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Review Article

Maritime decarbonization of shipping and ports: A system-oriented review of coordination, sequencing, and transition pathways

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Article information	Abstract
Received: May 29, 2026 Revision: July 30, 2026 Accepted: September 9, 2026	Decarbonization of global shipping and maritime ports has become a strategic priority for achieving international climate targets. Although research has expanded rapidly, existing reviews predominantly examine technological, operational, or policy dimensions separately, providing limited understanding of how interactions among vessels, ports, fuel infrastructure, and governance shape decarbonization pathways. This review addresses this limitation by introducing a system-level perspective that reconceptualizes maritime decarbonization as a coordination and sequencing challenge rather than a collection of independent technological solutions. An integrated review framework combining bibliometric science mapping with a PRISMA-based systematic review was adopted to analyze Scopus-indexed publications published between 2021 and early 2026. The bibliometric analysis examined 249 publications, while 62 studies meeting the PRISMA eligibility criteria were subjected to detailed qualitative synthesis. The study aims to identify the intellectual structure, emerging research themes, and cross-sector alignment challenges shaping maritime decarbonization pathways across vessels, ports, fuel infrastructure, and governance. Bibliometric analysis mapped the intellectual structure, thematic evolution, and collaborative landscape of the field, while qualitative synthesis examined empirical evidence related to alternative fuels, port decarbonization measures, and governance mechanisms. The findings reveal sustained growth in maritime decarbonization research, accompanied by persistent mismatches between vessel technology development, port infrastructure readiness, fuel supply systems, and regulatory implementation. The analysis further demonstrates that technological progress alone is insufficient to achieve effective maritime decarbonization unless these interconnected systems evolve in a coordinated manner. These persistent disconnects continue to constrain effective transition pathways despite significant advances in decarbonization technologies and policy initiatives. The proposed system-level analytical framework provides an evidence-based foundation for integrated policy development, infrastructure planning, and future research, supporting more coordinated and implementable maritime decarbonization strategies.
Keywords Alternative marine fuels; Bibliometric analysis; Energy transition; Maritime decarbonization; Port sustainability; PRISMA systematic review; Shipping emissions	

1. Introduction

Maritime transport forms the backbone of the global trading system, accounting for more than 80 percent of international trade by volume, while also generating a significant share of global greenhouse gas emissions. International shipping alone contributes close to 3 percent of global carbon

dioxide emissions, with projections indicating further growth if effective mitigation measures are not implemented. In response to escalating climate commitments, decarbonization has become a central policy and operational challenge for the maritime sector.

International regulatory initiatives, particularly those led by the International Maritime Organization, have established increasingly ambitious emission reduction targets, including the objective of achieving net zero greenhouse gas emissions from international shipping by mid-century. These commitments have stimulated extensive research on alternative marine fuels, vessel energy efficiency improvements, and operational optimization strategies. At the same time, maritime ports have emerged as critical enablers of decarbonization by supporting shore power deployment, alternative fuel bunkering, and energy efficient port operations. Evidence increasingly suggests that progress in shipping decarbonization depends not only on vessel-level technological change, but also on port infrastructure readiness, institutional capacity, and governance arrangements. Recent years have also witnessed substantial progress in maritime decarbonization. The adoption of the International Maritime Organization 2023 Greenhouse Gas Strategy has strengthened global commitments towards net-zero emissions, while advances in alternative marine fuels, shore power systems, port electrification, digital technologies, and green shipping corridors have accelerated the transition towards lower-carbon maritime operations (Dolatabadi et al., 2025). Increasing collaboration among governments, port authorities, shipping companies, and technology providers further demonstrates that decarbonization is progressing beyond conceptual planning towards practical implementation. These developments provide important momentum for the maritime sector, although significant coordination challenges remain in aligning technological innovation, infrastructure investment, and governance across the wider maritime system.

Despite these encouraging developments, progress has remained uneven across different components of the maritime system. The literature remains separated across technological, operational, and governance perspectives, limiting understanding of how interactions among vessels, ports, infrastructure, and policy influence coordinated decarbonization pathways. Existing narrative reviews and technology specific assessments are not designed to capture interdependencies across vessels, ports, and governance structures. As a result, they are unable to identify sequencing problems, such as cases where vessel technologies advance faster than port infrastructure, or where regulatory frameworks lag behind operational and investment requirements. Without a system-oriented perspective, the literature provides limited guidance on how integrated decarbonization pathways can be achieved in practice.

This study addresses these limitations through a structured and system-oriented review of recent research on maritime and port decarbonization. It integrates bibliometric science mapping with a systematic literature review guided by the PRISMA protocol, focusing on Scopus indexed publications from 2021 to early 2026. Bibliometric analysis is used to examine the intellectual structure and thematic evolution of the field, while qualitative synthesis evaluates empirical findings related to fuel-transition pathways, port-based interventions, and governance mechanisms.

The review is guided by the following research questions:

RQ1. How is knowledge on maritime and port decarbonization structured, and what dominant research themes and clusters have emerged in recent years?

RQ2. What forms of coordination failure and sequencing mismatch are evident between vessel technologies, port infrastructure, and regulatory frameworks?

RQ3. How can a combined synthesis of the literature contribute to theory development and policy design for system-level decarbonization transitions?

A PRISMA-based systematic review is essential for addressing these questions because it enables transparent, reproducible, and rigorous identification and synthesis of evidence across multiple subsystems of the maritime sector. When combined with bibliometric mapping, this

approach moves beyond descriptive theme identification and supports a diagnostic assessment of coordination challenges that cannot be achieved through conventional narrative reviews.

This review makes three principal contributions to the literature. First, it reconceptualizes maritime decarbonization as a system-oriented maritime transition and sequencing challenge rather than a collection of isolated technological or policy interventions. The analysis identifies persistent misalignments across vessel technology development, port infrastructure readiness, and multi-level governance frameworks, shifting attention from solution identification toward implementation dynamics. Second, the study combines bibliometric science mapping with a PRISMA-based qualitative synthesis to move beyond descriptive trend analysis and toward a structured assessment of cross-domain interdependencies.

This cohesive design reveals thematic silos, weak linkages, and structural gaps that remain obscured in single-method reviews. Third, the study positions ports as strategic integration nodes connecting global regulatory ambition with localized operational execution, clarifying their function in enabling coherent and implementable transition pathways. This perspective contributes an analytical framework that supports more aligned policy design, infrastructure planning, and fleet transition strategies in the pursuit of sustained maritime decarbonization.

1.1 Maritime decarbonization as a system coordination and sequencing challenge

Maritime decarbonization involves a complex transition across shipping fleets, ports, fuel supply systems, and regulatory institutions that operate under different technological and investment conditions. Although these components are closely connected, they often evolve at different speeds and according to different priorities. Emission reduction outcomes therefore depend not only on the availability of low-carbon technologies, but also on how effectively developments across the maritime sector progress alongside one another. Shipping fleets are shaped by long asset lifespans and high capital costs, which means fuel and technology decisions made today can remain in place for decades. Ports face a different set of constraints. Infrastructure investments are fixed, location-specific, and often dependent on uncertain demand for future fuels and energy systems. As a result, shipowners may hesitate to invest in alternative fuel vessels without reliable port infrastructure, while ports may delay investment decisions until future fuel demand becomes clearer. These uncertainties can slow transition pathways and increase the risk of fragmented investment decisions. (Deng et al., 2026).

Differences in governance structures add another layer of complexity. International regulations mainly focus on vessel standards and emission targets, whereas infrastructure planning and port operations are shaped more strongly by national and local institutions. This creates gaps between regulatory ambition and implementation capacity, particularly when infrastructure development and operational readiness do not progress at the same pace as policy commitments.

The maritime sector is also characterized by institutional fragmentation across shipping companies, port authorities, fuel suppliers, and regulators. These organizations often operate within separate institutional and financial structures, with limited long-term integration across the sector. As a result, decisions related to fuel adoption, infrastructure planning, and investment priorities are frequently made independently rather than through shared transition strategies (Deng et al., 2026).

This study approaches maritime decarbonization as a problem of alignment across technologies, infrastructure systems, investment timelines, and governance arrangements. Rather than examining vessels, ports, and policy instruments as isolated components, the review focuses on how interactions between these areas shape implementation outcomes and transition pathways across the wider maritime system.

Section 2, the literature review, builds on this perspective by examining how existing studies address technological pathways, port-based interventions, and governance mechanisms, while also identifying areas where interaction across these domains remains limited or insufficiently explored.

2. Literature review and analytical background

Research on maritime decarbonization has expanded rapidly in response to the sector's continued reliance on fossil fuels and its substantial contribution to global greenhouse gas emissions. Recent studies also show that the transition is increasingly being shaped by a combination of technological innovation, investment decisions, market readiness, and evolving environmental regulations, rather than by technological advances alone (Bayer et al., 2025). International shipping is widely recognized as a hard-to-abate sector because of long asset lifetimes, high capital intensity, and the limited availability of commercially mature zero-carbon fuel solutions at scale (International Maritime Organization, 2023). Since 2021, academic contributions have grown significantly, addressing vessel technologies, port infrastructure transformation, and governance reform. However, much of this literature remains organized along thematic lines that mirror institutional and technological boundaries rather than examining the interactions that shape decarbonization outcomes in practice.

This review examines the literature through an analytical lens centered on alignment, sequencing, and interdependence across vessels, ports, and governance frameworks. While existing studies provide valuable insights within their respective domains, many rely on simplifying assumptions that treat subsystems as independently optimizable. When these strands are read in isolation, integration blind spots emerge that help explain why progress toward maritime decarbonization has been uneven and difficult to implement despite growing technological and policy ambition. The literature is therefore reviewed not only for its substantive findings, but also for how it addresses or overlooks holistic interactions.

The review focuses on publications from the most recent five-year period in order to capture contemporary research trajectories, emerging technological pathways, and evolving policy frameworks. This temporal focus supports analytical coherence in a rapidly developing field and reflects established bibliometric practice. The analysis situates vessels, ports, fuels, and institutions within a single transition framework, allowing interdependencies and sequencing challenges to be examined explicitly.

At the vessel-level, the literature consistently identifies operational measures such as speed optimization, route planning, and enhanced energy management systems as capable of delivering near-term emission reductions at relatively low cost. Nevertheless, empirical and modelling studies indicate that these measures alone are insufficient to achieve emission reductions consistent with net-zero objectives. For example, Zhang et al. (2026) and Raihan et al. (2025) concluded that operational improvements should be complemented by broader technological and fuel-transition strategies to achieve long-term decarbonization targets. As a result, alternative marine fuels have emerged as a dominant long-term decarbonization pathway. Comprehensive assessments by Barone et al. (2025) identify green ammonia, hydrogen, and methanol as the leading candidates because of their potential to achieve substantial lifecycle emission reductions when produced using renewable energy. Deng et al. (2026) further emphasized that successful adoption depends not only on fuel storage, safety regulations, supply availability, and fleet-renewal costs but also on policy incentives and economic instruments that reduce the cost gap between conventional and low-carbon marine fuels.

Although vessel-focused studies frequently recognize the importance of fuel availability, they often assume that supporting infrastructure and supply chains will develop alongside fleet-level transitions. This assumption creates an important gap in the literature. Boone and Ganeshan (2025) argued that the limited availability of large-scale alternative fuel supply chains remains a major obstacle, discouraging shipowners from investing in new fuel technologies before reliable bunkering networks are established. Similar concerns were highlighted in the OECD (2025) assessment, which identified infrastructure readiness and coordinated investment as critical prerequisites for accelerating fuel-transitions. Sang et al. (2026) likewise reported that uncertainties surrounding fuel availability continue to delay fleet renewal decisions. The long replacement cycles of vessels further complicate this relationship, as investment decisions made today commit operators to specific fuel pathways for

decades, amplifying the consequences of early synchronization failures. Port focused research has increasingly reframed ports from passive infrastructure nodes to active enablers of maritime decarbonization. Studies identify ports as significant emission sources due to berthed vessels, cargo handling equipment, terminal operations, and hinterland connections (Song, 2024; Fadiga & Ferreira, 2024). In response, the literature highlights mitigation measures including shore power deployment, electrification of port equipment, energy efficiency improvements, and on-site renewable energy generation. Recent evidence also suggests that the effectiveness of these measures depends on how well they are integrated into wider port development strategies, operational planning, and long-term investment decisions rather than being implemented as stand-alone initiatives (Benghalia et al., 2025).

Shore power has received particularly strong attention due to its technological maturity and mitigation potential (Wang et al., 2024). Empirical evidence, however, demonstrates uneven implementation across regions driven by high upfront investment costs, grid capacity constraints, and the lack of harmonized technical standards (Fadiga & Ferreira, 2024).

A critical sequencing issue emerges when port studies are examined alongside vessel-level research. Port infrastructure investments typically follow shorter planning and financing cycles than vessel replacement, yet they require greater certainty regarding future fuel demand and regulatory stability. This asymmetry creates hesitation among port authorities to invest ahead of confirmed vessel uptake, particularly for alternative fuel bunkering and grid upgrades. While recent studies conceptualize ports as future energy hubs for hydrogen production and distribution, most initiatives remain at experimental or demonstration stages and face regulatory, safety, and economic uncertainty (Holder et al., 2024). When port decarbonization strategies are analyzed independently, these sequencing risks are often understated.

Governance and policy research complements technological and infrastructural perspectives by emphasizing the need for synchronization in a highly mobile and internationally regulated sector. The revised greenhouse gas strategy adopted by the International Maritime Organization in 2023 reflects a substantial increase in regulatory ambition and formally embeds alternative fuels and innovation within the global policy agenda (International Maritime Organization, 2023). Scholars argue that strong international governance frameworks are necessary to prevent regulatory breakup and competitive distortions. Economic instruments such as carbon pricing, fuel standards, and targeted incentives are widely discussed as mechanisms to narrow the cost gap between conventional and low or zero carbon fuels (OECD, 2025).

