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Sustainable Sea Transportation Management for Reducing Maritime Emissions and Strengthening Global Supply Chain Resilience

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Abstract: Maritime transportation plays a critical role in global trade but also contributes to greenhouse gas emissions and faces increasing risks associated with disruptions in international supply chains. This study examines how sustainable maritime transportation management can contribute to reducing maritime emissions while strengthening global supply chain resilience. The research employs a qualitative literature review approach based on academic publications, research reports, and other relevant scholarly sources. The selected literature was examined using qualitative content analysis to identify recurring themes, relationships, and strategic mechanisms linking sustainable shipping practices, emission reduction, and supply chain resilience. The findings highlight energy efficiency, alternative fuels, digitalization, operational optimization, stakeholder collaboration, and adaptive capabilities as key components of sustainable maritime transportation management. The synthesis suggests that environmental sustainability and supply chain resilience can reinforce each other when emission reduction strategies are integrated with operational and organizational capabilities. The study contributes to the existing literature by presenting an integrated management perspective that connects maritime decarbonization with supply chain resilience. The findings emphasize the importance of aligning environmental objectives with operational efficiency, risk management, and organizational adaptability. This approach offers practical insights for shipping companies, port operators, logistics providers, and policymakers seeking to reduce environmental impacts while maintaining reliable and resilient maritime supply chains. Overall, sustainable maritime transportation management is identified as an

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important strategic capability for supporting maritime decarbonization and strengthening the long-term resilience of global supply chains.

Keywords: sustainable shipping; maritime emissions; supply chain resilience; maritime decarbonization; sustainable transportation management; maritime sustainability.

可持续海上运输管理：减少海运排放与增强全球供应链韧性

摘要：海上运输在全球贸易中发挥着至关重要的作用，但同时也是温室气体排放的重要来源之一，并面临国际供应链中断所带来的日益增长的风险。本研究探讨可持续海上运输管理如何在减少海运排放的同时增强全球供应链韧性。研究采用定性文献综述方法，以学术出版物、研究报告及其他相关学术文献为基础，通过定性内容分析，识别可持续航运实践、减排措施与供应链韧性之间反复出现的主题、相互关系及战略机制。研究结果表明，能源效率提升、替代燃料应用、数字化转型、运营优化、利益相关者协作以及适应性能力是可持续海上运输管理的关键组成部分。文献综合分析表明，当减排战略与运营能力和组织能力有效整合时，环境可持续性与供应链韧性能够相互促进、形成协同效益。本研究通过提出将海运脱碳与供应链韧性相结合的一体化管理视角，为现有研究提供了新的理论参考。研究结果强调，应将环境目标与运营效率、风险管理及组织适应能力相协调。这一管理方法可为航运企业、港口运营商、物流服务提供商及政策制定者提供实践参考，帮助其在减少环境影响的同时，维持海上运输供应链的可靠性与韧性。总体而言，可持续海上运输管理可被视为支持海运脱碳和增强全球供应链长期韧性的重要战略能力。

关键词：可持续航运；海运排放；供应链韧性；海运脱碳；可持续运输管理；海运可持续性。

1. Introduction

Maritime transportation is essential to global trade, but its reliance on fossil fuels contributes significantly to greenhouse gas emissions and environmental degradation. At the same time, maritime supply chains face growing disruptions from geopolitical tensions, extreme weather, port congestion, and energy price volatility. These challenges require maritime transportation to balance operational efficiency, environmental sustainability, and supply chain resilience. However, conventional management approaches often treat these dimensions separately, creating tensions between emission reduction and service reliability. Therefore, sustainable sea transportation management has become a strategic priority, as environmental performance and supply chain resilience are increasingly interconnected with maritime competitiveness[1]. The central problem is that shipping systems must simultaneously respond to pressure for lower maritime emissions and the growing requirement for resilient global supply chains. This situation demonstrates the need for an integrated management perspective capable of connecting sustainable maritime operations with long-term supply chain resilience[2].

Existing literature has provided substantial explanations regarding maritime sustainability, emission reduction, green logistics, and supply chain resilience, but these streams of research frequently develop through relatively separate theoretical perspectives. Studies on sustainable shipping commonly emphasize fuel efficiency, alternative energy, vessel optimization, technological innovation, and environmental regulation as mechanisms for reducing emissions. Meanwhile, supply chain resilience literature primarily focuses on flexibility, redundancy, visibility, collaboration, risk management, and the ability of supply chains to absorb and recover from disruptions. Although these theoretical perspectives are valuable individually, they do not always adequately explain how sustainable sea transportation management can simultaneously contribute to emission reduction and strengthen the resilience of global supply chains. A management approach that focuses exclusively on environmental performance may overlook operational continuity, while a resilience-oriented approach that

prioritizes uninterrupted transportation may unintentionally reinforce dependence on carbon-intensive practices. This limitation indicates that existing theories do not fully capture the strategic interaction between maritime environmental performance and supply chain resilience. Furthermore, technological solutions alone cannot guarantee sustainable outcomes when organizational capabilities, transportation planning, stakeholder coordination, regulatory adaptation, and risk management are not integrated into decision-making. Therefore, there remains a conceptual and practical gap concerning how sea transportation management can reconcile environmental objectives with resilience requirements. Addressing this gap is important because global maritime systems increasingly operate under simultaneous pressures for decarbonization, efficiency, reliability, and adaptability, making an integrated sustainable management perspective increasingly necessary[3].

