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Systematic Review

Sustainable Measures in Green Maritime Transport: A State-of-the-Art Analysis

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Abstract

Maritime transport plays a pivotal role in global supply chains and is increasingly required to support decarbonisation objectives and broader sustainability transitions. While a wide range of sustainable measures has been proposed for shipping and port operations, existing research remains fragmented, limiting a comprehensive understanding of how these measures contribute to sustainable supply chain transformation. This study systematically reviews the development of sustainable measures in green maritime transport using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework and bibliometric analysis. The review synthesises the literature across the shipping and port sectors, examining various measures that support environmental performance, resource efficiency, and supply chain sustainability. The findings offer a structured roadmap for researchers, policymakers, and the industry seeking to advance maritime decarbonisation and sustainable supply chain development while identifying key research directions for future innovation and decision support.

Keywords: maritime decarbonisation; sustainable measures; green maritime transport; sustainable supply chain; systematic literature review

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1. Introduction

Over the past few decades, the continued expansion of global trade and economic globalisation has significantly increased the demand for maritime transport [1]. As the backbone of international trade, maritime transport plays a vital role in global supply chains and the world economy. However, this growth has also intensified environmental concerns, particularly greenhouse gas (GHG) emissions and air pollution associated with fossil fuel dependent shipping and port operations [2]. In this context, increasing attention has been directed towards the transition from conventional maritime transport systems to green maritime transport systems that support environmental sustainability and low-carbon development. Sustainability is commonly conceptualised as comprising three interrelated dimensions: environmental protection, social well-being, and economic viability, which are widely recognised as the environmental, social, and economic pillars of sustainability [3]. In this study, sustainable measures refer to operational, technological, infrastructural, and energy-related measures that primarily reduce the environmental impacts of shipping and port operations while recognising that their practical implementation also depends on social acceptability and economic viability.

To accelerate this transition, the International Maritime Organization (IMO), which is the United Nations specialised agency responsible for the prevention of marine and atmospheric pollution by ships, established its GHG reduction strategy in 2018 [4] and updated it in 2023 to strengthen long-term climate ambitions for the maritime sector. The revised strategy aims to reduce GHG emissions from international shipping by at least 20% by 2030 and at least 70% by 2040 compared to 2008 levels, while reaching net-zero emissions by, or around, 2050 [5]. These targets have increased pressure on maritime stakeholders to develop and implement sustainable measures across both shipping and port sectors. At the same time, regional initiatives such as the European Union (EU)'s "Fit for 55" package [6] have further accelerated the development of green maritime policies and technologies.

As a result, a wide range of sustainable measures has been proposed across maritime transport. In the shipping sector, previous studies have examined operational and technological measures such as voyage optimisation [7], energy efficiency improvements [8,9], alternative fuels [10,11], alternative energy propulsion [12], and carbon capture technologies [13]. Similarly, port-related studies have investigated sustainable measures including terminal efficiency improvements [14], shore power systems [15], renewable energy integration [16,17], and digital technologies [18,19]. Moreover, while some studies have focused on measures targeting individual pollutants, for example, carbon dioxide (CO_2) [20], nitrogen oxides (NOx) [21], sulphur oxides (SOx) [22], and particulate matter (PM) [23], this study examines the full range of measures capable of reducing them in order to address the multi pollutant nature of maritime emissions [24] more comprehensively than previous studies.

Despite the growing body of literature, existing review studies remain fragmented in several ways. Many studies focus primarily on either shipping [25,26] or ports [27,28] in isolation, while others concentrate on specific measures and assess their economic and environmental performance [20,26,29]. In addition, although numerous sustainable measures have been discussed in the literature, relatively limited attention has been paid to classifying these measures by implementation timelines and long-term transition pathways. This limitation is important because the environmental dimension of maritime transport needs to be considered within short-, medium-, and long-term strategies, particularly as the IMO GHG Strategy establishes key milestones for 2030, 2040, and 2050 [4,29]. Taken together, existing reviews provide valuable insights into green shipping, sustainable ports, or particular technology groups such as alternative fuels, but do not offer an integrated temporal classification of sustainable measures across the shipping and port sectors. Therefore, a clearer understanding of how these measures align with different transition periods is necessary to support more effective decision-making and strategic planning in green maritime transport.