At the same time, governance studies highlight additional integration challenges. Regulatory frameworks often operate at global or regional scales, while implementation capacity remains rooted in national and local institutions. Poorly coordinated policy design may therefore exacerbate regional inequalities and impose disproportionate adjustment burdens on developing economies and smaller ports. When governance analyses are treated separately from vessel and port studies, the operational and infrastructural constraints that shape policy effectiveness are insufficiently accounted for, reinforcing disconnection across the literature.

The reviewed literature reveals that substantial progress in understanding individual components of maritime decarbonization has been made, yet persistent gaps remain in addressing coordination, sequencing, and interdependence across the maritime system. Furthermore, these gaps provide the analytical foundation for this study. By integrating bibliometric analysis with a systematic literature review, the research identifies implementation challenges, reveals the interconnected technological, operational, policy, financial, and governance constraints across the maritime sector, and proposes directions for more coordinated and effective decarbonization pathways. Although the literature on maritime decarbonization has expanded considerably, important differences remain in how studies evaluate technological feasibility, infrastructure readiness, governance mechanisms, and implementation priorities. To facilitate a more critical synthesis, **Table 1** provides a comparative synthesis of representative studies by highlighting areas of agreement, divergent findings, remaining challenges, and their implications for holistic maritime decarbonization. This comparative synthesis

moves beyond descriptive reporting by identifying where evidence converges, where inconsistencies persist, and how these differences justify the need for a comprehensive review.

Table 1 Comparative analysis of key studies on maritime decarbonization.

Representative Studies	Research Focus	Areas of Agreement	Areas of Divergence	Implications for System-Level Maritime Decarbonization
Zhang et al. (2026); Deng et al. (2026); OECD (2025)	Alternative marine fuels	Green ammonia, hydrogen, and methanol are recognized as leading long-term decarbonization options.	Studies differ regarding technological readiness, lifecycle emissions, safety requirements, infrastructure availability, and economic feasibility.	Highlights that effective fuel transition depends on coordinated development of vessel technologies, port infrastructure, and governance mechanisms.
Wang et al. (2024); Song (2024); Fadiga and Ferreira (2024)	Port decarbonization	Shore power, terminal electrification, and renewable energy integration consistently reduce port emissions.	Regional implementation varies because of investment costs, electricity supply, regulatory support, and technical standards.	Emphasizes that port decarbonization should be evaluated alongside fleet transition, energy infrastructure, and policy implementation.
International Maritime Organization (2023); OECD (2025); Sang et al. (2026)	Governance and regulation	International coordination is widely recognized as essential for maritime decarbonization.	Differences remain regarding carbon pricing, regulatory instruments, financial incentives, and implementation priorities across jurisdictions.	Indicates that governance effectiveness depends on alignment with technological innovation and infrastructure development.
Holder et al. (2024); Deng et al. (2026)	System integration	Increasing recognition that vessels, ports, fuel infrastructure, and governance are interdependent.	Most studies continue to analyze these components separately, limiting understanding of implementation dynamics and sequencing.	Demonstrates the need for comprehensive analytical frameworks capable of explaining coordination and sequencing across the maritime transition system.

Although **Table 1** highlights areas of agreement, divergence, and remaining challenges across representative studies, the reviewed literature also demonstrates that maritime decarbonization encompasses multiple technological and operational pathways with distinct characteristics. These pathways differ considerably in terms of technological maturity, infrastructure requirements, implementation readiness, and operational constraints, making direct comparison essential for understanding their respective roles within the broader decarbonization transition. Rather than identifying a single optimal solution, the literature increasingly recognizes that complementary

implementation of multiple pathways will be necessary to achieve long-term emission reduction objectives. To facilitate this comparison, **Table 2** summarizes the principal maritime decarbonization pathways together with their main advantages, limitations, and current implementation readiness as reported in the literature.

Table 2 Comparison of major maritime decarbonization pathways.

Decarbonization Pathway	Main Advantages	Main Limitations	Current Implementation Readiness
Green Ammonia	High potential for deep greenhouse gas reduction; suitable for long-distance shipping	Toxicity, fuel storage complexity, safety regulations, limited bunkering infrastructure	Medium (pilot projects and demonstration phase)
Green Hydrogen	Zero direct carbon emissions; strong long-term decarbonization potential	High production cost, storage challenges, limited global infrastructure	Low-Medium (early commercial deployment)
Green Methanol	Easier storage and handling than hydrogen; compatible with existing engine retrofits	Renewable feedstock availability, higher production cost than conventional fuels	Medium-High (rapid commercial adoption)
Shore Power (Cold Ironing)	Immediate reduction of emissions during berthing; mature technology	High installation cost, electricity grid dependency, vessel compatibility	High (widely implemented in major ports)
Port Electrification and Renewable Energy Integration	Reduces terminal emissions; improves operational efficiency; supports future energy transition	Significant capital investment, grid capacity limitations, long implementation period	High (increasing global implementation)

Table 2 demonstrates that the principal maritime decarbonization pathways differ substantially in their technological maturity, infrastructure requirements, operational characteristics, and implementation readiness. While shore power and port electrification have achieved relatively high implementation readiness because of their technological maturity and increasing deployment in major ports, alternative fuels such as green hydrogen and green ammonia remain constrained by infrastructure availability, production costs, and safety considerations. Green methanol represents an intermediate pathway, benefiting from greater compatibility with existing maritime systems while still facing challenges related to renewable fuel production and supply. Overall, the comparison indicates that no individual pathway can independently achieve maritime decarbonization. Instead, complementary implementation of multiple pathways, supported by coordinated infrastructure development, governance mechanisms, and investment strategies, will be necessary to facilitate an effective transition. Building upon this comparison, the following section synthesizes how interactions across shipping, ports, and governance continue to shape the effectiveness of maritime decarbonization strategies.

2.1 Synthesis: Disciplinary separation across shipping, ports, and governance

Despite the growing sophistication and volume of research on maritime decarbonization, the literature remains structurally fragmented across three dominant streams, namely, vessel-level fuel-transitions, port centered infrastructure and energy systems, and governance and policy instruments. Vessel oriented studies typically analyze alternative fuels, propulsion systems, and onboard technologies while treating port infrastructure availability, fuel supply chains, and regulatory enforcement as external or assumed conditions. Conversely, port focused research prioritizes local emission reductions through shore power, electrification, and renewable energy integration, often without explicit consideration of fleet transition timelines, fuel choice uncertainty, or vessel demand dynamics (Song, 2024; Fadiga & Ferreira, 2024). Governance oriented analyses further reinforce this separation by focusing on policy ambition, target setting, and regulatory design at an abstract level, frequently without systematic linkage to technological readiness, infrastructure investment cycles, or operational feasibility (International Maritime Organization, 2023).

This development of research streams does not merely limit conceptual integration but may also hinder the effective implementation of coordinated decarbonization strategies in practice. When vessel-level studies assume future fuel availability without accounting for port investment risks, fleets face delayed transition decisions as shipowners hesitate to commit to technologies lacking assured bunkering and servicing capacity. At the same time, port authorities that invest in shore power systems or alternative fuel infrastructure based on port-centered analysis often encounter underutilization because fleet uptake evolves more slowly or along different fuel pathways than anticipated. Governance instruments developed in isolation from these technical and infrastructural constraints can become difficult to implement, as regulatory timelines, compliance mechanisms, and incentive structures fail to align with the actual pace of fleet renewal and infrastructure deployment. As a result, policy ambition, capital investment, and technological adoption advance unevenly, reinforcing uncertainty across the maritime transport system and increasing the risk of carbon-intensive development pathways becoming structurally embedded.

The separation of these research streams hinders the development of a coherent, system-level understanding of the technological, operational, regulatory, and governance interactions required to achieve coordinated maritime decarbonization at scale. Investment decisions are informed by partial system views, policy instruments lack operational grounding, and technological pathways evolve without clear sequencing across vessels, ports, fuels, and institutions. Rather than reinforcing one another, these research silos may encourage cautious and fragmented transition strategies that ultimately slow broader emissions reduction efforts. Addressing these limitations therefore requires integrative review approaches that move beyond isolated assessments of individual components and instead diagnose how interactions, timing mismatches, and governance gaps shape real world decarbonization trajectories.

To support a system-level understanding, the review adopts a search strategy explicitly designed to capture interactions among multiple maritime subsystems rather than treating technologies or policy domains as isolated components. Literature research combines keywords and inclusion criteria across vessel technologies, port infrastructure and energy systems, fuel supply chains, and governance instruments, ensuring that studies are selected not only for their individual focus but also for their relevance to cross system interactions. This approach enables the identification of alignment and misalignment between fleet transition pathways, port readiness, and regulatory frameworks, thereby supporting holistic understanding of maritime decarbonization challenges. The review is structured around these interdependencies to explain how disciplinary separation has contributed to disconnected implementation practices and to identify pathways toward more coordinated and implementable decarbonization strategies.

To illustrate the parallel yet weakly connected evolution of vessel oriented, port oriented, and governance-oriented research, **Table 3** summarizes representative studies published between 2023

and 2025 by linking research focus, methodological approach, principal findings, and their relevance to complementary decarbonization perspective.

Table 3 Summary of representative studies.

Author(s)	Focus	Method	Key findings	Relevance to the present review
Zhang et al. (2026)	Alternative marine fuels	Literature review	Ammonia, hydrogen, and methanol are main zero carbon fuel options; technical, cost, and safety challenges exist.	Guides understanding of ship fuel-transitions.
Douglas et al. (2025)	Green shipping corridors and well-to-wake assessment of alternative marine fuels	Scenario-based well-to-wake assessment.	Demonstrates that the environmental performance of alternative marine fuels depends on fuel production pathways, infrastructure availability, and operational conditions across the entire fuel life cycle.	Strengthens the discussion on alternative fuel pathways by highlighting the need to evaluate fuel-transition beyond vessel emissions and consider broader system interactions.
Fan et al. (2025)	Hydrogen fuel feasibility for marine vessels	Techno-economic feasibility assessment.	Hydrogen can substantially reduce greenhouse gas emissions, but practical deployment depends on onboard storage capacity, infrastructure availability, operational requirements, and lifecycle costs.	Provides practical evidence on hydrogen as an alternative marine fuel and highlights implementation considerations that influence fuel-transition pathways.
Ge et al. (2025)	Hydrogen-electricity integrated energy systems for ports	Multi-objective optimization modelling.	Demonstrates that integrating hydrogen and electricity storage with coordinated energy management can reduce both lifecycle costs and carbon emissions while improving the use of renewable energy in port operations.	Strengthens the discussion on port energy transition by illustrating how integrated energy systems can support port decarbonization beyond individual technologies.
Hu et al. (2025)	Carbon-aware optimization of multimodal transport networks	Mixed-integer optimization model.	Shows that optimizing storage node locations and freight flow routes simultaneously can reduce transport-related carbon emissions while improving network efficiency.	Extends the discussion beyond vessels and ports by demonstrating that logistics network planning also contributes to coordinated maritime decarbonization.
Kwon et al. (2025)	Life cycle assessment of shipbuilding materials under CBAM	Scenario-based life cycle assessment (LCA).	Shows that structural steel dominates embedded carbon emissions and that material sourcing, recycling strategies, and supply-chain transparency strongly influence future CBAM exposure.	Broadens the review by highlighting that maritime decarbonization also depends on reducing embodied emissions during ship construction, complementing operational decarbonization strategies.

Table 3 (continued) Summary of representative studies.

Author(s)	Focus	Method	Key findings	Relevance to the present review
Kosek et al. (2025)	Energy transition planning in seaports	Strategic assessment / case study.	Shows that successful port decarbonization depends on coordinated energy planning, infrastructure investment, and collaboration among port stakeholders.	Supports the review by demonstrating that ports play a central role in enabling maritime decarbonization through integrated energy transition strategies.
Mayanti et al. (2025); Katumwesigye et al. (2025)	Decarbonization pathways for short-sea RoPax ferries	Life cycle assessment and techno-economic analysis.	Demonstrate that the environmental and economic performance of low-carbon ferry operations depends on fuel selection, electricity sources, carbon pricing, and vessel operating conditions, with battery-electric propulsion offering substantial emission reductions where renewable electricity is available.	Provides practical evidence that decarbonization pathways differ according to vessel type, operating profile, and energy source, reinforcing the need for technology choices that reflect specific operational contexts rather than a single solution for all ships.
Wang et al. (2024)	Shore power in ports	Bibliometric analysis.	Shore power research is growing; it helps reduce emissions when ships are at berth.	Helps map port decarbonization measures.
Song (2024)	Decarbonization strategies	Literature review.	Identifies port emission sources and ways to reduce them.	Provides foundation for port focused research.
Fadiga and Ferreira (2024)	Port decarbonization	Systematic review.	Shows technical, financial, and governance barriers for port decarbonization.	Helps identify research gaps and informs PRISMA review.
Holder et al. (2024)	Hydrogen in ports	Systematic review.	Ports can act as hydrogen production and distribution hubs.	Extends port decarbonization to future energy systems.
International Maritime Organization (2023)	Shipping governance	Policy analysis.	Sets global emission targets and strategies.	Provides context for regulatory and governance issues.
OECD (2025)	Fuel supply and infrastructure	Policy and industry analysis.	Infrastructure readiness and coordination are major challenges for fuel-transition.	Links ship fuel choices with port infrastructure needs.

3. Methodology

3.1 Data and search strategy

This study followed a predefined integrated review framework that combines bibliometric science mapping with a PRISMA-based systematic literature review using a single Scopus-derived dataset. The review protocol consisted of sequential literature retrieval, eligibility screening, bibliometric analysis, qualitative evidence synthesis, and integrated system-level interpretation. Rather than applying these methods independently, the review was designed to exploit their complementary strengths. Bibliometric analysis provides a broad overview of the intellectual structure and development of the research field, whereas the PRISMA-based systematic review

enables a detailed examination of empirical evidence related to technological pathways, port-based interventions, fuel-transition strategies, and governance mechanisms.