This study aims to examine the strategic role of sustainable sea transportation management in reducing maritime emissions while strengthening the resilience of global supply chains. The research specifically seeks to develop an integrated understanding of how managerial practices within maritime transportation can support environmental sustainability without compromising the reliability, flexibility, and continuity required by increasingly complex international supply chains. To achieve this objective, the study focuses on the relationship between sustainable shipping practices, maritime emission reduction, and supply chain resilience as interconnected dimensions of contemporary transportation management. Sustainable shipping practices are considered not merely as environmental initiatives but as managerial mechanisms that may influence operational efficiency, resource utilization, risk exposure, and the capacity of maritime networks to respond to disruption. The study also seeks to identify how emission-oriented strategies, including cleaner energy utilization, operational optimization, technological adoption, and environmentally responsible transportation planning, can be aligned with resilience-oriented strategies such as flexibility, collaboration, diversification, and adaptive capacity. By examining these relationships collectively, the research intends to contribute to a more comprehensive conceptualization of sustainable maritime transportation management. The ultimate objective is to provide an analytical foundation for understanding how maritime organizations and supply chain stakeholders can pursue decarbonization while simultaneously maintaining robust transportation performance. Thus, the study positions sustainable sea transportation management as a strategic bridge between environmental responsibility and supply chain resilience, rather than treating these objectives as independent managerial priorities[4].

The central argument of this study is that sustainable sea transportation management can become an important strategic mechanism for simultaneously reducing maritime emissions and strengthening global supply chain resilience when environmental, operational, technological, and organizational dimensions are managed in an integrated manner. This argument is based on the premise that emission reduction should not be viewed solely as a regulatory obligation or environmental objective but also as an opportunity to improve the efficiency, adaptability, and long-term reliability of maritime transportation systems. Investments in cleaner technologies, alternative fuels, energy-efficient operations, digital monitoring, route optimization, and collaborative transportation planning may reduce environmental impacts while also improving resource efficiency and operational visibility. These improvements can increase the ability of maritime actors to anticipate risks, adjust transportation activities, and maintain service continuity when disruptions occur. Accordingly, the study advances the proposition that sustainable maritime management practices have the potential to generate a complementary relationship between decarbonization and resilience rather than an unavoidable trade-off. The importance of this research therefore lies in its effort to reposition maritime sustainability within a broader strategic framework of global supply chain management. If sustainability and resilience are systematically integrated, maritime transportation can contribute not only to lower emissions but also to more adaptive and robust international trade networks. Based on this reasoning, the study argues that sustainable sea transportation management should be treated as a strategic capability for addressing the simultaneous environmental and operational challenges confronting contemporary global supply chains[5].

2. Methods

2.1. Research Object

The object of this study is the phenomenon of sustainable sea transportation management in addressing the dual challenges of maritime emissions reduction and global supply chain resilience. The study examines the management practices, strategic approaches, and operational mechanisms through which maritime transportation can reduce its environmental impact while maintaining the continuity and adaptability of international supply chains. This object is selected because maritime transportation occupies a strategic position in global trade, connecting production centers, ports, distribution networks, and international markets, while simultaneously contributing to greenhouse gas emissions and exposure to various operational disruptions. The phenomenon is therefore not examined merely as an environmental problem, but as an interconnected management issue involving sustainability, transportation efficiency, technological development, risk management, and supply chain continuity. Particular attention is directed toward sustainable shipping practices, including energy

efficiency, cleaner fuels, technological innovation, route and fleet optimization, digitalization, and collaborative management among maritime stakeholders. At the same time, the study considers resilience dimensions such as adaptability, flexibility, risk anticipation, recovery capacity, and continuity of maritime logistics services. The object of analysis is consequently the relationship between sustainable transportation practices and the ability of global supply chains to withstand and respond to disruption. By positioning this phenomenon as the central research object, the study establishes a clear analytical boundary that remains focused on sustainable sea transportation management, maritime emissions, and supply chain resilience[6].

2.2. Research Type and Data Sources

This study employs a qualitative library research approach, in which the research process is conducted through systematic examination, comparison, interpretation, and synthesis of relevant written sources concerning sustainable sea transportation management, maritime emissions, and global supply chain resilience. Rather than collecting primary information through surveys, interviews, or field observations, the study treats relevant documentary literature as its primary source of analytical evidence, particularly scientific publications that directly discuss the phenomenon under investigation. The primary data therefore consist of relevant scholarly literature addressing sustainable shipping practices, maritime decarbonization, emission reduction strategies, transportation management, and supply chain resilience. Secondary data complement these sources by providing broader conceptual, theoretical, and contextual information related to the three principal keywords of the study: sustainable shipping, maritime emissions, and supply chain resilience. These secondary sources include academic books, peer-reviewed journal articles, conference papers, research reports, institutional publications, and other scientifically relevant documents. The selection of literature is guided by its relevance to the research problem, conceptual contribution, scientific credibility, and capacity to explain relationships among the variables or concepts examined. Literature published across different periods is considered when it provides foundational theoretical explanations or important developments in maritime sustainability and resilience. Through this approach, the study integrates diverse documentary evidence into a coherent analytical framework, allowing the research problem to be examined comprehensively through established knowledge and previous scholarly findings[7].

