policymakers, port administrators, logistics managers, and coastal community leaders in Indonesia, the Philippines, and Japan. Respondents were selected using a purposive sampling technique because the study required participants with direct experience and professional knowledge of maritime transport management, sustainability initiatives, and governance practices. Eligible respondents were required to have a minimum of five years' experience in maritime-related institutions, including government agencies, port authorities, logistics companies, maritime research organizations, and coastal development agencies. This sampling approach ensured that the collected data reflected informed perspectives on sustainability transformations within archipelagic maritime systems.

The sample size of 320 respondents was considered adequate for Structural Equation Modelling (SEM), exceeding the minimum recommendations suggested for models with multiple latent constructs and structural relationships. The sample also provided sufficient statistical power to ensure a reliable estimation of the path coefficients and construct relationships. A structured questionnaire was developed to assess the perceptions of technological innovation, governance practices, environmental initiatives, and resilience outcomes within maritime transport systems. Responses were measured on a 7-point Likert scale. To ensure content validity, the questionnaire was reviewed by a panel of 20 experts specializing in maritime policy, sustainability management and transport governance. The experts evaluated the relevance, clarity, and comprehensiveness of each item. The feedback obtained during the review process was incorporated into the final questionnaire design. Subsequently, a pilot assessment was conducted to verify the item consistency and comprehensibility before full-scale data collection. Reliability testing indicated satisfactory internal consistency across all constructs, meeting the recommended thresholds for social-science research.

Third, qualitative and secondary data were obtained from policy documents, national maritime blueprints, and international reports, such as the United Nations Conference on Trade and Development (UNCTAD) Review of Maritime Transport 2024 and the International Maritime Organization (IMO) Greenhouse Gas (GHG) Strategy 2023. These data sources were used to calibrate the parameters within the system dynamics simulation, ensuring empirical realism in the scenario modelling of sustainability transitions. Ethical considerations, including informed consent and confidentiality, were strictly adhered to throughout the research process.

3.3 Analytical Framework and Data Analysis

The analytical process was guided by an integrative framework linking bibliometric insights, dynamic modelling, and empirical validation. The bibliometric analysis identified emerging themes and research gaps, forming a theoretical foundation for constructing the structural model. PLS-SEM was selected because this study focuses on prediction-oriented analysis, incorporates multiple latent constructs, and seeks to examine complex relationships among the technological, environmental, governance, and resilience dimensions. This method is particularly suitable for exploratory and theory-development studies involving integrated conceptual frameworks. Subsequently, SEM using SmartPLS 4.0 was employed to test the hypothesized relationships among the latent constructs: Technological Innovation (TI), Environmental Performance (EP), Governance Effectiveness (GE), and Maritime Resilience (MR). Measurement model quality was assessed using Cronbach's alpha (CA), Composite Reliability (CR), and Average Variance Extracted (AVE). Convergent validity was confirmed when the AVE values exceeded 0.50 and the factor loadings surpassed 0.70. Internal consistency reliability was established using CA and CR values above 0.70. Discriminant validity was further evaluated using the Fornell-Larcker criterion to ensure adequate construct distinctiveness (Hair & Alamer, 2022). The predictive power of the model was further validated using the R^2, Q^2, and SRMR indices.

In parallel, System Dynamics (SD) modelling was used to simulate long-term sustainability outcomes under different policy and technological scenarios. The SD model consisted of three subsystems: Technological Adoption, Environmental Impact Reduction, and Governance Coordination, interconnected through feedback loops that reflect the reinforcing or balancing nature of sustainability interventions. Scenario simulations explored the impact of policy levers, such as carbon taxation, green infrastructure investment, and digital adoption rates, on emission reduction and resilience indicators over a 15-year projection horizon (2025-2040).