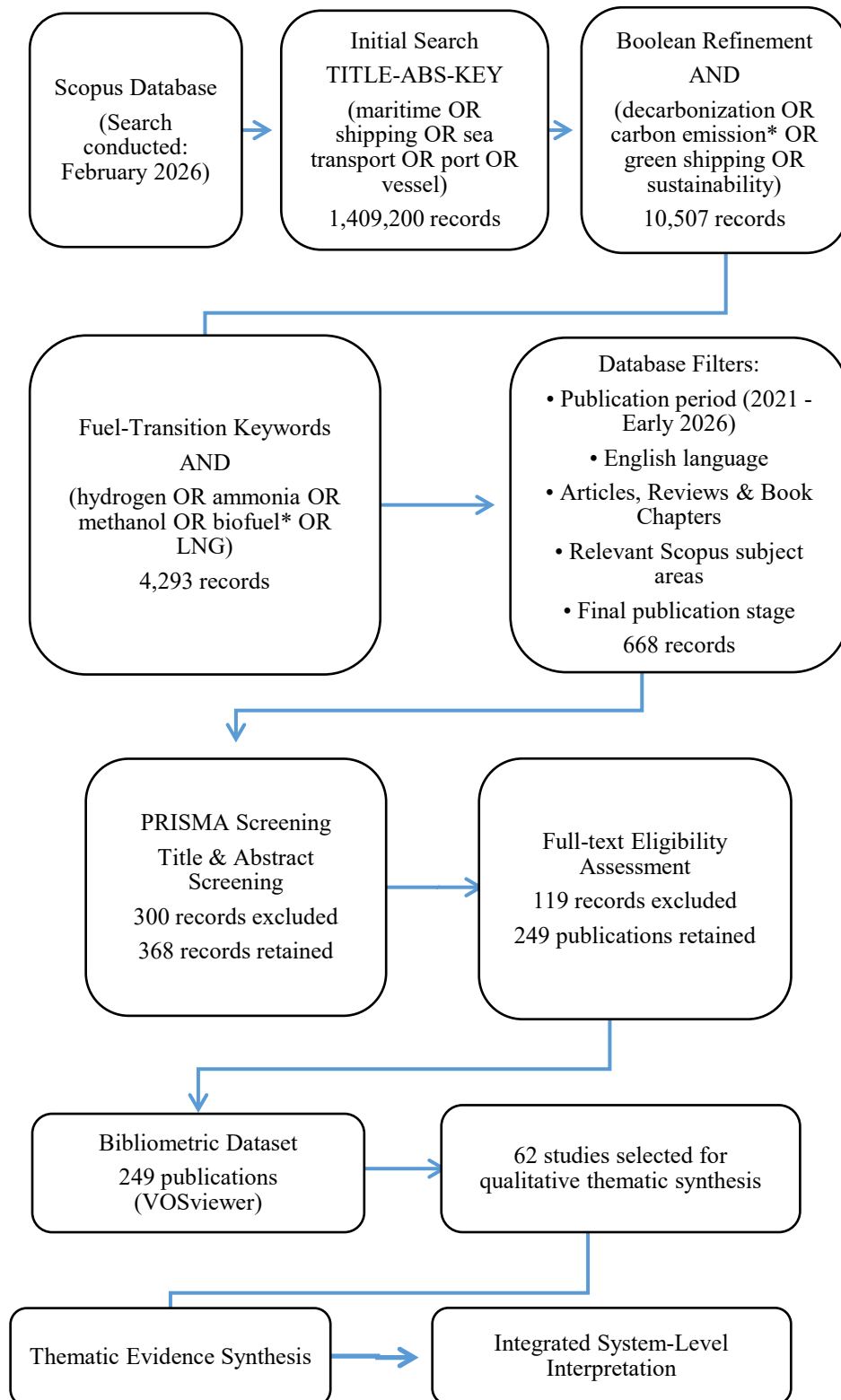


Figure 1 Integrated methodological framework illustrating the Scopus search strategy, study selection, and analytical workflow.

Source: Authors' own work

The integration of these approaches allows quantitative mapping of publication patterns, collaboration networks, citation structures, and thematic evolution to be interpreted alongside qualitative evidence from carefully selected studies. This combined framework facilitates a more comprehensive understanding of maritime decarbonization by linking macro-level knowledge structures with micro-level empirical findings. Consequently, the review moves beyond describing individual technologies or policy instruments to examine how interactions among vessels, ports, fuel infrastructure, and governance influence coordination, implementation, and transition sequencing take place across the wider maritime system.

Figure 1 summarizes the complete methodological framework adopted in this study, beginning with the sequential Scopus search strategy, Boolean refinement, database filtering, and PRISMA-based study selection, followed by the integration of bibliometric analysis and qualitative evidence synthesis. The workflow distinguishes between the bibliometric dataset (249 publications), which was analyzed to examine publication trends, collaboration networks, citation structures, and thematic evolution, and the subset of 62 studies selected through PRISMA-based eligibility assessment for detailed qualitative evidence synthesis. This distinction enables comprehensive mapping of the research landscape while ensuring that the qualitative interpretation is based on studies offering the greatest empirical relevance to the review objectives. This integrated design enabled broad mapping of the maritime decarbonization research landscape while supporting an in-depth examination of interactions among vessel technologies, port infrastructure, fuel-transition pathways, and governance mechanisms.

The review was implemented through two analytically linked stages. First, the bibliometric analysis was conducted using the complete dataset of 249 publications to examine publication trends, collaboration networks, citation structures, and thematic evolution across the maritime decarbonization literature. Second, the publications retained after the PRISMA-based screening process were subjected to detailed qualitative synthesis, with the study selection procedure described in Section 3.3. Using a single Scopus-derived corpus ensures that the systematic review remains grounded in the intellectual structure identified through the bibliometric analysis while enabling detailed interpretation of empirical findings from the same evidence base. Scopus was selected as the primary data source due to its extensive coverage of peer-reviewed journals, standardized indexing structure, and suitability for bibliometric analysis in interdisciplinary transport and sustainability research. Beyond its extensive journal coverage, the database offers standardized bibliographic metadata and comprehensive citation information that facilitate science mapping, citation analysis, and network visualization using Bibliometrix and VOSviewer. Employing a single curated database also minimizes duplicate records, improves metadata consistency, and enhances the reproducibility of bibliometric analyses. Although this approach may exclude publications indexed exclusively in other databases, it provides a transparent, reproducible, and methodologically consistent foundation for integrated bibliometric and systematic literature review research.

A sequential Boolean search strategy was developed to progressively refine the literature while maintaining alignment with the research objectives. The search was conducted in the Scopus database in February 2026 using the TITLE-ABS-KEY search field, which retrieves terms appearing in article titles, abstracts, and author keywords to maximize topic relevance while minimizing unrelated records. Broad maritime-related terms (maritime OR shipping OR "sea transport" OR port OR vessel) were first applied to establish the research domain, yielding 1,409,200 records. To focus the dataset on maritime decarbonization, decarbonization-related terms (decarbonization OR decarbonization OR "carbon emission" OR "green shipping" OR sustainability) were subsequently incorporated, reducing the dataset to 10,507 records. A final Boolean refinement introduced alternative fuel and energy transition keywords (hydrogen OR ammonia OR methanol OR biofuel OR LNG), resulting in 4,293 records for further eligibility filtering and PRISMA-based screening.

The refined dataset of 4,293 records was subsequently filtered using predefined eligibility criteria before title and abstract screening. The filters restricted the dataset to English-language, peer-

reviewed journal articles and reviews published between 2021 and early 2026 within relevant Scopus subject areas, specifically Engineering, Social Sciences, Environmental Science, and Energy, to ensure comprehensive coverage of both technical and governance dimensions of maritime transport. Records that did not satisfy these eligibility criteria, together with publications that were clearly outside the scope of maritime decarbonization, were excluded. Following the application of these database filters, the final screening dataset comprised 668 records, which subsequently underwent PRISMA-based title and abstract screening.

The search strategy was intentionally designed to capture multiple interacting subsystems rather than isolated technologies or policies. Keywords were combined to include vessels, port infrastructure, fuel pathways, and governance, ensuring that studies addressing interactions among these subsystems were included. This approach allows the review to examine alignment challenges across fleet transition, port readiness, and policy implementation, reflecting the complex and interconnected nature of maritime decarbonization.

Coordination across subsystems is examined through qualitative synthesis rather than keyword filtering. Bibliometric methods can identify clusters of research topics and trends but cannot fully capture the nuanced relationships, dependencies, and timing mismatches between vessel technologies, port infrastructure, and regulatory instruments. In-depth reading and thematic coding of the selected studies are required to interpret how these components interact in practice. This approach provides a better understanding of cross-sector integration but introduces limitations. The synthesis depends on the scope and selection of studies, and some subsystem interactions may remain underrepresented if not explicitly analyzed in the primary literature. Additionally, qualitative interpretation introduces subjectivity, which is mitigated through structured PRISMA procedures and cross-referencing findings with the bibliometric mapping.

3.2 Eligibility criteria and screening rules

Explicit eligibility criteria were established before the screening process to ensure methodological transparency, consistency, and reproducibility throughout the review. Anjomshoe et al. (2022) emphasized that predefined eligibility criteria help minimize selection bias and improve the transparency of evidence synthesis, while Gunnell et al. (2022) highlighted their importance for ensuring reproducibility during study selection. Because this review integrates bibliometric analysis with a PRISMA-based qualitative synthesis, the same eligibility framework was applied during dataset construction, with additional selection criteria introduced to identify studies suitable for detailed qualitative evaluation. Donthu et al. (2022) demonstrated that combining bibliometric techniques with systematic review methods provides complementary analytical perspectives, and Paul et al. (2023) further argued that such integration strengthens evidence synthesis by linking science mapping with in-depth qualitative interpretation. These principles guided the methodological design adopted in the present review.

Studies were included if they satisfied three conditions that together ensured topical relevance and analytical suitability for examining coordination and sequencing across maritime decarbonization subsystems. First, studies were required to address maritime shipping, ports, or their interface in relation to greenhouse gas emissions, decarbonization, or energy transition, ensuring relevance to the system components under investigation. Second, studies had to meet publication criteria, including publication between 2021 and early 2026, indexing in Scopus, availability in final published form, and use of the English language. This time frame captures intensified research activity associated with recent regulatory developments, technological experimentation, and infrastructure planning in maritime decarbonization. Third, studies were required to employ methodological approaches capable of generating evidence relevant to system interactions within maritime decarbonization. Eligible studies included empirical investigations, quantitative or qualitative modelling, and systematic or structured review articles with clearly defined analytical frameworks. These methodological approaches were considered appropriate because they provide sufficient evidence to

examine relationships, dependencies, and sequencing among vessel technologies, port infrastructure, fuel-transition pathways, and governance mechanisms.

Studies were excluded if they addressed sustainability or climate change without substantive consideration of maritime or port decarbonization, were purely conceptual or opinion-based without empirical evidence or structured analytical approaches, or consisted of editorials, commentaries, conference abstracts, or other non-peer-reviewed publications. Studies focusing exclusively on non-maritime sectors were also excluded unless they demonstrated explicit analytical relevance to shipping or port systems. These exclusion criteria ensured that the final dataset comprised studies capable of supporting a rigorous examination of interactions, dependencies, and transition sequencing across the principal components of maritime decarbonization.

During full-text review, coordination relevance was explicitly assessed. Retained studies were examined for evidence of interactions between system components, such as the influence of port infrastructure readiness on fleet transition decisions, the role of policy instruments in shaping technology adoption, or the sequencing of alternative fuel deployment across vessels and ports.

3.3 PRISMA-based screening and study selection

A total of 668 records underwent title and abstract screening following the application of the predefined eligibility criteria. Studies lacking substantive relevance to maritime or port decarbonization, or failing to meet the methodological requirements established in Section 3.2, were excluded, resulting in the removal of 300 records. The remaining 368 studies proceeded to full-text assessment, where their methodological characteristics, analytical scope, and relevance to the research objectives were evaluated against the predefined inclusion and exclusion criteria. Particular attention was given to studies employing empirical investigation, structured quantitative or qualitative modelling, or systematic review methodologies capable of informing the subsequent qualitative synthesis.

A further 119 studies were excluded during the full-text assessment because they lacked sufficient methodological detail, analytical depth, or direct relevance to the research objectives. This group primarily comprised narrative discussions, perspective papers, and descriptive studies that did not provide structured empirical evidence or systematic analytical frameworks suitable for the qualitative synthesis.

The screening process resulted in two complementary datasets serving different analytical purposes. The first dataset comprised 249 publications retained for the bibliometric analysis to examine publication trends, collaboration networks, citation structures, and thematic evolution across the broader maritime decarbonization literature. These publications continued to contribute to the science mapping and network analyses. Subsequently, the 249 publications were subjected to the quality appraisal described in Section 3.4 to evaluate their methodological transparency, analytical depth, and system boundary clarity. Based on this assessment, together with their direct relevance to the research objectives and the availability of sufficient empirical or systematic analytical evidence, 62 studies were retained for the PRISMA-based qualitative synthesis. This two-stage analytical design enabled the bibliometric analysis to provide a comprehensive overview of the intellectual structure of the field while allowing the qualitative synthesis to focus on the most robust evidence for interpreting coordination, implementation, and transition sequencing across the principal components of maritime decarbonization. The complete study identification, screening, eligibility, quality appraisal, and inclusion process is illustrated in **Figure 2**.

3.4 Quality assessment and mixed analytical approach

Quality assessment was undertaken to ensure that the evidence incorporated into the qualitative synthesis demonstrated sufficient methodological rigor and analytical credibility. Because this review integrates bibliometric analysis with an in-depth qualitative synthesis, evaluating the quality of the selected studies was essential for supporting transparent interpretation of the evidence.

Rather than relying solely on publication characteristics, the assessment focused on methodological attributes that influence the reliability and interpretability of the evidence. This approach is particularly important in maritime decarbonization research, where technological, operational, and governance components interact across multiple system-levels. Accordingly, three complementary evaluation dimensions were adopted: methodological transparency, analytical depth, and system boundary clarity. Together, these dimensions provide a structured basis for assessing the robustness of empirical evidence and its suitability for informing the subsequent qualitative synthesis.