2.3. Theoretical Foundation

The theoretical foundation of this study integrates sustainability and organizational resilience perspectives to explain why sustainable sea transportation management can contribute simultaneously to environmental performance and supply chain resilience. The sustainability perspective is primarily informed by the Triple Bottom Line theory introduced by John Elkington in 1997, which conceptualizes organizational sustainability through the interconnected dimensions of economic prosperity, environmental quality, and social responsibility[8]. This theory provides a foundation for understanding maritime sustainability as a multidimensional management responsibility rather than merely an effort to reduce emissions. In addition, the study draws upon the Dynamic Capabilities framework developed by Teece, Pisano, and Shuen in 1997, which explains how organizations can integrate, build, and reconfigure internal and external competencies to respond to rapidly changing environments. This perspective is relevant because maritime organizations operate within dynamic environments characterized by technological changes, environmental regulation, energy transitions, and supply chain disruptions. The study also incorporates the supply chain resilience perspective developed by Christopher and Peck in 2004, which emphasizes the capacity of supply chains to manage disruption through appropriate risk management, flexibility, collaboration, and organizational preparedness. These theoretical perspectives complement one another by connecting sustainability objectives with organizational adaptability and resilience. Collectively, they provide the assumptions necessary to interpret sustainable sea transportation management as a strategic capability that can support emission reduction while strengthening the capacity of maritime supply networks to respond to uncertainty and disruption[9].

2.4. Data Collection Process

The data collection process is conducted through systematic reading and examination of written literature relevant to the research problem[10]. The process begins with the identification of literature addressing sustainable sea transportation management, maritime emissions, sustainable shipping, decarbonization, transportation efficiency, and global supply chain resilience. Relevant materials are subsequently collected from academic books, previous research, scholarly journals, scientific articles, conference papers, institutional reports, research publications, and other credible written sources that provide substantive information related to the study. The collected literature is then screened according to its relevance to the research objectives and its ability to provide conceptual, theoretical, empirical, or contextual evidence concerning the relationship between sustainable maritime transportation and supply chain resilience. During the reading process, important information is recorded and organized according to recurring themes, theoretical concepts, research findings, strategic

practices, and identified challenges. Particular attention is given to statements and findings that explain mechanisms for reducing maritime emissions and those that demonstrate how sustainable transportation practices influence flexibility, adaptability, continuity, and risk management within global supply chains. Comparative reading is subsequently undertaken to identify similarities, differences, and developments across the selected literature[11]. This process enables the researcher to move beyond merely collecting references and instead construct an organized body of evidence relevant to the research questions. Accordingly, literature collection functions as an iterative process in which searching, reading, selecting, organizing, and interpreting sources are conducted continuously to establish a sufficiently comprehensive foundation for subsequent analysis[12].

2.5 Data Analysis Technique

The data analysis technique employed in this study is qualitative content analysis, which is used to systematically examine the meaning, patterns, relationships, and important information contained within the selected literature. The analysis begins by organizing the collected sources according to their relevance to the central themes of sustainable shipping, maritime emissions, and supply chain resilience[13]. Each source is then carefully read to identify significant concepts, arguments, findings, and explanations concerning sustainable sea transportation management. The identified information is subsequently coded and categorized into analytical themes, such as emission reduction strategies, energy efficiency, alternative fuels, technological innovation, operational optimization, environmental governance, risk management, adaptability, collaboration, and supply chain continuity. Following categorization, the researcher compares information across different sources to identify recurring patterns, complementary arguments, contrasting perspectives, and relationships among the themes. Particular attention is given to determining how sustainable transportation practices may simultaneously generate environmental and resilience-related benefits, as well as circumstances in which sustainability and resilience objectives may create managerial tensions[14]. The analysis then proceeds through interpretation and synthesis, whereby individual findings from different sources are connected to the theoretical foundations of the study[15]. The final stage involves constructing a coherent narrative that explains the relationship between sustainable maritime management, emission reduction, and global supply chain resilience. Through this content analysis process, the study transforms dispersed documentary information into structured analytical findings that directly address the research objective and remain focused on the central research problem[16].