Accordingly, this study aims to identify and systematically review sustainable measures across both shipping and port sectors through a comprehensive review of the existing literature. The study adopts the Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA) framework to ensure a transparent and replicable review process. A bibliometric analysis is conducted to examine the overall development trends and research patterns within the field of green maritime transport. Based on the findings, the identified sustainable measures are categorised according to their expected implementation horizons. By integrating shipping and port measures within a single classification aligned with the 2030, 2040, and 2050 transition milestones, this study advances existing sector-specific and technology-focused reviews by showing not only which measures are available, but also when they are expected to diffuse more widely and make their main contribution. The classification also highlights the need for vessel technologies, port infrastructure, and fuel/energy supply systems to develop in parallel. In practical terms, it provides a reference for shipping companies, port authorities, terminal operators, logistics operators, cargo owners, energy suppliers, and policymakers to sequence actions, coordinate investments, and prepare for future technological and infrastructure requirements.

The remainder of this paper is organised as follows: Section 2 presents the results of the bibliometric analysis and its implications, and Section 3 presents the classification of the various measures across different implementation horizons. Section 4 discusses the key findings and implications for green maritime transport development and policy. Finally, Section 5 concludes the paper and outlines recommendations for future research.

2. Systematic Literature Review and Bibliometric Analysis

2.1. Systematic Literature Review

A review of the relevant literature is a fundamental component of academic research [30]. It enables researchers to organise existing knowledge, assess current understanding, and identify research gaps within a specific field, thereby supporting the advancement of the knowledge base [31]. However, literature reviews can be affected by selection bias and methodological inconsistency. For this reason, the use of established guidelines is important for reducing potential bias and improving the transparency of the review process [32]. A clearly defined review protocol also strengthens the credibility of the review and allows future researchers to replicate, verify, or update the study [33]. Accordingly, this study adopted the PRISMA framework. PRISMA is a widely used approach that provides structured guidance for conducting systematic reviews and supports the quality, reliability, and reproducibility of the review process [34].

The systematic literature review was designed using a comprehensive but focused search strategy to capture studies related to sustainable measures in maritime transport. The search process was developed around the main research question of this review: "What sustainable measures have been developed in the literature for the shipping and port sectors?" To address this question, the search query combined relevant keywords with Boolean operators and truncation symbols, such as AND, OR, and *, to ensure that the retrieved literature was both broad enough to cover the topic and specific enough to remain relevant, as shown in Figure 1. Truncated terms, including 'harbo*' and 'sustainab*', were used to indicate different word forms and spelling variations, such as harbor, harbour, sustainable, and sustainability.

The initial screening was conducted by examining the titles, abstracts, and keywords of the identified literature. This stage was intended to remove publications that were clearly outside the scope of the research question. The remaining studies were then assessed using predefined inclusion and exclusion criteria. Studies were included when they addressed operational or technological measures aimed at reducing emissions in the shipping or port sectors. In contrast, market-based measures were excluded from the review because they generally act as enabling mechanisms for operational and technological measures rather than directly reducing emissions themselves [35].

The review considered English-language peer-reviewed journal articles and conference proceedings published from 2018 onwards, while relevant industry reports were identified through other search methods. This starting point was selected because 2018 marked the adoption of the IMO's initial GHG reduction strategy at MEPC 72 [4], and focusing on this period enables the review to reflect recent developments following this major policy milestone [20]. The search was carried out using both Scopus and Web of Science (WoS) on 21 August 2025, as the combined use of these databases can provide a broader understanding of sustainable maritime transport research [36]. The complete database-specific search strings are provided in Table S1 of the Supplementary Material.

Records retrieved from the two databases were combined and duplicates were removed by comparing bibliographic information, including titles, authors, and digital object identifiers (DOIs). No automation tool was used to determine the eligibility of records during screening. The records identified as ineligible by automation tools in Figure 2 refer to records removed using the built-in database filtering functions for publication year, language, and document type before manual screening.