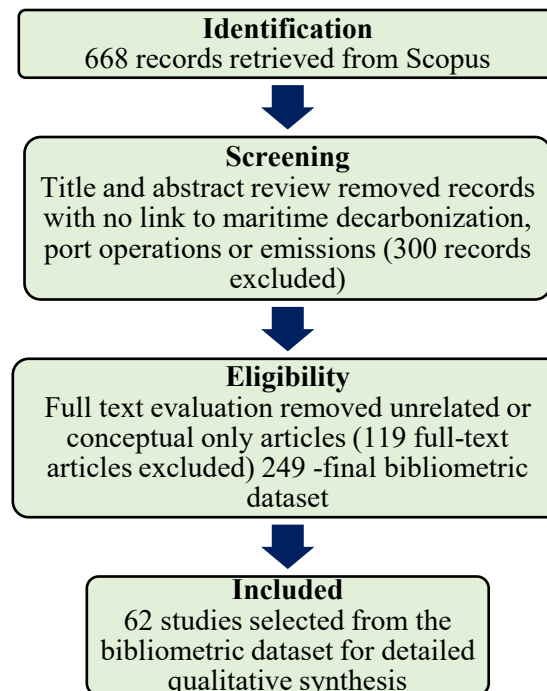


Figure 2 PRISMA selection flow.
 Source: Authors' own work

To improve methodological transparency, the quality appraisal was supported by a structured assessment matrix based on the three evaluation dimensions adopted in this study. Each study included in the PRISMA-based qualitative synthesis was evaluated using a three-point scoring scale (0 - 2) for methodological transparency, analytical depth, and system boundary clarity, where a score of 0 indicated that the criterion was not demonstrated, 1 indicated partial fulfilment, and 2 indicated comprehensive fulfilment. The three-point scale was adopted because it provides sufficient discrimination between studies while maintaining consistency and reducing subjective variation during evidence appraisal. The combined scores produced a maximum quality score of six, with studies scoring 5 - 6 classified as high quality, 3 - 4 as moderate quality, and 0 - 2 as low quality. **Table 4** summarizes the overall quality assessment outcomes and provides the basis for the subsequent qualitative synthesis.

Table 4 Summary of quality assessment outcomes.

Quality Category	Score Range	Number of Studies	Percentage
High	5 - 6	40	64.5
Moderate	3 - 4	22	35.5
Low	0 - 2	0	0.0

Table 4 summarizes the overall quality appraisal of the studies included in the qualitative synthesis. The assessment indicates that the evidence base is predominantly characterized by studies demonstrating moderate to high methodological quality, providing an appropriate foundation for the subsequent synthesis and interpretation of findings. No studies were classified as low quality because the PRISMA-based screening process had already excluded studies that did not satisfy the predefined methodological and relevance criteria for inclusion in the qualitative synthesis. High-quality studies consistently demonstrated clear methodological reporting, comprehensive analytical approaches, and well-defined system boundaries, whereas moderate-quality studies generally satisfied the assessment criteria but exhibited minor limitations in reporting or analytical scope.

The quality assessment informed both the selection of studies for qualitative synthesis and the subsequent interpretation of the evidence by assigning greater interpretive weight to studies demonstrating stronger methodological rigor and analytical depth, while studies of moderate quality were used to provide complementary contextual evidence. As highlighted by Passas (2024), integrating bibliometric analysis with qualitative evidence synthesis provides a more comprehensive understanding of complex research domains than relying on either approach independently. Building on this perspective, the present review combines macro-level publication patterns, collaboration networks, and thematic developments with detailed qualitative evidence concerning technological pathways, port-based interventions, and governance mechanisms. This integrated analytical approach strengthens the robustness of the review by linking broad knowledge structures with evidence-based interpretation of maritime decarbonization pathways.

3.5 Limitations of the review approach

Although the combined bibliometric and PRISMA-based systematic review provides a comprehensive overview of maritime decarbonization research, several methodological limitations should be acknowledged. First, the study relied exclusively on the Scopus database. Although Scopus offers broad multidisciplinary coverage and consistent bibliographic metadata, relevant publications indexed exclusively in other databases, such as Web of Science, Dimensions, or regional repositories, may not have been captured. Consequently, the findings should be interpreted as representing the Scopus-indexed scholarly landscape rather than the entirety of global maritime decarbonization research.

Second, bibliometric analysis is subject to citation-related limitations. Recently published studies may receive fewer citations because of citation lag rather than lower scientific significance, while highly cited publications may disproportionately influence network structures and citation patterns. Therefore, citation-based indicators should be interpreted alongside qualitative evidence rather than as standalone measures of research importance.

Third, publication bias may influence the available evidence because peer-reviewed journal articles are more likely to report successful or positive findings, whereas negative, inconclusive, or unpublished studies are less frequently represented within bibliographic databases. Similarly, restricting the review to English-language publications may have excluded relevant contributions published in other languages, particularly regional studies addressing local maritime decarbonization initiatives.

Finally, bibliometric networks are inherently influenced by keyword selection, indexing practices, and author-defined terminology. Variations in keyword usage, spelling, and indexing may affect the identification of thematic clusters and collaboration networks. To mitigate these limitations, the bibliometric findings were interpreted together with the PRISMA-based qualitative synthesis, enabling quantitative science mapping to be complemented by critical evaluation of the underlying evidence. This mixed approach improves the robustness of the review by balancing quantitative publication patterns with qualitative interpretation of the reviewed studies.

4. Results and bibliometric analysis

4.1 Publication trends in maritime and port decarbonization research

The temporal evolution of publications reveals a rapid expansion of research on maritime and port decarbonization since 2021. The sharp increase after 2023 indicates a shift from exploratory studies toward applied, policy- and implementation-oriented research, reflecting the growing urgency of aligning maritime transport with net-zero targets. This acceleration coincides with the adoption of the revised International Maritime Organization Greenhouse Gas Strategy in 2023, increasing governmental and industrial commitments toward net-zero shipping, and growing investment in alternative marine fuels, port electrification, and digital decarbonization technologies.

Analysis of publication patterns shows that early studies predominantly focused on conceptual sustainability and efficiency improvements, while recent research increasingly addresses alternative fuels, port electrification, and regulatory implementation mechanisms. The prominence of publications related to International Maritime Organization strategies suggests that evolving regulatory frameworks have become an increasingly important focus within maritime decarbonization research. The growing emphasis on regulatory developments also appears to have encouraged greater research attention towards technological, infrastructural, and governance dimensions, while contributing to the emergence of specialized subfields examining vessels, ports, and institutional interactions. Overall, the growth pattern reflects both the expansion and diversification of maritime decarbonization research, with intellectual trajectories increasingly oriented towards alignment across vessels, ports, and policy, consistent with the observations reported by Christodoulou and Cullinane (2022) and Bakar et al. (2023).

Figure 3 illustrates the annual publication trend of the 249 studies included in the bibliometric analysis. Research output increased from 15 publications in 2021 to 111 publications in 2025, demonstrating substantial growth in scholarly attention to maritime and port decarbonization. The six publications recorded for early 2026 reflect partial-year coverage at the time of data extraction rather than a decline in research activity.

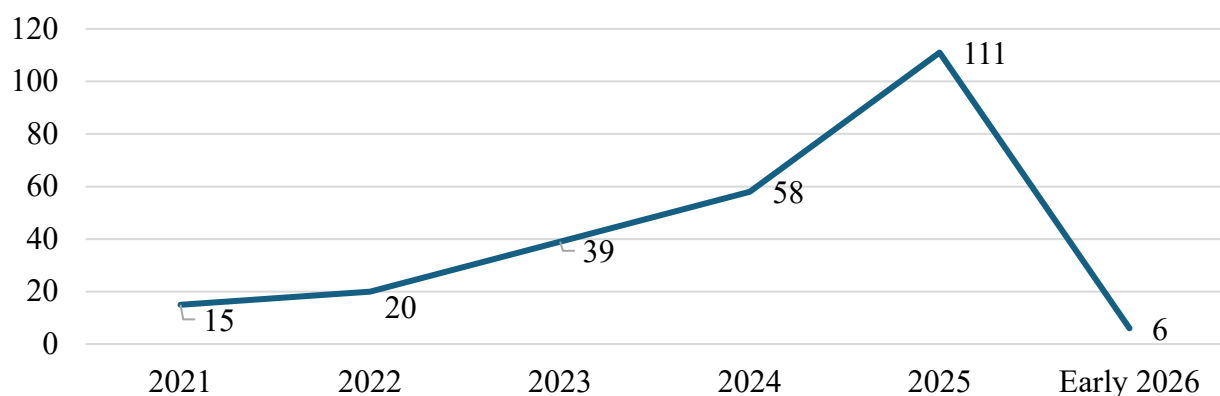


Figure 3 Annual publication trend of the 249 Scopus-indexed publications included in the bibliometric analysis (2021 - Early 2026). Data labels indicate the number of publications for each year.

Source: Authors' own work

As shown in **Figure 3**, research on maritime and port decarbonization expanded rapidly after 2023, indicating that the field has progressed beyond exploratory investigations towards implementation-oriented studies. This acceleration coincides with increasing international commitments to greenhouse gas reduction, evolving International Maritime Organization decarbonization strategies, and growing investment in alternative fuels, port electrification, and digital technologies.

While the annual publication trend demonstrates the rapid expansion of maritime decarbonization research, the distribution of publications across scientific journals provides further insight into the disciplinary structure and maturity of the field. Examining the leading publication sources helps identify the journals that have played the most influential role in advancing research on shipping decarbonization, port sustainability, alternative fuels, and maritime policy. **Table 5** summarizes the leading publication sources represented in the present review.

Table 5 Leading publication sources in maritime decarbonization research based on the Scopus dataset (2021 - Early 2026).

Rank	Publication Source	Publications
1	Sustainability (Switzerland)	31
2	Ocean and Coastal Management	15
2	Energies	15
4	Ocean Engineering	13
5	Transportation Research Part E: Logistics and Transportation Review	11
5	Journal of Marine Science and Engineering	11

Table 5 indicates that maritime decarbonization research is concentrated within a relatively small group of specialized journals spanning sustainability, marine engineering, coastal management, transport, and energy research. Sustainability (Switzerland) emerged as the leading publication source with 31 publications, followed by Ocean and Coastal Management and Energies, each contributing 15 publications. Ocean Engineering, Transportation Research Part E: Logistics and Transportation Review, and Journal of Marine Science and Engineering also represent major publication outlets, demonstrating the multidisciplinary nature of maritime decarbonization research. This distribution suggests that the field has evolved beyond a purely maritime engineering perspective to incorporate environmental management, energy transition, transport systems, and sustainability science, thereby reinforcing the importance of mixed approaches to maritime decarbonization.

Beyond identifying the principal publication sources, examining the most-cited publications provides further insight into the intellectual foundations of maritime decarbonization research. Citation analysis identifies the studies that have exerted the greatest scholarly influence on the evolution of the field by shaping subsequent research, methodological development, and policy discussions. Rather than reflecting publication productivity alone, citation performance highlights the landmark contributions that have influenced research on alternative marine fuels, greenhouse gas mitigation, energy efficiency, port decarbonization, digital transformation, and system-oriented transition strategies. **Table 6** presents the ten most-cited publications identified in the Scopus dataset analyzed in this review.

Table 6 presents the ten most-cited publications identified in the Scopus dataset, highlighting the studies that have exerted the greatest influence on the development of maritime decarbonization research. The most influential publications primarily focus on alternative marine fuels, greenhouse gas emission reduction, shipping energy efficiency, digital transformation, and decarbonization strategies. Foundational review studies by Ampah et al. (2021) and Mallouppas and Yfantis (2021) established comprehensive perspectives on technological and policy pathways for reducing shipping emissions, while Lindstad et al. (2021), Fan et al. (2021), Liu et al. (2022), and Shi et al. (2023) advanced knowledge on low-carbon fuels and propulsion technologies. Research by Del Giudice et al. (2022), Yan et al. (2021), and Wang et al. (2023) further expanded the field by addressing digital transformation, operational efficiency, and port decarbonization. Although Yang et al. (2022) was among the most highly cited publications in the retrieved dataset, its contribution provides broader environmental context rather than focusing exclusively on maritime decarbonization. Collectively, these highly cited publications illustrate how the field has progressed from technology-oriented

investigations towards more integrated perspectives that consider operational, infrastructural, and governance dimensions of decarbonization.

Table 6 Ten most-cited publications in the Scopus dataset as of 2021 - Early 2026.

Rank	Authors	Total citations	Main research focus	Contribution to the reviewed field
1	Ampah et al., 2021	292	Cleaner alternative marine fuels	Reviews two decades of research on cleaner marine fuels and compares their potential to support International Maritime Organization emission-reduction targets.
2	Mallouppas and Yfantis, 2021	219	Shipping decarbonization technologies and innovation	Reviews technological, operational, regulatory, and innovation pathways available for deep decarbonization of shipping.
3	Lindstad et al., 2021	209	E-fuels and maritime GHG reduction	Examines the well-to-wake potential of renewable hydrogen, ammonia, and hydrocarbon e-fuels for reducing maritime emissions.
4	Del Giudice et al., 2022	148	Digitalization at the ship-port interface	Maps research on digital technologies and sustainable business models linking shipping and port operations.
5	Fan et al., 2021	146	Inland-vessel power-system decarbonization	Evaluates alternative power options and assessment methods for greener, lower-carbon, and increasingly electrified inland shipping.
6	Liu et al., 2022	128	Ammonia-diesel marine-engine technology	Investigates stratified ammonia-diesel injection as a potential low-carbon marine-engine configuration.
7	Yang et al., 2022	126	COVID-19, pollution, and global carbon emissions	Reviews the wider environmental and carbon-emission effects of COVID-19; its connection to maritime decarbonization is indirect.
8	Shi et al., 2023	119	Green hydrogen, ammonia, and methanol pathways	Reviews production and marine-engine utilization pathways for major renewable marine fuels.
9	Yan et al., 2021	111	Data analytics for maritime fuel management	Reviews data-analytics methods for monitoring, predicting, and reducing ship fuel consumption and emissions.
10	Wang et al., 2023	87	Port-emission sources and mitigation technologies	Synthesizes port carbon-emission sources, technical reduction measures, and the influence of policy on port decarbonization research.