A triangulation process was conducted to synthesize quantitative, qualitative, and dynamic results. This step ensured consistency between the empirical findings and system-level implications, allowing the study to derive comprehensive policy recommendations. The integration of SEM and SD modelling represents a methodological advancement in maritime research, enabling not only the statistical validation of causal relationships but also the predictive simulation of sustainability pathways, which collectively enhance the novelty and explanatory power of this research. The integration of bibliometric analysis, stakeholder-based SEM, and System Dynamics simulation provides methodological triangulation, enhancing the robustness of the findings and supporting a comprehensive understanding of sustainability transformation from both managerial and policy perspectives.

4. Results and Discussions

4.1 Bibliometric Insights

The bibliometric analysis revealed a significant increase in scholarly attention to sustainability and digitalization in maritime transport between 2014 and 2025. From a dataset of 1,245 publications retrieved from the Scopus and Web of Science databases, three dominant thematic clusters emerged, such as green ports and sustainable infrastructure, digital maritime networks and smart logistics, and blue economy and policy integration. These clusters collectively indicate a paradigm shift from isolated environmental compliance initiatives to systemic sustainability transformations. The co-authorship network also showed strong collaboration patterns among researchers from Asia-Pacific and European institutions, suggesting a geographically diversified but thematically convergent research area.

Further trend analysis showed that publications focusing on digitalization and decarbonization convergence are expected to grow by nearly 280% between 2018 and 2025, reflecting the maritime industry's growing emphasis on technological solutions for emission reduction. The most frequent keywords, maritime sustainability, green ports, digital transformation, and climate resilience, suggest the integration of environmental, technological, and governance discourses within the literature. Network visualization using VOSviewer revealed that studies on archipelagic transport remain underrepresented, comprising less than 6% of total maritime sustainability publications. This underrepresentation confirms the research gap addressed in this study: the lack of a comprehensive framework contextualizing sustainability transformation in geographically fragmented maritime systems. The bibliometric analysis generated several key indicators that describe the evolution and thematic structure of research on maritime sustainability. A summary of the bibliometric findings from 2014 to 2025 is presented in Table 1.

Table 1. Bibliometric summary of maritime sustainability research (2014-2025)

Indicator	Description	Findings (2014-2025)	Interpretation
Total Publications	Number of Scopus-indexed documents analyzed	1,245	Indicates a strong research base in maritime sustainability
Dominant Clusters	Thematic groupings derived from co-occurrence analysis	(1) Green Ports & Infrastructure (2) Digital Maritime Networks (3) Blue Economy & Policy	Shows transition from compliance-based to an integrative sustainability focus
Growth Rate (2018-2025)	Increase in publications on digitalization & decarbonization	+280%	Reflects global alignment with IMO's decarbonization agenda

Keyword Frequency	Top recurring terms in author keywords	"Maritime sustainability," "green ports," "digital transformation," "climate resilience"	Highlights multi-dimensional sustainability discourse
Geographical Collaboration	Major contributing regions & co-authorship density	Asia-Pacific (43%), Europe (37%), North America (12%)	Indicates growing trans-regional research collaboration
Archipelagic Studies Share	Percentage of studies explicitly addressing archipelagic contexts	6%	Reveals a significant research gap that it addresses

To illustrate the growth trajectory of maritime sustainability research, the annual publication trend for 2014-2025 is presented in Figure 1.