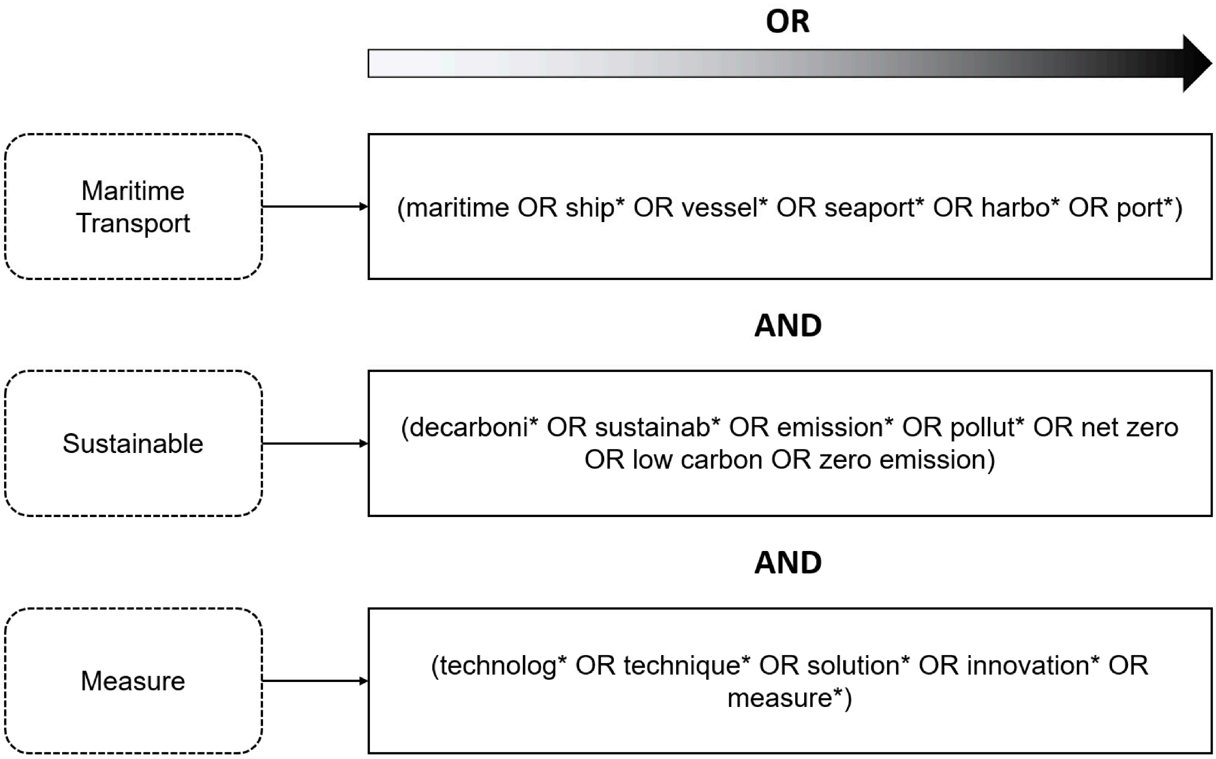

Figure 1. Keywords set for the literature search. *(Asterisk denotes wildcard truncation).*

In addition to database searches, this study applied a snowballing procedure based on the guidelines of Wohlin [37]. This involved reviewing the reference lists of selected studies through backward snowballing and identifying later studies that cited them through forward snowballing. This process helped to locate additional relevant publications that were not captured during the initial database search. Following the effective approach used by Belabyad et al. [38], the hybrid search strategy was further supported by the "berry picking" approach [39] to identify relevant grey literature, particularly industry and technical reports. It encompasses, for example, reports and publications produced by Classification Societies and international organisations, including Det Norske Veritas (DNV), the International Maritime Organization (IMO), the International Energy Agency (IEA), and the United Nations Conference on Trade and Development (UNCTAD).

The study selection process is presented in the PRISMA flow diagram in Figure 2. After applying the search strategy described above and screening the literature through titles, abstracts, and, where necessary, full texts, a total of 137 documents were considered eligible for inclusion, comprising 102 journal articles identified through the database searches and 35 conference proceedings and reports identified through other methods. In accordance with PRISMA 2020 Item 17, all included studies were identified and reported. A complete list of publications and reports included in the final dataset, together with links to the full-text sources, is provided in Table S2 of the Supplementary Material.

During the full-text screening stage, several types of studies were excluded to maintain consistency with the scope of this review: (i) modelling-intensive papers that mainly focused on mathematical modelling or algorithm development without sufficient discussion of practical application; (ii) multi-modal transport studies covering several transport modes, such as road, rail, and aviation, with limited relevance to maritime transport; (iii) studies on market-based measures that focused primarily on policy or regulation rather than operational or technological measures; (iv) studies on non-commercial vessels, including yachts, naval ships, and fishing vessels, rather than commercial fleets; (v) studies that discussed sustainability without a clear maritime application; and (vi) studies on domestic shipping that focused on inland, local, or coastal shipping rather than international operations.