The publication trends, leading publication sources, and most influential studies together demonstrate the rapid expansion and intellectual maturation of maritime decarbonization research. While these bibliometric performance indicators reveal how the field has evolved and where influential knowledge has been generated and disseminated, they do not fully explain the relationships among vessels, ports, fuel-transition pathways, and governance systems. These interactions are examined in greater depth through the subsequent qualitative synthesis. Before exploring those system-level relationships, the following section analyzes the international co-authorship network to

identify the principal research hubs and collaboration patterns shaping global maritime decarbonization research.

4.2 Country-level co-authorship and collaboration patterns

The country-level co-authorship analysis reveals a geographically diverse research landscape with varying collaboration intensity. China emerged as the dominant contributor, recording the highest publication output (87 publications) and the greatest Total Link Strength (TLS = 37), indicating the strongest level of international research collaboration. The United Kingdom ranked second (29 publications; TLS = 29), followed by Germany (TLS = 22), France (TLS = 19), Greece (TLS = 16), Sweden (TLS = 15), Denmark (TLS = 15), Italy (TLS = 14), and Spain (TLS = 14), all of which demonstrated substantial collaborative influence within the global research network. These quantitative indicators demonstrate that the leading contributors are supported not only by high research productivity but also by extensive international collaboration, reinforcing their role in shaping the global maritime decarbonization research agenda. Contributions from Southeast Asian countries, such as Singapore and Malaysia, reflect emerging regional engagement with port-level decarbonization strategies, particularly shore power deployment and energy efficiency measures (Alamoush, 2022; Bakar et al., 2023).

Figure 4 presents the international co-authorship network in maritime shipping and port decarbonization research from 2021 to early 2026. Node size represents research productivity, whereas the connecting links illustrate co-authorship relationships between countries. The strength of these collaborative relationships is reflected by the Total Link Strength (TLS), which indicates the intensity of international research collaboration. The network structure demonstrates that collaboration extends beyond publication productivity, with several countries functioning as important connectors between regional research communities. While China and the United Kingdom serve as the principal collaboration hubs, European countries collectively form a dense network that facilitates knowledge exchange across multiple research domains. Despite these strong collaborative connections, the network still exhibits signs of thematic and disciplinary silos, with collaboration concentrated within established country clusters and limited cross-domain interaction between shipping, port operations, and policy-focused research.

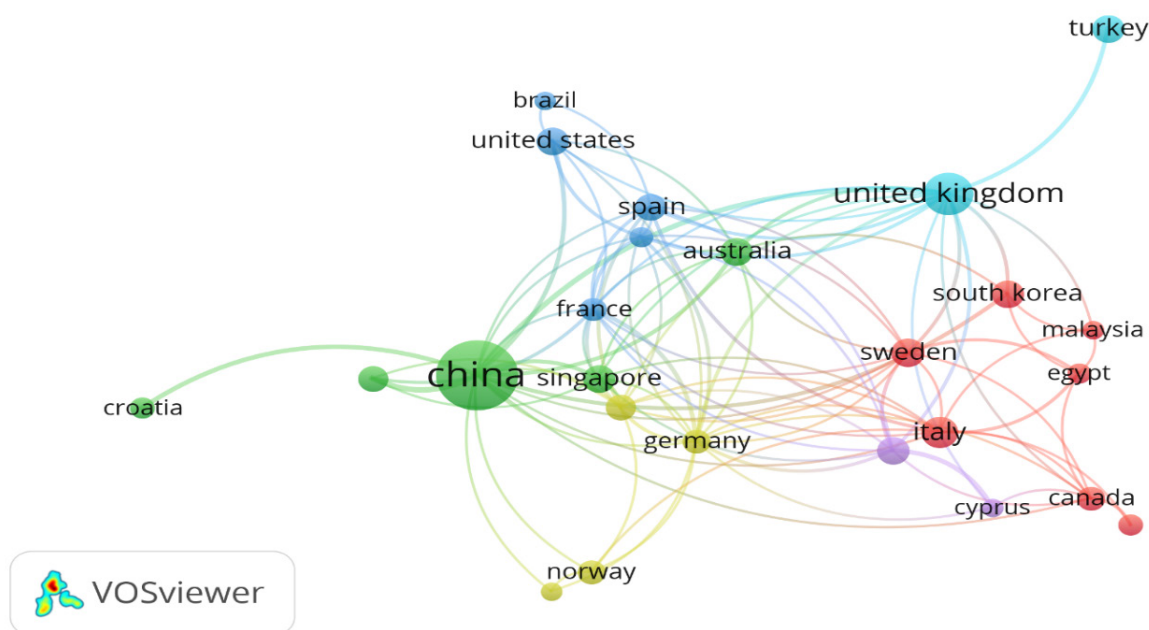


Figure 4 International research collaboration network in maritime decarbonization studies.
Source: Authors' own work

These patterns indicate that perspectives from countries with strong maritime industries and regulatory leadership dominate knowledge production. This collaboration pattern may contribute to fragmented knowledge development, as research partnerships remain concentrated within established networks and disciplinary boundaries. Such concentration may limit opportunities to integrate technological, operational, and governance perspectives across the broader maritime decarbonization system. Emerging contributions from Southeast Asia highlight opportunities to diversify the global research landscape. However, their comparatively peripheral position within the collaboration network suggests that stronger international partnerships could further enhance knowledge exchange and support more comprehensive maritime decarbonization research.

This collaboration pattern also suggests that cross-sector maritime decarbonization research remains concentrated within established international research networks, highlighting opportunities for broader interdisciplinary and cross-regional collaboration capable of integrating technological, infrastructural, and governance perspectives.

4.3 Thematic structure based on keyword co-occurrence (Minimum threshold 5)

The keyword co-occurrence analysis reveals a structured thematic landscape with several interconnected but partially siloed research clusters. A minimum threshold of five occurrences was selected to balance analytical precision and interpretability. Using this threshold ensures that dominant themes are captured while excluding extremely rare keywords that may represent outliers or single-study topics. The trade-off is that emerging or niche topics with fewer mentions, such as alternative propulsion systems or specific regional policies, may be underrepresented in the network. This approach provides a manageable view of the research field while focusing attention on themes that have achieved broader scholarly traction.

The co-occurrence map demonstrates that maritime decarbonization research is organized into overlapping clusters of technological, infrastructural, policy, and digitalization themes, yet the network also reveals persistent silos. Central keywords such as decarbonization, greenhouse gas emissions, shipping, and carbon emission occupy dominant positions, indicating that emission reduction remains the organizing principle of the field. However, their links to port infrastructure, policy instruments, and digital tools are uneven, highlighting that cross-sector integration remains limited. High-frequency terms include shipping (109 occurrences), decarbonisation/decarbonization (combined occurrences: 202), and carbon emission (79 occurrences), confirming that emission reduction constitutes the dominant thematic focus of maritime decarbonization research. The separate occurrence counts reflect differences in British and American spelling conventions within the indexed literature.

Beyond identifying individual thematic clusters, the keyword co-occurrence network also reveals important relationships among them. The alternative fuels cluster is closely associated with decarbonization objectives but demonstrates comparatively weaker connections with port infrastructure and policy-related keywords. Likewise, digitalization themes, including machine learning, optimization, and decision support, occupy bridging positions between operational efficiency and emission reduction, yet remain only partially unified with governance and fuel-transition research. These patterns indicate that although major research themes have matured independently, stronger conceptual integration across technological, infrastructural, regulatory, and digital domains remains necessary to support coordinated maritime decarbonization.

The alternative fuels cluster, including hydrogen, ammonia, methanol, biofuels, and liquefied natural gas, demonstrates sustained attention on fuel substitution strategies (Ampah et al., 2021; Christodoulou & Cullinane, 2022; Zhang et al., 2026; Nunes, 2025; Mahmud et al., 2025; Sang et al., 2026). While research emphasizes technical performance and environmental evaluation, the co-occurrence network shows weak integration with port infrastructure and policy clusters. This indicates that vessel-level decarbonization research often proceeds independently of the port-side and governance context, reinforcing siloed development pathways.

Port-based decarbonization measures form another cluster, with keywords such as port, port operation, ports and harbors, shore power, electrification, and energy management (Zhang et al., 2026; Nian et al., 2025; Sevgili et al., 2025; Bakar et al., 2023; Alamoush, 2022). Ports are increasingly studied as active energy transition hubs rather than passive infrastructure, yet their linkages to alternative fuel research are relatively weak. This suggests that research on port infrastructure and vessel fuel adoption remains insufficiently coordinated, limiting actionable insights for cross-sector deployment.

Policy and economic considerations constitute a further cluster, with terms such as carbon tax, emissions trading, cost-benefit analysis, regulatory framework, and investments (Chen et al., 2025; Zhang et al., 2026; Lehmann et al., 2025; Zhang & Woo, 2025; Bach, 2023). While this cluster demonstrates the influence of governance on operational and investment decisions, its separation from technological and infrastructural clusters indicates that policy analysis often does not integrate with implementation realities. Fragmented incentives and regulatory misalignment may therefore impede coordinated decarbonization.

An emerging digitalization and optimization cluster includes machine learning, optimization, decision support, and big data (Nguyen et al., 2025; Liu et al., 2025; Wang et al., 2025). These technologies are increasingly applied to predict fuel consumption, optimize berth allocation, manage vessel operations under emission constraints, and support more informed operational decision-making across maritime transport systems (Choi et al., 2025). Yet the network reveals that digital tools remain insufficiently connected to alternative fuel and port infrastructure clusters, suggesting that their potential to facilitate cross-cluster alignment is not fully realized.

The emergence of digital twins and Internet of Things (IoT) technologies further demonstrates the ongoing digital transformation of maritime decarbonization research. Recent studies increasingly combine digital twins, IoT-enabled sensing, and machine learning to support real-time emissions monitoring, predictive maintenance, energy management, and operational optimization across ships and ports. Although these technologies have not yet become dominant themes within the keyword network, their growing integration with artificial intelligence and decision-support systems indicates considerable potential to strengthen coordination between vessel operations, port infrastructure, and decarbonization planning.

The keyword co-occurrence map therefore illustrates both the structural organization of maritime decarbonization research and the persistent silos that limit integrative insights. While clusters reflect mature thematic domains, weak interconnections between vessels, ports, policy, and digitalization indicate that integrative, cross-sector approaches are not yet dominant. This analysis highlights where future research should focus on bridging silos, aligning vessel and port interventions, integrating governance mechanisms, and leveraging digital tools to operationalize coordinated decarbonization strategies. **Figure 5** presents the keyword co-occurrence network generated using VOSviewer, illustrating the principal thematic clusters and their interrelationships across the maritime decarbonization literature.

4.4 Integration of bibliometric mapping and PRISMA review

Bibliometric analysis was used to identify publication trends, influential themes, and relationships among keywords, while the PRISMA review provided a detailed examination of empirical findings, methodological approaches, and contextual insights within selected studies. The thematic clusters identified in the keyword co-occurrence map, as described in Section 4.3, actively informed the organization of the qualitative synthesis. For example, the emissions reduction and operational strategies cluster guided the selection of studies examining low-carbon shipping technologies and port operational practices. Similarly, the cluster on alternative fuels, including hydrogen and ammonia, shaped the review of studies assessing fuel adoption challenges, supply chain readiness, and cost implications. The digitalization and optimization cluster informed analysis of

studies on AI-based energy management and port efficiency tools, ensuring that empirical evidence was interpreted in alignment with the broader intellectual structure of the field.

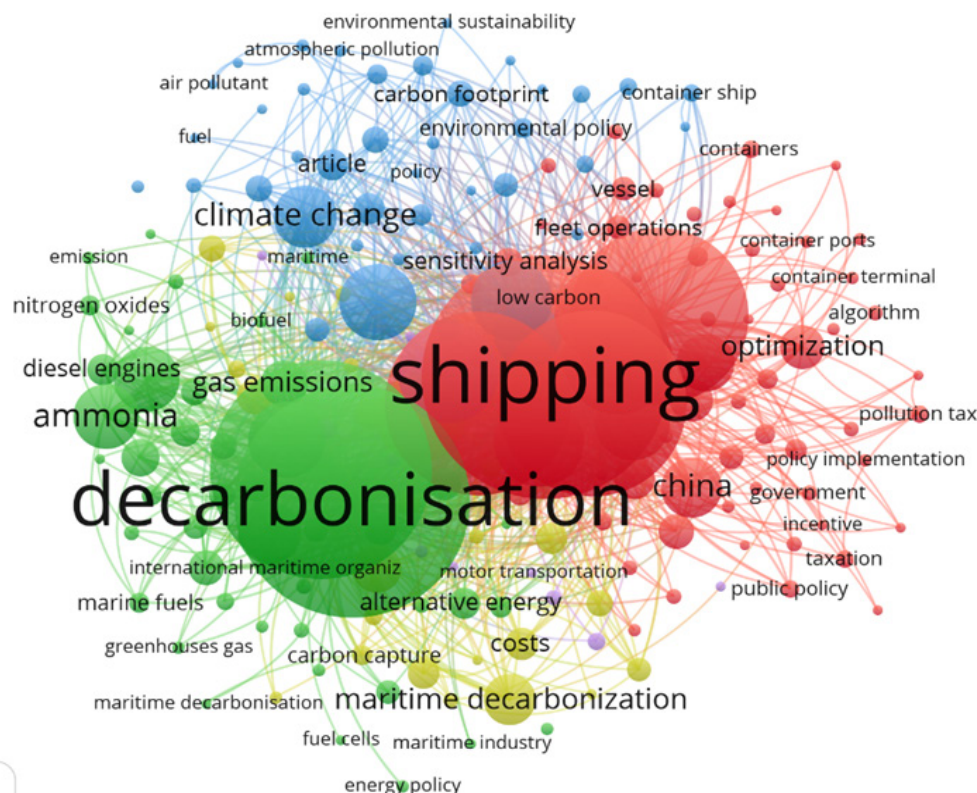


Figure 5 Keyword co-occurrence
Source: Authors' own work (visualized using VOSviewer)

The integration of these two methods revealed synchronization failures and thematic gaps that would have remained hidden if only one approach had been employed. Bibliometric analysis alone captures research volume, dominant themes, and inter-cluster relationships but does not provide detailed information on technological performance, operational practices, or implementation challenges. Conversely, a standalone PRISMA review offers rich empirical insights but might overlook the relative prominence of themes or the structural connections across the literature. For instance, weak links between vessel-level fuel-transition research and port infrastructure studies identified in the keyword map prompted the PRISMA review to focus on implementation gaps, revealing challenges in sequencing technology adoption and aligning operational practices with infrastructure readiness.