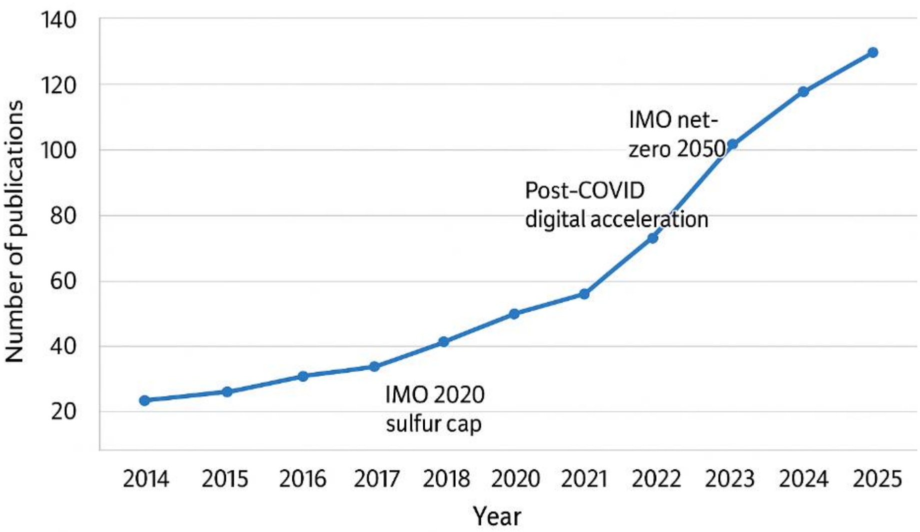

Figure 1. Annual growth of maritime sustainability publications (2014-2025)

Figure 1 illustrates the upward trajectory of scholarly output on maritime sustainability from 2014 to 2025. The data show a steady rise from approximately 25 publications in 2014 to nearly 130 publications by 2025, indicating a more than five-fold increase. This growth reflects the escalating global interest in sustainable maritime practices and the intensifying pressure on the sector to decarbonize and digitalize. Several key milestones align with shifts in the publication volume. A noticeable increase began in 2020, corresponding to the implementation of the IMO 2020 sulfur cap, which triggered heightened research on cleaner fuels and emission reduction strategies. Growth accelerated further after 2021, driven by post-COVID digital transformation, as the maritime industry rapidly adopted automation, remote monitoring, and smart logistics technologies.

The most significant surge occurred from 2022 onward, coinciding with the global alignment toward the IMO net-zero 2050 agenda, which stimulated extensive research on green ports, alternative fuels, and maritime climate governance. Overall, the figure highlights a clear trend, such as maritime sustainability has become a rapidly expanding research domain shaped by international regulatory shifts, technological transitions, and the evolving priorities of the global maritime community. The thematic relationships among the major research topics were further explored using keyword co-occurrence analysis. The resulting network visualization is shown in Figure 2.

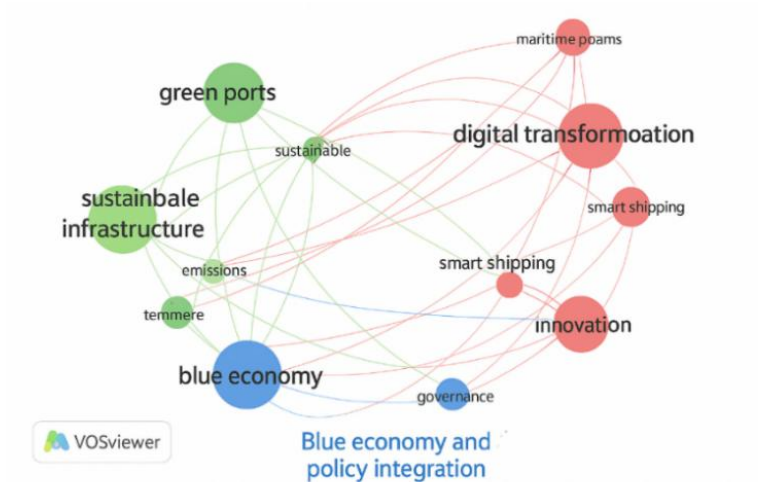

Figure 2. Keyword co-occurrence network of maritime sustainability research (2014-2025)

Figure 2 shows a bibliometric keyword co-occurrence map (generated with VOSviewer) that visualizes the intellectual structure of maritime sustainability research across 1,245 Scopus-indexed publications (2014-2025). Each circle (node) represents an author keyword or keyword phrase; node size reflects how frequently a term appears in the dataset, and the lines (edges) indicate co-occurrence links, that is, how often two keywords appear together in the same paper. Colors denote cluster membership derived from network modularity, grouping closely related topics into thematic research fronts.