3. Result

3.1 Sustainable Sea Transportation as an Integrated Management Approach

The literature analysis indicates that sustainable sea transportation management is increasingly understood as an integrated managerial approach rather than a narrowly defined environmental program. The reviewed literature consistently connects sustainable shipping with energy efficiency, cleaner fuels, technological innovation, operational optimization, environmental governance, and coordination among maritime stakeholders[17]. This finding suggests that sustainability in maritime transportation cannot be achieved through a single technological intervention because emissions are influenced by vessel characteristics, fuel selection, voyage planning, port operations, cargo utilization, and broader logistics decisions. The International Maritime Organization's 2023 GHG Strategy reinforces this integrated direction by combining carbon-intensity reduction, adoption of zero- and near-zero-emission technologies and fuels, and a long-term pathway toward net-zero emissions. The literature further indicates that sustainable transportation management becomes more effective when environmental objectives are embedded within routine operational and strategic decision-making. Consequently, shipping companies, ports, logistics providers, regulators, and cargo owners need to consider environmental performance alongside cost, reliability, flexibility, and service continuity[18]. The results therefore establish sustainable sea transportation management as a multidimensional management system in which environmental performance is connected to operational performance. This integrated interpretation provides the foundation for examining how emission reduction can be pursued without weakening the resilience of global maritime supply chains[19].

3.2 Maritime Emissions Reduction through Energy Efficiency

The second major finding concerns the importance of energy efficiency as an immediate mechanism for reducing maritime emissions. The literature demonstrates that improvements in vessel energy performance can reduce fuel consumption and associated greenhouse gas emissions without necessarily requiring a complete transformation of existing maritime transportation infrastructure. Operational measures such as voyage optimization, speed management, weather routing, improved cargo planning, vessel maintenance, and efficient engine operation can contribute to lower energy consumption. At the regulatory level, the IMO has explicitly incorporated improvements in ship energy efficiency and carbon intensity into its decarbonization strategy[20]. The 2023 IMO GHG Strategy establishes an ambition to reduce CO_2 emissions per transport work

by at least 40% by 2030 compared with 2008. This indicates that emission reduction is not exclusively dependent on future fuel technologies but also requires better management of existing transportation assets. From a supply chain perspective, energy-efficient operations may provide additional benefits through lower fuel exposure, improved resource utilization, and potentially greater operational predictability. However, the literature also indicates that efficiency improvements alone are insufficient to achieve long-term decarbonization because shipping remains dependent on the carbon characteristics of its energy sources. Therefore, energy efficiency should be regarded as an important transitional and complementary strategy that supports both environmental improvement and operational performance while the maritime sector progressively moves toward cleaner energy systems.

3.3 Alternative Fuels and Low-Carbon Energy Transition

A third finding identifies alternative fuels and low-carbon energy sources as central components of long-term maritime decarbonization. The literature emphasizes that the transition away from conventional fossil fuels requires the development and adoption of alternative energy options, including renewable and low- or zero-carbon fuels, supported by appropriate infrastructure and regulatory frameworks. The importance of this transition is reflected in the IMO's 2023 strategy, which seeks to increase the uptake of zero- and near-zero-GHG technologies, fuels, and energy sources to at least 5% of international shipping energy by 2030, while striving for 10%. The IMO also indicates that alternative low- and zero-carbon fuels could provide a substantial share of the emissions reductions required by 2050. Nevertheless, the literature reveals that fuel transition creates managerial challenges related to availability, cost, infrastructure, safety, technological compatibility, and supply security. Consequently, sustainable fuel adoption should not be treated simply as a technical substitution of one energy source for another. It requires coordinated planning across shipowners, ports, fuel suppliers, regulators, cargo owners, and energy producers. The results therefore suggest that alternative fuels contribute most effectively to sustainable sea transportation when their deployment is integrated with fleet strategy, port readiness, energy supply planning, and risk management. This integrated approach is essential because an environmentally preferable fuel cannot strengthen sustainability if its supply chain remains unreliable or inaccessible[21].

3.4 Digitalization and Operational Optimization

The fourth finding shows that digitalization represents an important enabling mechanism for sustainable maritime transportation management. The literature indicates that digital technologies can improve information visibility, voyage planning, vessel monitoring, cargo coordination, port management, and decision-making. These capabilities can indirectly reduce emissions by allowing maritime actors to optimize routes, reduce unnecessary waiting times, improve vessel utilization, coordinate arrival schedules, and minimize inefficient operations. Digitalization also has implications for supply chain resilience because real-time information can increase the ability of organizations to identify disruptions, assess their consequences, and modify transportation decisions. This finding is particularly important because sustainability and resilience both depend on the quality and timeliness of information. A maritime system that can monitor fuel consumption and emissions while simultaneously tracking congestion, weather conditions, port availability, and cargo flows can make more adaptive decisions than a system based on fragmented information. Recent literature on sustainable maritime supply chains similarly identifies digital and technological innovation as an important component alongside port efficiency, environmental sustainability, safety, and transparency. Therefore, digitalization should be understood not merely as an administrative modernization initiative but as a strategic infrastructure supporting both environmental and operational objectives. The result suggests that digital capabilities can create a connection between emission management and resilience by enabling maritime organizations to continuously adjust operations according to environmental conditions, resource availability, and supply chain disruptions.