Insights from bibliometric analysis actively shaped the interpretation of qualitative evidence. The peripheral position of emerging topics, such as energy storage systems and shore power optimization in smaller ports, directed attention toward underexplored areas in empirical studies, highlighting gaps that could otherwise be overlooked. This iterative integration ensured that the PRISMA review did not merely summarize findings but interpreted them within the broader intellectual organization of the field, connecting high-level thematic patterns with detailed operational and governance insights. To highlight the application of the combined methodology, **Figure 6** presents the integration of bibliometric analysis with the PRISMA framework.

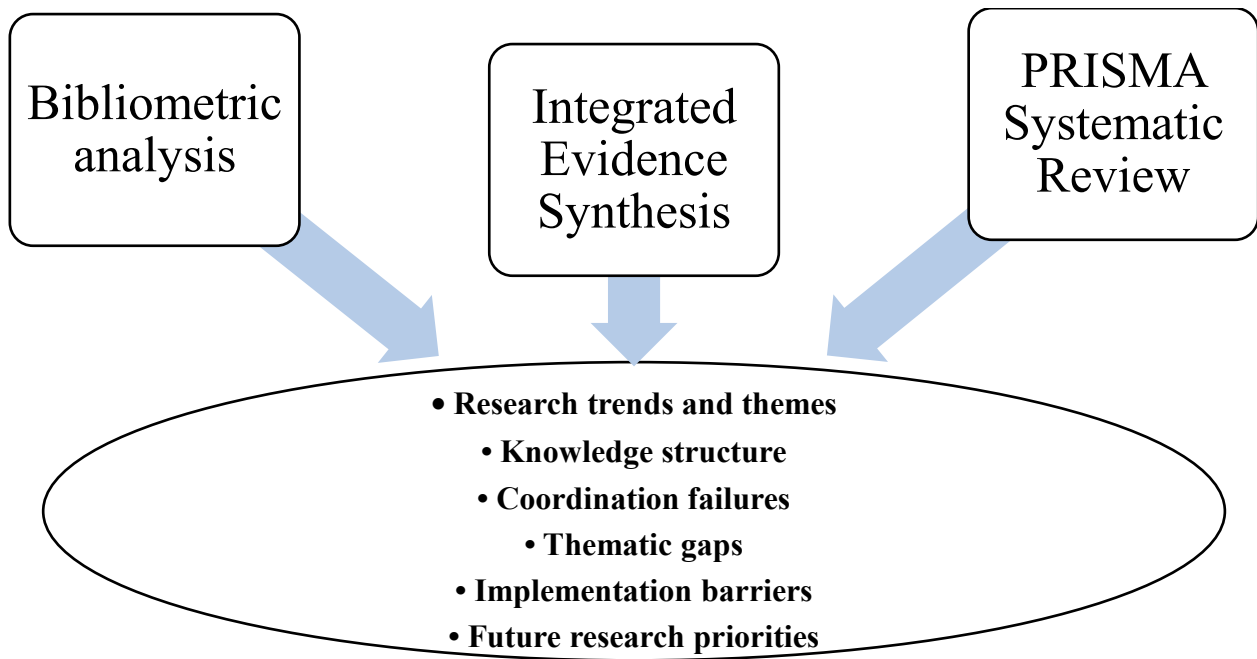


Figure 6 The integration of bibliometric analysis with the PRISMA framework.
Source: Authors' own work

Integrating bibliometric analysis with the PRISMA review enhanced analytical coherence and provided a more complete understanding of the maritime decarbonization research landscape. The combination allowed identification of sequencing challenges, synchronization failures, and knowledge gaps that neither method could fully expose on its own, forming a solid foundation for the in-depth discussion presented in Section 5.

5. Discussion

This discussion integrates evidence from the bibliometric analysis and the PRISMA-based qualitative synthesis to provide a system-level interpretation of maritime decarbonization research. Rather than considering publication trends, thematic clusters, and empirical evidence as independent outcomes, the combined analysis explains how interactions among vessel technologies, port infrastructure, fuel-transition pathways, and governance frameworks collectively shape decarbonization pathways. The findings demonstrate that progress towards low-carbon maritime systems depends not only on technological innovation but also on the coordination and sequencing of investments, infrastructure development, regulatory frameworks, and operational practices. This complementary perspective extends beyond conventional descriptive reviews by interpreting the underlying mechanisms that generate implementation challenges and identifying the structural conditions required for effective maritime decarbonization. Consequently, the discussion provides a stronger foundation for advancing theory, informing policy development, supporting infrastructure planning, and guiding future research on system-level maritime transitions.

The PRISMA-based qualitative synthesis identifies four dominant domains in maritime decarbonization research: emissions measurement, fuel-transition pathways, port-based interventions, and governance mechanisms. The following sections examine each domain in detail (Bolat, 2026; Jang et al., 2025). Despite this thematic convergence, research remains uneven because each domain has developed largely in isolation, with limited integration across the maritime transport system. This fragmentation extends beyond disciplinary boundaries and is reflected in practical implementation, where technological, operational, and governance initiatives frequently evolve independently. As a result, synchronization failures occur not only in knowledge generation but also

in the planning and implementation of decarbonization strategies across the maritime sector (Ampah et al., 2021; Christodoulou & Cullinane, 2022).

Emissions monitoring, fuel-transition strategies, port-level interventions, and governance instruments are often designed and evaluated independently rather than as components of a coordinated transition pathway. This fragmented approach contributes to operational mitigation measures, infrastructure investments, and policy initiatives being implemented at different stages and with different priorities, limiting their collective effectiveness. The evidence suggests that the principal challenge is not the absence of technological or policy solutions, but the limited coordination between these interconnected domains. This weak integration hinders effective planning and decision-making, particularly in sequencing investments in low-carbon fuels alongside port electrification and aligning regulatory incentives with operational practices (Zhang et al., 2026; Nunes, 2025; Sang et al., 2026). Viewed from a system-level perspective, the recurring misalignments identified across the literature illustrate structural constraints that extend beyond individual studies and highlight the need for cross-sector decarbonization pathways that simultaneously consider technology, infrastructure, operations, and governance (Mahmud et al., 2025; Wang et al., 2025).

Fuel-transition research represents the largest and most influential thematic domain. Studies on hydrogen, ammonia, methanol, biofuels, and liquefied natural gas dominate the literature, with lifecycle assessment serving as the principal method to evaluate environmental performance (Kaiser & Chowdhury, 2025). While these fuels offer substantial mitigation potential, research consistently highlights constraints in production pathways, safety requirements, storage, and infrastructure readiness (Hazar & Seyhan, 2025; Zhang et al., 2026). These constraints reveal interdependencies that are rarely addressed in a coordinated manner, creating gaps between technology availability, operational deployment, and policy support (Nian et al., 2025).

Port-focused research emphasizes the role of ports as enablers of decarbonization through shore power, terminal electrification, energy management systems, and operational optimization (Sevgili et al., 2025; Bakar et al., 2023). Evidence shows that these interventions can deliver immediate emission reductions while supporting longer-term fuel-transitions. Variation in implementation outcomes across ports, however, reflects differences in institutional capacity, energy systems, and governance arrangements (Alamouh et al., 2022). Such variation underscores the systemic challenge of translating local success into coordinated, industry-wide decarbonization.

Governance and policy studies examine the influence of international regulation, market instruments, and economic incentives on decarbonization outcomes (Chen et al., 2025; Lehmann et al., 2025). The literature highlights the importance of policy coherence and regulatory clarity in shaping investment decisions, while uneven regional impacts and economic feasibility remain persistent challenges (Zhang & Woo, 2025; Bach & Hansen, 2023). Governance isolated approaches further compound operational and technological misalignments, demonstrating that even well-designed policies cannot fully compensate for gaps in coordination across vessels, ports, and technologies (Chen et al., 2025).

These findings suggest that maritime decarbonization is shaped by multiple interconnected domains, yet systemic integration remains limited. The literature demonstrates that integration failures arise when research focuses narrowly on individual technologies, operational practices, or governance instruments without considering cross-domain interdependencies (Liu et al., 2025). This insight extends beyond the specific dataset, suggesting that effective decarbonization requires comprehensive research frameworks capable of integrating diverse sources of evidence (Nguyen et al., 2025), together with holistic approaches that simultaneously consider technological, operational, and policy dimensions of the maritime transition (Wang et al., 2025).

5.1 Emissions measurement, monitoring, and mitigation strategies

Theme 1 encompasses studies focusing on the quantification, monitoring, and mitigation of greenhouse gas emissions in maritime transport. A substantial portion of the reviewed literature

emphasizes emission inventories, carbon intensity indicators, and performance assessment frameworks. These instruments do not operate as neutral technical tools; they actively shape cross-domain interaction across regulatory bodies, shipping operators, and port authorities, influencing which decarbonization pathways are feasible and which remain constrained (Bayraktar & Yuksel, 2023; Sontakke et al., 2026; Tavasszy et al., 2026).

Several studies highlight the importance of standardized emission accounting methodologies to enable comparability across vessel types, shipping segments, and geographical contexts. Research examining instruments such as the Carbon Intensity Indicator and the Energy Efficiency Existing Ship Index demonstrates that their regulatory relevance extends beyond compliance. These measurement frameworks coordinate operational practices and investment decisions, while their limitations in capturing operational variability and long-term outcomes can reinforce fragmented responses to decarbonization challenges (Bayraktar & Yuksel, 2023). Complementary studies on ship and port-level emission inventories show how monitoring frameworks can guide mitigation priorities and inform policy decisions while connecting operational practices, regulatory oversight, and investment planning across the maritime system.

Mitigation-oriented research within this theme frequently examines operational measures such as speed optimization, route planning, and energy efficiency improvements. These measures serve as integration mechanisms that can align vessel operations with regulatory requirements and short-term environmental targets. They provide immediate emission reductions while longer-term fuel-transition strategies are implemented. However, the literature demonstrates that when measurement and mitigation systems are decoupled from broader transition strategies, such as fuel adoption and port infrastructure investments, they can inadvertently limit the range of decarbonization pathways that can be pursued (Bayraktar & Yuksel, 2023). Fragmented measurement frameworks risk reinforcing short-term, compliance-focused actions rather than supporting coordinated, system-oriented maritime transition planning.

At the system-level, emissions measurement and monitoring constitute foundational infrastructures that coordinate knowledge, resources, and operational behavior across the maritime sector. Their design and implementation influence which decarbonization pathways are prioritized, how policy and investment decisions are sequenced, and which technologies and operational practices receive greater attention. Beyond their technical function, these frameworks shape strategic decision-making by providing the evidence base for regulatory compliance, infrastructure planning, and investment prioritization. This finding suggests that improving measurement systems alone is insufficient unless they are embedded within broader governance and transition strategies that align operational practices with long-term decarbonization objectives. From this perspective, emissions measurement should be viewed as a strategic coordination mechanism rather than simply a technical monitoring tool, reinforcing its role in enabling cross-sector and system-level maritime decarbonization (Bayraktar & Yuksel, 2023).

5.2 Fuel-transition pathways and propulsion technologies for shipping decarbonization

Theme 2 synthesizes studies examining alternative fuels and propulsion technologies as central components of coordinated pathways for reducing greenhouse gas emissions from shipping. The literature demonstrates strong consensus that deep decarbonization depends on substituting fossil fuels with low- or zero-carbon options, yet the feasibility of these pathways is shaped by port infrastructure readiness, supply chain development, and regulatory sequencing (Ampah et al., 2021; Al-Enazi et al., 2021; Sang et al., 2026).

Hydrogen, ammonia, methanol, biofuels, and liquefied natural gas emerge consistently as the most extensively studied fuels. Lifecycle assessments reveal substantial variation in emission reduction potential depending on production pathways, energy sources, and integration across the supply chain (Ampah et al., 2021). Hydrogen and ammonia are frequently highlighted as promising

zero-carbon or low-carbon fuels when produced using renewable energy, yet their deployment depends critically on storage solutions, port-side infrastructure, and operational alignment across shipping routes (Christodoulou & Cullinane, 2022; Karvounis et al., 2025; Sontakke et al., 2026; Tavasszy et al., 2026).

Transitional fuels such as methanol and liquefied natural gas are often positioned as near-term options capable of delivering incremental emission reductions. Several studies emphasize that methane slip and lifecycle emissions constrain their long-term compatibility with net-zero targets (Balcombe et al., 2021; Christodoulou & Cullinane, 2022; Ismail et al., 2025). Across these studies, lifecycle assessment emerges as a critical method for evaluating how fuel switching interacts with vessel efficiency, port infrastructure, and broader cross-sector constraints (Bouman et al., 2017).