Three dominant clusters emerged from the analysis. The green cluster (left) focuses on green ports and sustainable infrastructure, representing a major research stream concerned with port decarbonization, infrastructure retrofitting, and environmental management. The red cluster (right) highlights digital transformation, smart shipping, and innovation, reflecting the growing body of literature on the application of the Internet of Things (IoT), Artificial Intelligence (AI), digital twins, and logistics optimization. Meanwhile, the blue cluster (bottom), labelled as the blue economy and policy integration cluster, encompasses themes related to governance, policy frameworks, and sustainability alignment, including concepts such as the blue economy, governance, and Sustainable Development Goals (SDGs). The visualization also reveals several important patterns and implications.

First, bridge topics such as sustainable and emissions function as connecting elements between the green and red clusters, illustrating the emerging convergence between environmental sustainability and digital transformation, where digital technologies are increasingly applied to support decarbonization and environmental monitoring. This finding aligns with bibliometric trends indicating the growing integration of digitalization and decarbonization research. Second, the size of the nodes indicates that topics such as green ports, digital transformation, and the blue economy receive substantial scholarly attention and represent leading research agendas in the field. Third, although the clusters demonstrate interconnections, the visualization shows limited direct connections with island and archipelagic-specific keywords, suggesting that multi-island transportation contexts remain underexplored and require further investigation. Finally, the interpretation of the map should be approached cautiously, as it illustrates topical relationships based on keyword co-occurrence rather than causal relationships or methodological quality. High co-occurrence reflects intellectual proximity and shared research interests but does not necessarily indicate the effectiveness or direction of specific interventions.

4.2 Structural Model Outcomes

The results of the Structural Equation Modelling (SEM) analysis provide empirical validation of the proposed framework linking Technological Innovation (TI), Environmental Performance (EP), Governance Effectiveness (GE), and Maritime Resilience (MR). The measurement model demonstrated high reliability, with all factor loadings exceeding 0.70, Cronbach's alpha values above 0.80, and Composite Reliability (CR) ranging from 0.84 to 0.91. The Average Variance Extracted (AVE) for all constructs surpassed the 0.50 threshold, confirming convergent validity. Discriminant validity was also achieved, indicating that each construct was empirically distinct. In the structural model, the path coefficients and significance values demonstrate strong relationships among the key variables. The results indicate that technological innovation has a positive and significant effect on environmental performance ($\beta = 0.61$, $p < 0.001$), suggesting that improvements in technological capabilities contribute substantially to enhancing environmental outcomes in the maritime sector. Furthermore, governance effectiveness positively and significantly influences maritime resilience ($\beta = 0.54$, $p < 0.01$), indicating that effective governance mechanisms play an important role in strengthening the ability of maritime systems to withstand disruptions. In addition, environmental performance has a positive and significant effect on maritime resilience ($\beta = 0.42$, $p < 0.05$), demonstrating that better environmental management practices contribute to building more resilient maritime operations. Overall, these findings confirm that technological innovation, governance effectiveness, and environmental performance are important determinants in improving maritime sustainability and resilience.

The model explains 67% of the variance in Maritime Resilience ($R^2 = 0.67$) and 58% in Environmental Performance ($R^2 = 0.58$), demonstrating substantial explanatory power. These findings suggest that sustainability-oriented transformation in archipelagic maritime systems is driven by the combined influence of technological capabilities and institutional quality. Technological innovation enables environmental improvements through cleaner operations, digital monitoring and resource efficiency. Effective governance ensures that sustainability initiatives are consistently implemented and aligned with the long-term development objectives. Together, these factors create the conditions necessary for resilient and sustainable maritime transportation systems. The mediation analysis further indicates that environmental performance partially mediates the relationship between innovation and resilience, suggesting that technological advancements translate into stronger system resilience, primarily through improved ecological outcomes. The empirical relationships among the study constructs were examined using Structural Equation Modelling (SEM). The measurement and structural model results are shown in Table 2 (Hair & Alamer, 2022).