3.5 Sustainable Port and Maritime Logistics Coordination

The fifth finding concerns the strategic role of coordination between ships, ports, logistics providers, cargo owners, regulators, and other stakeholders. The literature demonstrates that maritime transportation operates as an interconnected network rather than an isolated shipping activity. Consequently, improvements in vessel sustainability may be undermined when port operations, inland transportation, cargo handling, or fuel infrastructure remain inefficient or environmentally intensive. Sustainable maritime transportation therefore requires coordination across organizational and geographical boundaries. Recent literature on sustainable maritime supply chains emphasizes the importance of stakeholder interactions, planning decisions, regulatory conditions, and coordination within maritime networks. Coordination also has direct implications for resilience because disruptions in one part of the maritime network can generate cascading effects throughout connected supply chains. A coordinated system can respond through information sharing, alternative routing, capacity adjustment, port

substitution, and collaborative planning. The results indicate that sustainability-oriented coordination can simultaneously support emission reduction and resilience when stakeholders share information and align operational objectives. For example, better coordination between vessels and ports can reduce waiting and idling time, while coordinated contingency planning can facilitate rapid responses to congestion or route disruptions. Thus, sustainable sea transportation management should move beyond individual firm-level optimization toward network-level management. The effectiveness of emission reduction and resilience strategies depends increasingly on the capacity of maritime stakeholders to coordinate decisions across the entire transportation ecosystem.

3.6 Maritime Emission Reduction and Supply Chain Resilience

The sixth finding demonstrates that maritime emission reduction and supply chain resilience should not necessarily be regarded as competing objectives. Instead, the literature indicates the possibility of complementary effects when sustainable practices are strategically designed. Energy-efficient operations can reduce fuel dependence, cleaner technologies can reduce exposure to future environmental regulations, digital monitoring can improve visibility, and diversified energy sources can potentially reduce dependence on a single fuel system. These characteristics may strengthen the capacity of maritime organizations to adapt to external changes. At the same time, resilience strategies such as diversification, flexibility, redundancy, and collaboration can support sustainable transportation by allowing organizations to select alternative routes, fuels, ports, or logistics arrangements when environmental or operational conditions change. Recent research specifically examining emission reduction policies in green liner shipping networks finds that stricter emission policies can place pressure on network resilience, while green technologies and cleaner fuels can mitigate these negative effects and delay network deterioration. This finding is important because it demonstrates that the relationship between sustainability and resilience is conditional rather than automatically positive. Poorly planned environmental transitions may create operational vulnerabilities, whereas well-designed transitions can strengthen both objectives. Therefore, the results support an integrated management perspective in which sustainability strategies are evaluated according to their environmental benefits as well as their consequences for transportation continuity, adaptability, and network stability.

3.7 Strategic Capabilities for Maritime Supply Chain Resilience

The seventh finding identifies several strategic capabilities that determine whether sustainable sea transportation can strengthen supply chain resilience. The literature points toward flexibility, visibility, collaboration, adaptability, technological capability, risk anticipation, and resource diversification as particularly important capabilities. Maritime supply chains face disruptions originating from climate-related events, geopolitical tensions, pandemics, port congestion, infrastructure failures, and economic uncertainty. Research on maritime transport resilience confirms that these disruptions have intensified scholarly attention toward the resilience of maritime systems. Sustainable transportation management can contribute to resilience when it increases the ability of maritime organizations to anticipate and respond to such disturbances. For example, digital visibility can facilitate early warning, diversified fuel options can reduce energy dependence, efficient vessel operations can preserve resources, and collaborative planning can improve responses to congestion. However, resilience also requires organizational capabilities because technological solutions alone cannot guarantee continuity. Firms need appropriate governance structures, skilled personnel, contingency planning, and cross-organizational coordination. The results therefore indicate that sustainable shipping should be evaluated as a strategic capability rather than merely as a collection of environmental practices. When sustainability is embedded within organizational routines and strategic planning, it can enhance the capacity of maritime actors to adapt to environmental, technological, regulatory, and geopolitical changes. This finding strengthens the argument that maritime sustainability and resilience should be managed through interconnected capabilities rather than through isolated initiatives.

3.8 Integrated Sustainable Maritime Transportation Framework

The synthesis of the reviewed literature produces an integrated framework consisting of five interconnected dimensions: sustainable operational management, clean energy transition, digitalization, stakeholder collaboration, and resilience capability. Sustainable operational management addresses vessel efficiency, voyage optimization, cargo utilization, and resource conservation. Clean energy transition focuses on alternative fuels and technologies capable of reducing the carbon intensity of maritime transportation. Digitalization supports information visibility, monitoring, prediction, and adaptive decision-making. Stakeholder collaboration connects shipping companies, ports, logistics providers, cargo owners, regulators, and energy suppliers. Finally, resilience capability concerns the ability of the maritime supply chain to anticipate disruption, absorb shocks, adapt operations, and recover service continuity. These dimensions are mutually reinforcing rather than independent. For example, alternative fuels require port infrastructure and supply

coordination, while digital systems facilitate efficient utilization of those resources. Similarly, resilience requires information sharing and operational flexibility, which can also improve environmental performance. The framework is consistent with the direction of contemporary maritime policy, which emphasizes technological innovation, alternative fuels, energy efficiency, logistics optimization, capacity building, and research and development as components of the transition toward net-zero shipping. The resulting framework therefore provides a conceptual explanation of how sustainable sea transportation management can connect environmental objectives with supply chain resilience. It also establishes a structured basis for interpreting the strategic implications discussed in the following section.