The synthesis identifies a central implementation linkage challenge: fuel and propulsion pathways are rarely assessed in conjunction with port infrastructure readiness, supply chain maturity, or regulatory sequencing. This disconnect produces uncertainty regarding dominant fuel options, delays investment decisions, and increases the risk of stranded assets. The findings indicate that technological feasibility alone is insufficient to accelerate fuel-transitions unless supported by coordinated infrastructure development, stable regulatory frameworks, and aligned operational planning. A system-level perspective therefore shifts attention from identifying the "best" alternative fuel towards understanding how different fuel pathways can be implemented within system-oriented maritime transition strategies. This interpretation reinforces that successful decarbonization depends on synchronizing technological innovation with infrastructure investment, policy support, and operational readiness, thereby reducing implementation risks and enabling more resilient transition pathways (Ampah et al., 2021; Christodoulou & Cullinane, 2022).

5.3 Port-based interventions and operational decarbonization measures

Theme 3 addresses port-related interventions as strategic synchronization choices that support shipping decarbonization through infrastructure development, operational optimization, and governance initiatives. The literature increasingly highlights the role of ports as active coordinators in aligning vessel operations, fuel adoption, and policy implementation rather than as passive providers of technical services (Bakar et al., 2023).

Shore power systems, commonly referred to as cold ironing, are frequently examined port-level measures. Evidence indicates that onshore power supply can substantially reduce emissions from berthed vessels, particularly in containers and cruise terminals, when electricity is sourced from low-carbon grids. Their effectiveness depends on interconnection with vessel readiness, fuel availability, and local grid capacity, illustrating that infrastructure alone cannot ensure decarbonization outcomes (Bakar et al., 2023; Chen et al., 2025; Sontakke et al., 2026; Tavasszy et al., 2026). Terminal electrification, energy management systems, and port-level carbon emission accounting serve not only as monitoring tools but also as strategic mechanisms for identifying emission hotspots, prioritizing emission reduction measures, and aligning operational decisions, investment timing, and policy compliance within the port ecosystem (Li et al., 2025).

Several studies highlight incentive schemes implemented by port authorities to promote cleaner vessel operations and accelerate fuel adoption. These include differentiated port fees, priority berth, and collaborative governance arrangements involving shipping lines, terminal operators, and public authorities (Alamouch et al., 2022). Operational measures such as optimized berth allocation, equipment electrification, and digital monitoring systems are often positioned as cost-effective interventions. However, their performance varies widely across ports, influenced by local regulatory frameworks, financial capacity, and the ability of stakeholders to coordinate effectively.

The synthesis underscores that port interventions are not universally applicable technical upgrades, but strategic choices shaped by demand uncertainty, governance constraints, and interdependencies across the maritime system. Ports can deliver localized and short-term emission

reductions, yet their contribution to system-wide decarbonization remains constrained when vessel technologies, fuel-transition pathways, and regulatory incentives evolve without sufficient coordination (Bakar et al., 2023; Alamoush et al., 2022). From a system-level perspective, ports should be viewed not merely as infrastructure providers but as strategic coordinators capable of aligning operational practices, energy infrastructure, and stakeholder collaboration. This interpretation highlights the importance of comprehensive planning by port authorities, enabling infrastructure investments, shore power deployment, and alternative fuel facilities to be implemented in parallel with evolving shipping technologies and regulatory requirements. Such alignment reduces implementation uncertainty and strengthens the capacity of ports to facilitate coordinated maritime decarbonization.

5.4 Governance frameworks, economic instruments, and policy effectiveness

Theme 4 synthesizes studies examining governance structures, market-based measures, and economic instruments as mechanisms for coordinating maritime decarbonization across vessels, ports, and investment decisions. Governance is not only a collection of policies but also a set of institutional arrangements that shape the sequencing, timing, and alignment of technological adoption, operational practices, and infrastructure development (International Maritime Organization, 2018; International Maritime Organization, 2023).

International Maritime Organization greenhouse gas strategies provide foundational reference points for research and industry practice, establishing long-term targets and signaling expectations to shipping operators, port authorities, and investors. Despite their strategic importance, studies highlight persistent gaps in enforcement, ambition, and alignment with technological and infrastructure readiness (Bach & Hansen, 2023). These gaps illustrate how multi-level alignment challenges can constrain the translation of international targets into actionable system-level pathways.

Evidence indicates that these measures can influence investment behavior, innovation, and operational choices when regulatory stringency is consistent and institutional interconnection is effective. However, misalignment across jurisdictions or inconsistent implementation reduces their ability to synchronize vessel operations, fuel adoption, and port infrastructure development.

Economic feasibility and investment requirements emerge as recurrent coordination challenges. High capital costs for alternative fuels, vessel retrofitting, and port electrification frequently constrain the ability of stakeholder to implement decarbonization strategies, particularly in regions with limited access to finance and institutional capacity (Balcombe et al., 2021; Ampah et al., 2021; Sontakke et al., 2026; Tavasszy et al., 2026). Public-private collaboration is critical for mobilizing capital, coordinating investment timing, and reducing the risk of stranded assets, demonstrating how governance structures can actively shape the sequencing of decarbonization pathways.

At the system-level, governance frameworks determine which decarbonization pathways are feasible and which are delayed or fragmented. Misalignment between international targets, technological readiness, infrastructure deployment, and external geopolitical conditions contributes to investment uncertainty and uneven regional outcomes, highlighting the importance of adaptive governance capable of responding to changing trade dynamics and emerging geopolitical risks (Li et al., 2025). Effective governance therefore requires stronger integration across vessels, ports, fuel supply systems, and financial mechanisms to ensure that policy objectives are translated into coordinated implementation strategies (International Maritime Organization, 2023; Bach & Hansen, 2023). From a policy perspective, the findings suggest that regulatory ambition alone is unlikely to accelerate maritime decarbonization unless accompanied by coordinated infrastructure planning, stable investment signals, and institutional collaboration across the maritime sector. This interpretation highlights the importance of governance as an enabling mechanism that aligns

technological innovation with operational implementation, providing policymakers and industry stakeholders with a more coherent pathway towards system-level maritime decarbonization.

5.5 Combined synthesis of PRISMA themes

Building on the thematic analysis above, the combined synthesis identifies three core synchronization failure mechanisms that constrain maritime decarbonization. Analysis of emissions measurement frameworks, fuel-transition pathways, port-based interventions, and governance mechanisms reveals three recurring integration failure mechanisms that shape decarbonization outcomes.

First, sequencing misalignment occurs when technological, operational, and policy developments progress in parallel rather than in a comprehensive manner. Long-term fuel-transitions, for instance, depend on coordinated investments in port infrastructure and regulatory clarity, yet studies indicate that infrastructure readiness, fuel availability, and vessel adoption timelines are often disconnected (Ampah et al., 2021; Tavasszy et al., 2026). This misalignment delays adoption, increases investment risk, and may result in stranded assets.

Second, operational fragmentation emerges when ports, vessels, and supply chains evolve without sufficient synchronization. Ports' capacity to enable decarbonization is shaped by vessel technology choices and fuel availability, while operational interventions such as shore power, terminal electrification, and energy optimization deliver variable outcomes depending on regulatory alignment and stakeholder collaboration (Alamouch et al., 2022; Chen et al., 2025). Without mechanisms to integrate operational, infrastructural, and technological decisions, interventions remain locally effective but fail to contribute to system-wide decarbonization.

Third, governance gaps and institutional misalignment limit the ability of multi-level regulatory frameworks to coordinate investment, technology adoption, and operational practices. International targets frequently outpace infrastructure and technological readiness, while economic instruments operate unevenly across jurisdictions (International Maritime Organization, 2023; Bach & Hansen, 2023; Sontakke et al., 2026; Tavasszy et al., 2026). These gaps further increase uncertainty and contribute to uneven transition outcomes across regions and industries.

The combined bibliometric evidence and qualitative synthesis suggest that progress in maritime decarbonization depends less on individual technological advances than on how different parts of the maritime system evolve together. Investment decisions on vessels, alternative fuels, port infrastructure, and supporting regulations are closely linked, meaning that delays in one area can slow progress across the entire transition. Recent studies also point out that uncertainty in financing, supply chains, and infrastructure planning continues to discourage long-term investment in low-carbon technologies (Boone & Ganeshan, 2025; Barone et al., 2025).

The review highlights three broad observations. The first is that technological deployment, infrastructure development, and regulatory measures need to progress in step to reduce investment uncertainty and avoid stranded assets. The second is that ports have become more than operational facilities; they increasingly act as locations where shipping companies, fuel suppliers, technology providers, and regulators converge to support the transition towards lower-carbon shipping (Benghalia et al., 2025; Alamouch et al., 2022). The third is that regulatory ambition alone is unlikely to deliver meaningful change unless it is supported by practical implementation, financial incentives, and institutional capacity that reflect the realities of the maritime sector (Bach & Hansen, 2023; Tavasszy et al., 2026).

Taken together, these findings reinforce the view that maritime decarbonization should be approached as a connected transition rather than a series of separate technological solutions. Progress will depend on whether operational practices, infrastructure investment, governance arrangements, and technological innovation develop in a mutually supportive way across the wider maritime system (Ampah et al., 2021; Bakar et al., 2023; Sontakke et al., 2026).

To further illustrate these system-level relationships, **Figure 7** synthesizes the conceptual framework developed from the findings of this review and visually illustrates how the three coordination failure mechanisms interact to influence maritime decarbonization outcomes.

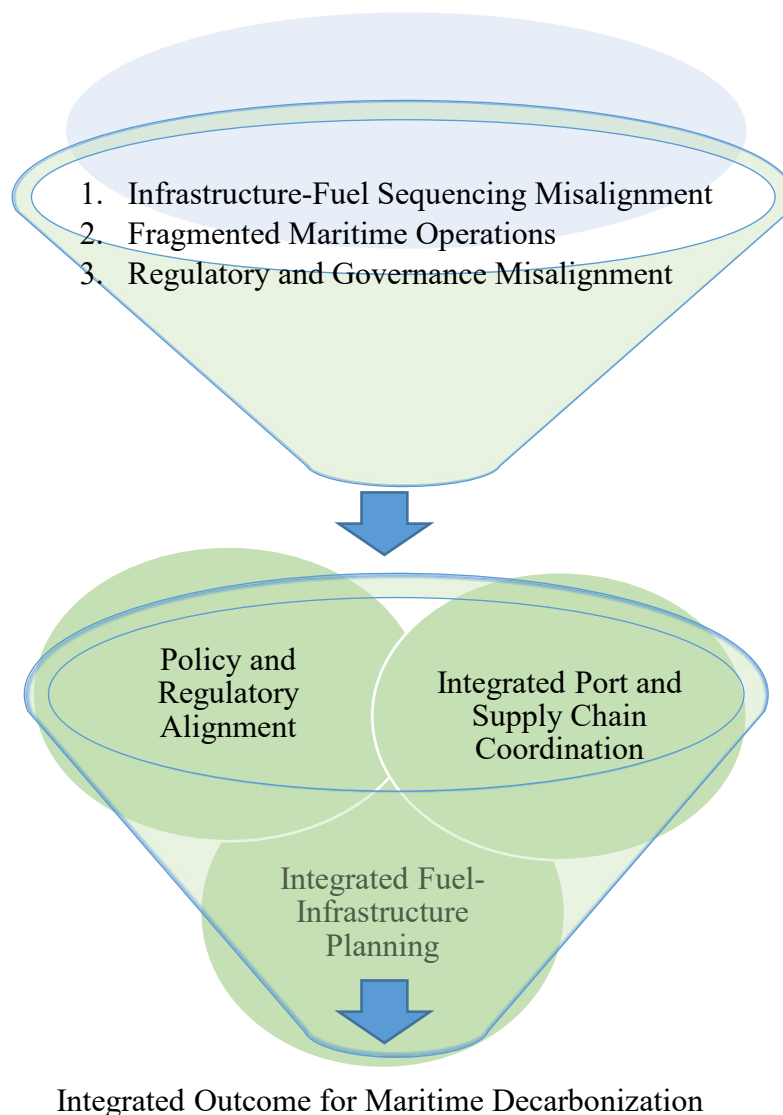


Figure 7 Key coordination challenges shaping maritime decarbonization outcomes.

Source: Authors' own work

A key challenge is the lack of theorization regarding timing and sequencing of interventions. Regulatory ambitions and technological innovations are evolving rapidly, yet research rarely addresses how fleet transitions, port development, and energy system integration can be coordinated. The absence of this systemic perspective increases the likelihood of delayed implementation, inefficient investment, and suboptimal decarbonization outcomes.

Institutional and economic factors further constrain coordination. Fragmented policy environments, regulatory uncertainty, and uneven financial capacity limit the ability of both ports and shipping operators to implement large-scale solutions. Ports have the potential to act as strategic nodes by coordinating energy supply chains and aligning stakeholders, but their effectiveness is constrained by governance structures, financial resources, and integration with national and international policies. This highlights that successful decarbonization depends not only on

technological feasibility but also on institutional design, cross-domain interaction mechanisms, and investment alignment.

The findings of this review contribute to literature in three principal ways.

First, it identifies persistent alignment failures across vessels, ports, and governance systems. Second, it emphasizes the importance of sequencing interventions to align fleet transitions with port development and energy systems. Third, it frames decarbonization as an adaptive and context-sensitive system transformation rather than a collection of disconnected technological or policy interventions. This conceptual approach offers policymakers, port authorities, and shipping operators a framework for anticipating misalignments and designing more coherent strategies for global maritime decarbonization.

5.6 Future research priorities

The combined bibliometric analysis and PRISMA-based qualitative synthesis indicate that several important research priorities are emerging as maritime decarbonization evolves from technology-centered investigations towards more transition-oriented perspectives. The evidence synthesized throughout this review suggests that future research should place greater emphasis on understanding how vessels, ports, fuel systems, governance arrangements, and energy infrastructure evolve as interconnected components of a broader maritime transition system. This shift reflects growing recognition that technological innovation alone is unlikely to achieve long-term decarbonization unless accompanied by coordinated infrastructure planning, institutional development, and adaptive policy implementation under conditions of uncertainty.