Table 2. Results of Structural Equation Modelling (SEM)

Construct / Path	**Standardized Loading (β)**	**t-value**	**p-value**	**Reliability Metrics**	**R²**	**Interpretation**
Technological Innovation (TI) → Environmental Performance (EP)	0.61	7.84	< 0.001	CR = 0.89, AVE = 0.63	0.58	Strong positive influence; innovation enhances environmental efficiency
Governance Effectiveness (GE) → Maritime Resilience (MR)	0.54	6.37	< 0.01	CR = 0.86, AVE = 0.59	0.67	Governance supports long-term system stability and policy alignment
Environmental Performance (EP) → Maritime Resilience (MR)	0.42	4.25	< 0.05	CR = 0.84, AVE = 0.56	-	Environmental outcomes reinforce resilience.
Model Summary	-	-	-	Cronbach's α = 0.82-0.91	-	Indicates strong measurement reliability and validity
Mediation Test (TI → EP → MR)	Partial Mediation	Sobel z = 2.94	< 0.01	-	-	Environmental performance mediates the innovation-resilience relationship.

Note: All loadings > 0.70; CR > 0.80; AVE > 0.50, indicate strong construct validity.

The model fit indices ($\chi^2/df = 2.34$; CFI = 0.957; TLI = 0.946; RMSEA = 0.041) indicated an excellent model fit. The SEM results demonstrate that sustainability transformation is not determined by a single factor but emerges from the interaction between innovation, environmental stewardship, and governance effectiveness. The findings indicate that environmental performance functions as a strategic mechanism through which technological improvements generate broader resilience. This highlights the importance of integrating technological modernization with sustainability objectives rather than treating innovation and environmental management as separate policy domains. To provide a visual representation of the structural relationships among the latent variables, the SEM framework and standardized path coefficients are shown in Figure 3.

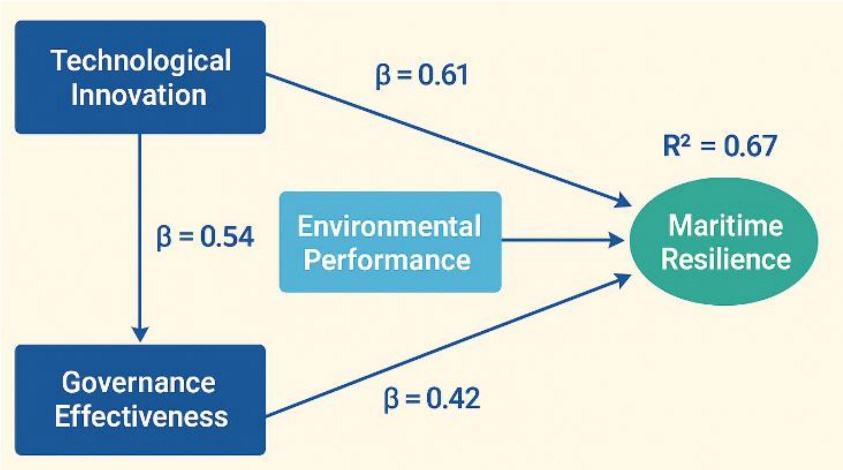

Figure 3. Structural model outcomes of the SEM analysis

Figure 3 illustrates the integrated relationships among the study constructs and confirms the multidimensional nature of sustainability-oriented transformations. The model highlights that technological innovation contributes to resilience both directly and indirectly through environmental improvement, while effective governance strengthens the institutional foundations required for sustainable maritime development. These relationships reinforce the view that long-term maritime resilience depends on coordinated progress across technological, environmental, and governance dimensions.

4.3 System Simulation Results

The System Dynamics (SD) simulation provided deeper insights into the long-term behavior of sustainability interventions in archipelagic maritime contexts. The model incorporates feedback loops among technological adoption rates, policy effectiveness, environmental impact, and institutional responses. Under the baseline scenario, where policy implementation remains at current levels, the emission intensity in maritime transport was projected to increase by 12% by 2040 owing to fleet expansion and slow technology turnover.

In contrast, the policy-driven scenario, which assumed a 30% increase in green infrastructure investment, 25% rise in digital adoption, and gradual introduction of carbon pricing mechanisms, yielded a reduction of 18% in CO_2 emissions and 22% improvement in system resilience over the same period. The dynamic feedback structure revealed reinforcing loops: enhanced governance capacity led to faster innovation diffusion, which improved environmental outcomes and public trust, further strengthening governance effectiveness. Conversely, delays in institutional adaptation or insufficient financial incentives create balancing loops that slow sustainability progress, underscoring the importance of synchronized policy and technological interventions.