3.9 Synthesis of Main Literature Findings

The overall results demonstrate that sustainable sea transportation management has the potential to become a strategic mechanism for addressing two interconnected challenges: maritime emissions and global supply chain vulnerability. The literature does not support the interpretation that emission reduction is simply an additional cost imposed on maritime transportation. Instead, sustainable practices can generate operational, technological, and strategic benefits when implemented systematically. Nevertheless, the results also show that sustainability initiatives may generate short-term operational pressures, particularly when alternative fuels, new technologies, infrastructure investments, and stricter regulations are introduced without adequate preparation. The relationship between sustainability and resilience is therefore dependent on management quality, coordination, technological readiness, and resource availability. The most important finding is that no single intervention is sufficient to achieve both objectives. Energy efficiency must be combined with cleaner fuels, digitalization, stakeholder collaboration, and resilience planning. This conclusion is consistent with recent research that calls for integrated frameworks connecting maritime transportation, sustainable supply chains, planning decisions, stakeholder relationships, and regulatory conditions. The results consequently support a systems perspective in which maritime transportation is treated as a network of interdependent activities rather than a collection of isolated operational functions. From this perspective, sustainable shipping becomes an organizational and network capability that contributes to both environmental performance and supply chain robustness. The following discussion interprets these findings in relation to theory, managerial implications, and the broader strategic transformation of global maritime transportation.

Table 1. Synthesis of Main Results

No.	Main Finding	Sustainable Shipping Dimension	Emission Reduction Contribution	Resilience Contribution
1	Integrated transportation management	Operational sustainability	Reduces inefficient fuel consumption	Improves operational continuity
2	Energy efficiency	Vessel and voyage optimization	Reduces fuel use and CO_2 intensity	Preserves resources and reduces cost exposure
3	Alternative fuels	Clean energy transition	Reduces dependence on carbon-intensive fuels	Diversifies energy sources
4	Digitalization	Smart maritime management	Optimizes routes, speed, and vessel utilization	Improves visibility and response capability
5	Port-stakeholder coordination	Network sustainability	Reduces waiting and inefficient operations	Facilitates coordinated disruption response
6	Sustainable-resilience integration	Strategic management	Supports long-term decarbonization	Strengthens adaptability
7	Organizational capabilities	Dynamic capabilities	Enables continuous environmental improvement	Supports adaptation and recovery
8	Integrated framework	Systems management	Combines multiple emission-reduction mechanisms	Connects sustainability with network resilience

4. Discussion

4.1 Sustainability as a Strategic Maritime Management Capability

The findings indicate that sustainable sea transportation should be interpreted as a strategic management capability rather than simply as an environmental compliance requirement. This interpretation is important because maritime organizations operate under simultaneous pressures involving cost efficiency, environmental regulation, customer expectations, technological change, and supply chain uncertainty. The Triple Bottom Line perspective is useful in explaining this condition because sustainability requires the balancing of environmental, economic, and social considerations. In maritime transportation, reducing emissions cannot be separated completely from operational efficiency and commercial continuity. The findings show that energy-efficient vessels, optimized voyages, cleaner fuels, digital monitoring, and collaborative logistics can contribute to environmental performance while also influencing operational outcomes. The Dynamic Capabilities perspective further explains why maritime organizations must continuously develop and reconfigure their resources as the industry moves toward decarbonization. Regulatory requirements and technological alternatives are evolving, meaning that capabilities appropriate for current conditions may become insufficient in the future. The strategic implication is that shipping companies need to treat sustainability as an organizational capability that must be developed continuously rather than as a one-time investment. This perspective also explains why technological acquisition alone cannot guarantee sustainable performance. Technologies must be accompanied by managerial competencies, organizational learning, information systems, and collaborative relationships. Therefore, sustainable maritime management becomes strategically valuable when environmental objectives are embedded within broader organizational processes and continuously connected to operational and supply chain decision-making.

4.2 Reconciling Decarbonization and Resilience

The second discussion point concerns the apparent tension between decarbonization and resilience. The findings demonstrate that environmental policies and technological transitions can initially create additional operational pressures. New fuels may have limited availability, new infrastructure requires substantial investment, and changes in transportation practices can create uncertainty for shipping networks. These issues explain why sustainability and resilience cannot automatically be assumed to reinforce one another. Nevertheless, the findings also indicate that appropriate sustainable strategies can create resilience benefits through diversification, efficiency, technological flexibility, and reduced dependence on vulnerable resources. The recent literature on green liner shipping networks provides evidence that although stricter emission policies can reduce network resilience under certain conditions, green technologies and cleaner fuels can mitigate these negative effects. This relationship can be explained through the resilience perspective, which emphasizes the ability of systems to absorb disruption and adapt to changing conditions. A maritime organization that develops multiple energy options, digital visibility, alternative routes, and collaborative contingency mechanisms may become better prepared for both environmental regulation and operational disruptions. Therefore, the central managerial challenge is not choosing between decarbonization and resilience but designing transition strategies that minimize the vulnerability created during decarbonization. This requires phased implementation, infrastructure preparation, stakeholder coordination, and continuous assessment of operational consequences. Consequently, the study argues that resilience should be incorporated into maritime decarbonization planning from the beginning rather than treated as a separate objective after environmental strategies have been implemented.