One important research priority emerging from this review is the expansion of carbon governance mechanisms, particularly maritime emissions trading systems and carbon pricing frameworks. Their growing prominence reflects recognition that technological innovation alone cannot deliver maritime decarbonization without complementary economic and regulatory instruments that influence investment behavior and operational decision-making. Recent studies indicate that, although these mechanisms strengthen decarbonization incentives, they also introduce challenges associated with uneven regional impacts, compliance complexity, and carbon leakage risks. This suggests that future research should move beyond evaluating policy effectiveness in isolation and instead examine how carbon governance interacts with infrastructure readiness, technological deployment, and institutional capacity across different maritime contexts.

Another growing area of research focuses on green shipping corridors and coordinated fuel-transition networks. Rather than treating decarbonization as an individual port or fleet issue, recent studies increasingly examine corridor-based approaches that connect vessels, bunkering infrastructure, renewable energy supply, and logistics systems across multiple locations. These studies suggest that future transition pathways may depend less on isolated technological breakthroughs and more on the ability of maritime regions to develop coordinated energy and infrastructure ecosystems.

At the same time, ports are increasingly being examined as multi-functional energy platforms rather than conventional transport infrastructure alone. Emerging research highlights the role of ports in hydrogen production, energy storage integration, and renewable electricity management. This development expands the role of ports beyond cargo handling and operational efficiency, positioning them more directly within wider energy transition systems.

Digitalization is also becoming more closely linked to decarbonization planning. Recent studies on machine learning, predictive analytics, and real-time operational optimization indicate growing interest in data-driven approaches, such as Blockchain for fuel lifecycle tracing and AI-driven 'Just-in-Time' arrival systems, to facilitate better synchronization between vessel speeds and port berth availability. While these technologies remain at an early stage of implementation, they may contribute to improving operational flexibility and supporting more adaptive transition strategies across vessels and ports.

These research priorities reinforce the central conclusion of this review that maritime decarbonization should be understood as a coordinated system transition rather than a collection of independent technological interventions. Future studies should therefore place greater emphasis on interdisciplinary research capable of integrating technological innovation, infrastructure planning, governance mechanisms, operational decision-making, and economic considerations within a common analytical framework. Advancing this holistic perspective will not only strengthen scientific understanding of maritime decarbonization but also provide more robust evidence to support long-term policy development, strategic investment planning, and coordinated implementation across the maritime sector.

6. Research gaps

Despite the growing body of research on maritime decarbonization, several important knowledge gaps continue to hinder both scientific understanding and practical implementation. These gaps extend beyond individual technological solutions and reflect limited understanding of how vessels, ports, fuel systems, governance arrangements, financial mechanisms, and digital technologies interact within an interconnected maritime transition system. Closing these gaps is essential for developing more robust evidence base capable of supporting coordinated, scalable, and resilient decarbonization pathways

A major gap concerns the coordination of vessel and port transitions. While research on vessels and ports has expanded, these streams often evolve in parallel rather than in alignment. Many fuel-transition studies assume that port infrastructure will be ready without examining the timing or sequencing of bunkering facilities and energy supply chains. Conversely, port-focused studies frequently assess electrification, shore power, and energy management without integrating fleet transition timelines or vessel technology choices (Alamouch et al., 2022). This indicates a need for research that explicitly models the interactions between vessels, ports, and regional energy systems, identifying mechanisms that ensure mutually reinforcing transitions. Existing evidence provides only limited analytical frameworks capable of explaining how coordinated deployment of vessel technologies and port infrastructure can be operationalized across different maritime contexts. Another important research gap concerns the alignment of conceptual models with empirical evidence. Although modeling and scenario studies examine existing literature, there is still limited understanding of how integration occurs under real-world conditions, including pilot projects, operational trials, and early-stage deployments of emerging fuels (Ampah et al., 2021; Bouman et al., 2017). Existing evidence remains constrained by the limited availability of longitudinal case studies and post-implementation evaluations capable of explaining how technological, operational, and governance mechanisms interact throughout the implementation process. This limitation restricts current understanding of the practical constraints, institutional enablers, and operational uncertainties that influence coordinated maritime decarbonization.

Economic and investment mechanisms remain another critical area where system integration is insufficiently understood. Existing studies continue to rely on static cost assumptions and short-term economic comparisons that often overlook the interdependencies among policy evolution, market volatility, infrastructure investment, and technology adoption. Current evidence also provides limited understanding of financing models, risk-sharing arrangements, and public-private partnerships capable of coordinating investments across ports, shipping operators, and energy providers (Balcombe et al., 2021). As a result, the economic conditions that enable synchronized fleet renewal, infrastructure development, and fuel-transition remain inadequately addressed within the existing maritime decarbonization literature.

Geographical and institutional alignment represents another important research gap. Existing evidence remains concentrated in Europe, China, and other advanced maritime economies, while developing regions continue to be underrepresented despite their growing significance in global shipping and port operations (Bouman et al., 2017; Al-Enazi et al., 2021). This geographical

imbalance limits current understanding of how institutional capacity, stakeholder collaboration, and regional energy systems influence maritime decarbonization under different socioeconomic and regulatory conditions. As a result, the transferability of existing knowledge across diverse maritime contexts remains uncertain, highlighting an important limitation in the current evidence base.

Policy and governance research similarly exhibits important limitations in explaining multi-level institutional alignment. Although existing studies extensively discuss international regulations and the International Maritime Organization's decarbonization strategies, comparatively little evidence explains how these frameworks are translated into coordinated implementation at national, regional, and port authority levels (Bach & Hansen, 2023; International Maritime Organization, 2023). Current understanding remains limited regarding the institutional mechanisms through which policies, economic incentives, regulatory enforcement, and stakeholder collaboration interact to support coherent maritime decarbonization. This gap constrains the ability to explain how governance structures influence both technological adoption and infrastructure development across different implementation contexts.



Figure 8 Research gaps in coordinated maritime decarbonization.

Source: Authors' own work

Digitalization represents another emerging area where important knowledge gaps remain. Existing studies increasingly recognize the potential of digital technologies, including real-time data integration, decision support systems, and optimization algorithms, to support maritime decarbonization. However, these technologies are frequently examined as supplementary operational

tools rather than as strategic mechanisms capable of coordinating energy management, emissions monitoring, infrastructure planning, and operational decision-making across interconnected maritime systems (Alamouh et al., 2022). Current evidence therefore provides only limited understanding of how digital platforms can facilitate better decision-making and adaptive system-wide coordination under evolving technological, regulatory, and market conditions.

The research gaps identified throughout this review demonstrate that current maritime decarbonization research continues to be constrained by fragmented analytical perspectives that frequently examine technological, operational, economic, and governance dimensions independently. Existing evidence provides only limited understanding of how these interdependent components interact throughout the transition process, particularly across different institutional and regional contexts. This limitation restricts the development of comprehensive analytical frameworks capable of explaining coordinated maritime decarbonization at the system-level. **Figure 8** synthesizes these principal research gaps, illustrating the areas where evidence remains limited and where greater analytical integration is required to strengthen future knowledge development.

7. Policy and practical implications

The findings of this review indicate that maritime decarbonization is as much a governance and integration challenge as a technological one. Effective outcomes require aligning actions across policymakers, port authorities, shipping operators, and financiers, while sequencing interventions to ensure coherence across the system.

For policymakers, the evidence emphasizes the importance of coordinating international, national, and regional instruments to guide decarbonization pathways. International Maritime Organization strategies serve as foundational reference points for research and industry response (International Maritime Organization, 2018; International Maritime Organization, 2023). Early-stage actions should focus on establishing consistent regulatory frameworks, including emission intensity standards, fuel quality regulations, and reporting requirements. In the medium term, policymakers should harmonize regional and national policies to reduce compliance uncertainty and provide clear investment signals for ports and shipping operators. Long-term interventions should involve monitoring, evaluation, and adaptive adjustments that ensure fleet transitions remain aligned with port development and regional energy capacity.

Port authorities hold strategic influence in coordinating maritime decarbonization. In the short term, ports should expand shore power, terminal electrification, and energy management systems while assessing institutional capacity and access to low-carbon electricity (Bakar et al., 2023). Ports should adopt energy planning functions and integrate decarbonization objectives into development plans and concession agreements. In the medium term, ports should actively coordinate with shipping lines, fuel suppliers, and regulators to align the deployment of alternative fuels and infrastructure with fleet transitions. Longer-term actions involve ports functioning as central interconnection platforms, facilitating operational planning and digital monitoring to ensure alignment between vessels, infrastructure, and energy systems.

Shipping operators should adopt phased and flexible transition strategies that account for port readiness and evolving policy landscapes. Immediate actions include operational efficiency improvements and early engagement with ports and fuel suppliers to reduce stranded asset risks (Balcombe et al., 2021; Ampah et al., 2021). Medium-term actions involve the progressive adoption of low- and zero-carbon fuels in coordination with available port infrastructure and regional energy systems. Long-term strategies require adaptive investment planning that synchronizes fleet transitions with emerging policies, market conditions, and energy networks.

Economic and financial synchronization is critical for enabling these transitions. In the short term, targeted financial mechanisms such as investment subsidies, green financing instruments, and risk-sharing schemes should support early adopters and reduce market entry barriers (Bach & Hansen, 2023). Medium-term actions should explore market-based measures that internalize environmental

costs while minimizing disproportionate burdens on smaller operators and developing economies. Long-term financial strategies should link investments in fleets and port infrastructure with broader decarbonization timelines to ensure scalable deployment of technologies.

Digitalization and data-driven alignment are essential for timely decision-making. Initially, ports and regulators should implement accurate emissions measurement, reporting, and verification systems to evaluate policy and operational performance. In the medium term, decision support tools, real-time monitoring, and predictive analytics should be integrated to align vessel operations and port infrastructure. Over the long term, digital platforms can serve as central coordination nodes, supporting adaptive operational management and enabling continuous optimization of decarbonization pathways (Alamouch et al., 2022).

These findings demonstrate that orchestrating regulatory, infrastructural, financial, and operational interventions across regions and over time is critical for translating maritime decarbonization ambitions into measurable outcomes. Aligning international frameworks, empowering ports as interconnection hubs, supporting phased fleet transitions, and embedding digital integration tools will be essential for achieving sustained emission reductions across the global maritime transport system.

These stakeholder-specific implications reinforce the central finding of this review that successful maritime decarbonization depends on coordinated action across technological, institutional, operational, and financial dimensions. The concluding section summarizes the principal contributions of this review and highlights their significance for advancing coordinated maritime decarbonization research and practice.

8. Conclusions

This review synthesizes recent advances in maritime and port decarbonization research through the complementary use of bibliometric analysis and PRISMA-based qualitative synthesis. Rather than viewing decarbonization as a series of independent technological solutions, the evidence consistently points to a broader transition challenge in which vessel technologies, port infrastructure, fuel supply systems, investment decisions, and governance arrangements evolve at different rates and with differing levels of institutional readiness. The review therefore shows that implementation barriers increasingly arise from how these elements interact across the maritime system rather than from technological limitations alone.

An important contribution of this review lies in reframing maritime decarbonization from a technology-centered perspective towards a system-oriented understanding of transition processes. By bringing together evidence that has traditionally been examined in separate research streams, the study demonstrates how sequencing, institutional readiness, infrastructure planning, and operational decision-making jointly influence the effectiveness of decarbonization strategies. This perspective extends current review literature by offering a more comprehensive explanation of why promising technological solutions often experience uneven implementation despite continued scientific and industrial progress.

The review also provides practical value for maritime stakeholders. For policymakers, the findings emphasize the importance of developing regulatory frameworks that evolve alongside infrastructure investment and fuel-transition strategies. For port authorities, they highlight the need to plan energy infrastructure, shore power facilities, and alternative fuel readiness in parallel with changing fleet requirements. Shipping companies can use these insights to support more informed fleet renewal and investment decisions while reducing uncertainty associated with emerging technologies, infrastructure availability, and evolving regulatory expectations.

Several limitations should also be acknowledged. The review was restricted to peer-reviewed publications indexed in the Scopus database and published between 2021 and early 2026. Although the approach ensured methodological consistency and captured the most recent developments in the field, relevant studies indexed elsewhere or published in other languages may not have been included.

In addition, bibliometric patterns are influenced by citation dynamics, database coverage, and keyword indexing, while qualitative synthesis inevitably involves informed interpretative judgement despite the use of structured review procedures.

Ultimately, this review argues that meaningful progress in maritime decarbonization will depend less on identifying individual technological solutions than on improving the way technologies, infrastructure, governance, financing, and operational practices evolve throughout the transition process. Viewing maritime decarbonization through this broader systems perspective offers a stronger foundation for future research, more informed policy development, and more effective implementation strategies capable of supporting long-term emission reduction across the global maritime sector.

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Declaration of generative AI in scientific writing

The authors used ChatGPT (OpenAI), Grammarly, and QuillBot solely to assist with English language editing, grammar checking, stylistic refinement, and improving the clarity and readability of the manuscript during its preparation. VOSviewer was used exclusively to generate bibliometric visualizations and science mapping. ChatGPT (OpenAI), Grammarly, and QuillBot were not used to generate scientific content, conduct the literature review, interpret findings, formulate conclusions, or make research decisions. All study design, literature selection, data interpretation, critical analysis, manuscript revisions, and final editorial decisions were undertaken entirely by the authors. With or without AI applications, the authors are fully accountable for every process of the work and manuscript writing. All final edits, interpretations, and conclusions are the sole responsibility of the authors. The authors academically and ethically confirmed that the stated AI statements are true, and the authors are ultimately responsible and accountable for the contents of the published work, including the correctness of the references in the reference list.

CRedit contribution statement

Amayrol Zakaria: Conceptualization; Methodology; Formal analysis; Investigation; Data Curation; Writing-Original Draft; Writing-Review & Editing; Visualization; Project administration. **Aminuddin Md Arof:** Validation; Supervision; Writing-Review & Editing. **Ruth Banomyong:** Validation; Supervision; Writing-Review & Editing.

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