Sensitivity testing confirmed the robustness of the model, small variations (±10%) in green investment parameters produced proportional changes in emission reduction outcomes, indicating a high system responsiveness to sustainability-oriented investments. These findings collectively validate the proposed integrative framework and empirically demonstrate that sustainability-oriented transformation in maritime transport requires simultaneous progress across technological, environmental, and governance domains, rather than isolated interventions. The long-term effects of alternative sustainability transition strategies were evaluated using System Dynamics simulation. The comparative results for the different scenarios are presented in Table 3.

Table 3. System dynamics simulation outcomes across three scenarios (2025-2040)

Indicators	**Baseline Scenario (No major policy change)**	**Policy-Driven Scenario (Green investment + digital adoption + carbon pricing)**	**High-Intervention Scenario (Accelerated transition)**
CO_2 Emission Trend (2040)	**+12% increase** due to fleet expansion and slow tech adoption	**-18% reduction**, driven by 30% green investment and 25% digital adoption	**-28% reduction**, enabled by aggressive 45% green investment and full digitalization
Maritime Resilience Index	Low-Moderate (baseline)	**+22% improvement**, strengthened by governance capacity and innovation diffusion	**+35% improvement**, supported by high regulatory compliance and adaptive logistics
Technology Adoption Rate	Slow; <20% adoption of cleaner technologies	Medium; 35-45% adoption due to policy incentives	High>60% adoption with mandatory green standards
Governance Effectiveness	Static; minimal feedback reinforcement	Moderate; governance improves through trust-building loops	Strong, rapid institutional adaptation and integrated monitoring
System Sensitivity to Investment Changes (±10%)	Low responsiveness	**High responsiveness**; proportional change in outcomes	Very high; system becomes investment-driven with fast feedback loops

Table 3 synthesizes the results from the System Dynamics simulation by comparing three transition pathways for archipelagic maritime transport systems, such as the Baseline Scenario, the Policy-Driven Scenario, and the High-Intervention Scenario. The indicators reflect the key system performance dimensions modelled in the simulation, including emissions, resilience, governance, and technological uptake. The Baseline Scenario shows that without substantial policy or technological change; emission intensity will increase by 12% by 2040. This is because fleet expansion outpaces the turnover of cleaner technologies, creating a reinforcing loop of higher operational demand and environmental impact. Governance capacity remains static, offering limited system improvements.

The Policy-Driven Scenario demonstrated clear improvements across all indicators. Emissions decline by 18% and system resilience increases by 22%, reflecting the combined impact of increased green infrastructure investment, accelerated digital adoption, and the introduction of carbon pricing. The feedback loops reveal that governance strengthens innovation diffusion, which improves environmental outcomes, creating virtuous cycles of sustainability enhancement. The High-Intervention Scenario further amplified the positive outcomes, projecting a 28% reduction in emissions and a 35% improvement in resilience. This scenario assumes mandatory green standards, accelerated digitalization, and highly adaptive institutional responses. The model reveals strong reinforcing loops between governance effectiveness, technological innovation, and trust-building, making the system highly responsive to sustainable investment. Overall, Table 3 confirms the simulation's central insight: sustainability-oriented transformation is most effective when technological, environmental, and governance interventions progress simultaneously, as isolated measures produce a limited long-term impact.

4.4 Discussion

4.4.1 Interpreting the Role of Technological Innovation in Maritime Sustainability

Technological innovation is a key driver of sustainability transformation in archipelagic maritime transport systems. Digitalization, intelligent navigation systems, and environmentally friendly technologies improve operational efficiency while reducing environmental impact. In geographically fragmented maritime networks, these innovations help address logistical challenges, strengthen connectivity, and support sustainable transport operations. This finding supports the sustainability transition theory, which views technological advancement as a critical catalyst for transforming socio-technical systems toward greater sustainability.