4.3 The Role of Technology and Digital Transformation

The findings also demonstrate that technology plays a bridging role between maritime sustainability and supply chain resilience. Clean propulsion systems and alternative fuels directly address emission reduction, whereas digital technologies improve the information and coordination capabilities necessary to operate sustainable transportation systems effectively. This distinction is important because technological sustainability depends not only on the existence of cleaner equipment but also on the ability to manage that technology efficiently. Digital monitoring can provide information about fuel consumption, emissions, vessel performance, route conditions, port congestion, and cargo status. Such information enables decision-makers to identify inefficiencies and adjust transportation activities before problems become more severe. From a resilience perspective, the same information infrastructure supports early warning, scenario planning, rerouting, and contingency decisions. This creates a dual function in which digitalization contributes simultaneously to environmental performance and adaptive capacity. The literature on sustainable maritime supply chains similarly identifies technological innovation as a major category alongside environmental sustainability, port efficiency, safety, and transparency. However, digital transformation should not be understood as a substitute for organizational capability. Data are valuable only when organizations possess the skills and governance mechanisms required to interpret and use them. Therefore, maritime firms should

combine technological investment with human-resource development, data governance, cybersecurity, and inter-organizational information sharing. The broader implication is that digital transformation can become an important enabling infrastructure for sustainable and resilient maritime transportation when it is integrated with strategic management.

4.4 Implications for Global Supply Chain Management

The findings have broader implications for global supply chain management because maritime transportation functions as a critical connection between suppliers, manufacturers, ports, distributors, and markets. Disruptions in maritime networks can therefore propagate across multiple stages of international supply chains. Recent research on maritime resilience highlights the vulnerability of maritime systems to climate change, pandemics, geopolitical events, and economic uncertainty. Sustainable transportation management can reduce some forms of vulnerability by improving resource efficiency, diversifying energy sources, strengthening information visibility, and encouraging collaboration among network participants. This means that sustainability should be incorporated into supply chain risk management rather than treated as a separate corporate responsibility program. For supply chain managers, the selection of maritime transportation providers should increasingly consider not only freight cost and delivery time but also environmental performance, energy strategy, technological capability, and disruption preparedness. Similarly, cargo owners can support maritime decarbonization by incorporating sustainability requirements into procurement and logistics contracts. Ports can contribute by developing infrastructure capable of supporting cleaner fuels, efficient vessel operations, digital information exchange, and rapid disruption responses. Regulators, meanwhile, need to create predictable policy environments that encourage investment while avoiding unnecessary fragmentation across jurisdictions. The broader implication is that maritime sustainability requires a shift from firm-level optimization toward supply-chain-level coordination. Such coordination can ensure that environmental improvements in one part of the network do not create new operational vulnerabilities elsewhere.

4.5 Theoretical and Managerial Contribution

The theoretical contribution of this study lies in connecting three analytical domains that are often examined separately: sustainable shipping, maritime emissions, and supply chain resilience. The findings indicate that the Triple Bottom Line perspective provides a useful foundation for understanding the multidimensional nature of maritime sustainability, while Dynamic Capabilities explains how maritime organizations can adapt their resources and competencies to technological and regulatory change. The resilience perspective complements these theories by explaining how transportation networks can absorb disruption, adapt operations, and maintain continuity. Integrating these perspectives produces a more comprehensive explanation of sustainable sea transportation management. The managerial contribution is equally important because the findings provide a strategic basis for maritime organizations to design integrated sustainability programs. Rather than prioritizing individual interventions, managers should develop portfolios combining energy efficiency, alternative fuels, digitalization, operational flexibility, stakeholder collaboration, and contingency planning. Such an approach can reduce the risk that a sustainability initiative creates unintended operational vulnerabilities. The findings also suggest that performance evaluation should include both environmental and resilience indicators. Emission intensity, fuel efficiency, and adoption of cleaner energy should be evaluated alongside service continuity, recovery capability, route flexibility, and disruption response. This integrated performance logic can help organizations determine whether sustainability investments are generating broader strategic value. Thus, the study contributes to a shift from compliance-oriented environmental management toward strategic sustainable transportation management in which environmental performance and supply chain resilience are evaluated as interconnected outcomes.