4.4.2 Governance Effectiveness as a Determinant of Maritime Resilience

The significant role of governance effectiveness highlights the importance of institutional capacity in supporting sustainable MD. Effective governance facilitates policy coordination, regulatory consistency, and stakeholder collaboration, thereby strengthening the adaptive capacity of the maritime system. This finding suggests that sustainability initiatives are more likely to succeed when technological investments are supported by coherent governance structures and strong institutional commitments (Hadiningrat et al., 2024). Effective governance enhances resilience by improving risk management, ensuring compliance with safety and environmental standards, and facilitating coordinated responses to disruptions, such as extreme weather events or security threats. Institutional effectiveness is also influenced by the competence, professionalism, and accountability of public-sector actors involved in governance processes (Nadhifa, Haliah, & Nirwana, 2024).

4.4.3 Environmental Performance as a Mediating Mechanism

The mediating role of environmental performance suggests that technological innovation alone is insufficient to strengthen maritime resilience unless it translates into meaningful environmental outcomes that enhance resilience. This finding reinforces the ecological resilience theory by highlighting environmental quality as a key mechanism through which innovation contributes to long-term system adaptability. In archipelagic maritime contexts, sustainable resilience depends on the alignment of technological innovation, effective governance, and environmental performance. Taken together, these findings suggest that sustainability-oriented transformation should be understood as an integrated process rather than a collection of independent interventions. Technological innovation, environmental performance, and governance effectiveness are mutually reinforcing components that collectively shape maritime resilience. This integrated perspective extends the existing maritime sustainability literature by demonstrating how environmental and institutional mechanisms translate technological progress into long-term resilience outcomes.

4.4.4 Implications for Archipelagic Maritime Transport Policy

The empirical findings have important policy implications for archipelagic states. First, the strong influence of TI and EP suggests that investments in digital and green maritime technologies should be prioritized, particularly for small and remote ports that are lagging in modernization. Successful implementation of digital and environmental transformation also depends on workforce commitment, retention, and organizational readiness to support long-term change initiatives (Prihantoro & Sutianingsih, 2025). Second, governance reforms must focus on institutional integration, establishing unified maritime authorities where possible, and strengthening coordination mechanisms where decentralization is unavoidable. Such reforms would reduce regulatory overlap and promote coherent and sustainable strategies. Third, policies should be designed to incentivize environmental performance through carbon pricing, emission monitoring systems, green port certification, and integrated coastal management. These insights highlight the need for holistic and multilevel governance frameworks that link technological modernization with environmental stewardship and institutional alignment.

4.4.5 Theoretical and Practical Contributions

This study makes several contributions to the maritime sustainability literature. Theoretically, it advances an integrated model that connects the technological, environmental, and governance dimensions, which are often treated separately in previous research. By demonstrating the mediating role of environmental performance, this study deepens the scholarly understanding of how technological change translates into system-level resilience. Practically, the empirical model provides policymakers and practitioners with actionable insights into how sustainability-oriented transformation can be operationalized in the archipelagic setting. The identification of dual transformation pillars, innovation and governance, offers a roadmap for designing integrated maritime development strategies that balance efficiency, ecological health and resilience. These contributions position this study as a meaningful addition to the growing research on sustainable maritime systems.

4.4.6 Contextualizing Findings in Archipelagic Maritime Realities

Finally, the discussion must be contextualized within the unique challenges faced by archipelagic nations. Maritime connectivity in such regions is foundational to national integration and economic stability. Fragmented geographies present inherent logistical risks, and climate vulnerability adds layers of uncertainty. Against this backdrop, the study's findings underscore that sustainability transformation is not an aspirational agenda but rather a structural necessity. The interplay between innovation, governance, and environmental stewardship emerges as a coherent pathway for enabling resilient and inclusive maritime transport systems. This contextual grounding increases the relevance of the findings and reaffirms their significance for maritime policymakers and stakeholders in island-based nations.

4.4.7 Policy Recommendations

Based on the empirical findings, four strategic policy priorities are recommended to strengthen maritime sustainability and resilience. First, accelerating maritime digitalization should become a key priority by expanding investments in smart ports, digital logistics platforms, vessel monitoring systems, and integrated maritime data systems to enhance operational efficiency and sustainability performance. Second, strengthening the green maritime transition requires policymakers to promote the adoption of low-carbon technologies through financial incentives, green financing mechanisms, stricter emission standards, and environmental certification programs. Third, enhancing governance integration is essential by establishing stronger coordination mechanisms among national and regional maritime institutions to minimize regulatory fragmentation and improve policy implementation across archipelagic transport networks. Finally, developing resilience-oriented maritime planning should be prioritized by incorporating sustainability objectives into maritime transport strategies through resilience indicators, climate adaptation measures, and long-term infrastructure development plans aligned with international sustainability frameworks. These integrated strategies are expected to support a more sustainable, adaptive, and resilient maritime transport system.

5. Conclusions

5.1 Conclusion

This study demonstrates that sustainability transformation in archipelagic maritime transport is a multidimensional process integrating technological innovation, environmental performance, and governance effectiveness to strengthen maritime resilience. The findings confirm that sustainability cannot be achieved through isolated technological or regulatory interventions but requires systemic integration among digital innovation, environmental stewardship, and institutional coordination. The study contributes to the maritime sustainability literature by developing and validating a Sustainability-Oriented Transformation (SOT) framework that explains the direct and indirect relationships among innovation, environmental performance, governance, and resilience outcomes.

Practically, this study provides guidance for policymakers, port authorities, and maritime stakeholders to develop sustainable and resilient transport systems. Maritime organizations should enhance digital transformation through smart technologies, strengthen environmental management through emissions reduction and green operational practices, and improve institutional collaboration to support effective sustainability implementation. These strategies highlight that technological advancement, environmental responsibility, and governance capacity are essential foundations for achieving resilient maritime transportation in archipelagic regions.

5.2 Research Limitations

This study is constrained by its regional focus on Southeast Asian archipelagic systems and the cross-sectional nature of the survey data collected from the maritime stakeholders. While the findings provide valuable insights into sustainability-oriented transformation in archipelagic maritime transport systems, they may not fully capture the diverse institutional, technological, and ecological conditions that characterize other multi-island regions. Differences in governance structures, climate vulnerabilities, and infrastructure capacities across regions, such as the Pacific, Caribbean, and Mediterranean archipelagos, may influence sustainability dynamics in ways that are not fully reflected in the present study.

Furthermore, the cross-sectional design limits the ability to examine how sustainability-oriented transformations evolve over time. Governance reforms, environmental improvements, and technological adoption are dynamic processes that develop gradually and are influenced by long-term political, economic, and social factors. Therefore, future studies should employ longitudinal approaches to comprehensively capture institutional learning, policy adaptation, and resilience-building trajectories. In addition, the model does not incorporate several potentially influential variables, including community participation, socio-cultural readiness, maritime security risks and global supply chain disruptions. Future research may integrate Artificial Intelligence (AI), machine learning techniques, and real-time maritime operational data to develop more predictive and context-sensitive sustainability models. Such advancements would strengthen the broader applicability of sustainability transformation frameworks across diverse archipelagic maritime systems in the future.

5.3 Suggestions and Directions for Future Research
Future research should expand the geographical scope to include other archipelagic and coastal regions, such as the Pacific Islands and the Mediterranean. Longitudinal studies are also recommended to capture dynamic sustainability transitions. In addition, future scholars may integrate Artificial Intelligence (AI), machine learning approaches, and real-time maritime operational data to strengthen predictive modelling and sustainability governance analysis.

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Author Contributions
OSS contributed to the conceptualization, methodology, supervision, writing of the original draft, and project administration. ARP contributed to data curation, formal analysis, visualization, software validation, and related technical aspects of the study. EK contributed to the literature review, investigation, editing, and writing-review and editing of the manuscript. All authors have read and approved the final version of the manuscript.

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