4.6 Strategic Model for Sustainable and Resilient Sea Transportation

The final discussion establishes a strategic model in which sustainable sea transportation management develops through a continuous interaction between environmental objectives, operational capabilities, technological resources, stakeholder collaboration, and resilience outcomes. The model begins with pressure for emission reduction arising from environmental concerns, regulatory requirements, market expectations, and the long-term transition toward low- and zero-carbon shipping. These pressures encourage maritime organizations to improve energy efficiency, adopt alternative fuels, deploy cleaner technologies, and optimize transportation operations. However, these measures must be supported by digital capabilities, infrastructure development, organizational learning, and stakeholder collaboration. When these supporting capabilities are present, sustainability initiatives can strengthen resource efficiency, visibility, flexibility, and adaptability, which in turn contribute to supply chain resilience. The process is therefore iterative rather than linear because resilience capabilities can also support sustainability by enabling organizations to adjust operations during disruption without returning to

inefficient or carbon-intensive practices. This interpretation is consistent with the direction of the IMO 2023 strategy, which combines emissions reduction targets with technological innovation, alternative fuels, logistics optimization, and research and development. The strategic model developed from this study consequently emphasizes integration rather than isolated interventions. Its principal implication is that maritime organizations should pursue decarbonization and resilience through a shared strategic architecture. In this architecture, sustainable shipping becomes a pathway toward more efficient and adaptive maritime supply chains, while resilience becomes a mechanism for ensuring that the transition toward lower emissions remains operationally viable and strategically sustainable.

Table 2. Integrated Strategic Model

Strategic Dimension	Core Management Action	Expected Environmental Outcome	Expected Resilience Outcome
Energy efficiency	Optimize speed, routing, vessel utilization	Lower fuel consumption and emissions	Lower resource dependence
Clean energy	Adopt alternative/low-carbon fuels	Lower carbon intensity	Energy-source diversification
Digitalization	Real-time monitoring and predictive analytics	Better operational efficiency	Faster disruption response
Port integration	Coordinate vessel-port-logistics activities	Lower waiting and idle emissions	Better network coordination
Collaboration	Share information and coordinate decisions	Consistent sustainability practices	Collective adaptive capacity
Risk management	Identify environmental and operational risks	Prevent inefficient responses	Stronger preparedness and recovery
Organizational capability	Develop skills and adaptive routines	Continuous environmental improvement	Long-term adaptability
Regulatory alignment	Integrate compliance into strategy	Supports decarbonization targets	Reduces regulatory uncertainty

Table 3. Relationship between the Three Core Concepts

Sustainable Shipping	Maritime Emissions	Supply Chain Resilience	Integrated Interpretation
Energy-efficient vessels	Reduced fuel-related emissions	Greater resource efficiency	Efficiency creates environmental and operational benefits
Alternative fuels	Lower carbon intensity	Reduced energy dependence	Diversification can improve adaptive capacity
Digital maritime systems	Optimized voyages and operations	Improved visibility	Information enables both sustainability and resilience
Green port operations	Reduced vessel waiting and port emissions	Better network coordination	Port efficiency supports continuity
Collaborative planning	Coordinated emission reduction	Faster collective response	Collaboration links environmental and resilience objectives
Flexible transportation strategies	Avoids inefficient rerouting	Maintains service during disruption	Flexibility supports both sustainability and continuity

Overall, the results and discussion establish that sustainable sea transportation management should be positioned as an integrated strategic capability rather than a stand-alone environmental initiative. The evidence indicates that maritime emissions reduction is most effective when combined with energy efficiency, alternative fuels, digital transformation, stakeholder collaboration, and resilience planning. At the same time, supply chain resilience can be strengthened when sustainability strategies increase flexibility, visibility, diversification, and adaptive capacity. This relationship is particularly important because international shipping is moving toward increasingly demanding decarbonization targets, including net-zero GHG emissions close to 2050 under the IMO 2023 strategy. Therefore, the central contribution of the study is the proposition that environmental sustainability and supply chain resilience should be managed as interconnected strategic objectives. Such an approach enables maritime stakeholders to pursue emission reduction while maintaining the reliability and adaptability required by global trade. The resulting framework provides a conceptual basis for the final conclusion that sustainable maritime transportation can serve not only as an instrument of environmental responsibility but also as an important foundation for resilient global supply chain management.

5. Conclusion

This study concludes that sustainable sea transportation management represents a strategic approach for simultaneously reducing maritime emissions and strengthening global supply chain resilience. The literature synthesis demonstrates that emission reduction cannot depend on a single intervention but requires an integrated combination of energy efficiency, alternative low-carbon fuels, digitalization, operational optimization, stakeholder collaboration, and adaptive risk management. These practices can generate environmental benefits while also improving resource efficiency, transportation visibility, flexibility, and the ability of maritime supply chains to respond to disruption. The findings further indicate that sustainability and resilience should not be treated as separate managerial objectives because both are increasingly influenced by technological transformation, regulatory developments, energy transitions, and global supply chain uncertainty. The integration of the Triple Bottom Line, Dynamic Capabilities, and supply chain resilience perspectives provides a theoretical foundation for understanding sustainable maritime transportation as an organizational and network capability. Therefore, maritime stakeholders should incorporate environmental performance into broader transportation and supply chain strategies while simultaneously developing capabilities for adaptation and continuity. The study ultimately argues that a well-designed sustainable sea transportation system can contribute not only to maritime decarbonization but also to the development of more efficient, flexible, and resilient global supply chains. Future research should complement the literature-based findings through empirical studies examining the effectiveness of specific sustainable maritime practices across different shipping routes, ports, technologies, and regulatory environments.

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