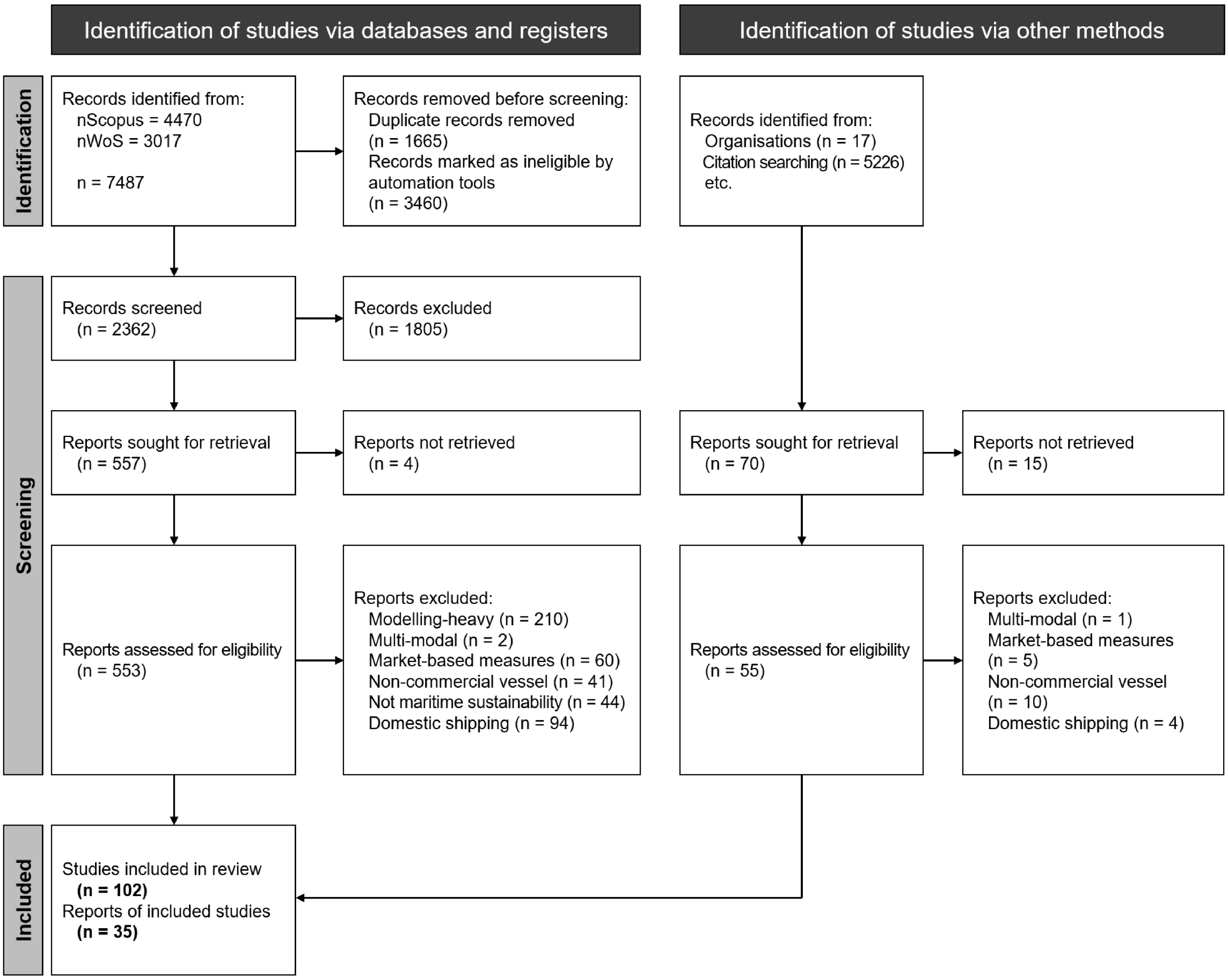

Figure 2. PRISMA flow chart for the literature selection process.

2.2. Bibliometric Analysis

After collecting the data, a bibliometric analysis was conducted to quantitatively explore the structure and dynamics of included research. Bibliometric analyses provide a systematic and reproducible means of evaluating the intellectual and conceptual structure of a research field, enabling the identification of influential publications, emerging trends, and patterns of collaboration across studies. To conduct the bibliometric analysis, we employed the Bibliometrix package in the R environment [40]. The following bibliometric analysis concentrates on the academic papers included in the dataset (n = 102). A summary is provided in Table 1.

The results show that academic research on sustainable measures in maritime transport has received increasing attention in recent years. The dataset covers the period from 2018 to 2025, which aligns with the year when the IMO first adopted its initial GHG reduction strategy. Overall, the number of publications increased from 2 in 2018 to 36 in 2025, which is broadly consistent with the findings of Fadaie et al. [20]. The overall annual growth rate of articles is 51.1%. However, the increase was not consistent across all years, as illustrated by the decline from 18 publications in 2023 to 16 in 2024. Moreover, despite the overall increase, the annual number of publications remains relatively modest. The findings therefore indicate increasing, although fluctuating, academic attention to the sustainability of shipping and port operations. Figure 3 presents the number of publications per year.

Table 1. Dataset descriptive statistics.

Data	Description	Results
Main information about data	Timespan	2018:2025
	Sources (Journals, Books, etc.)	48
	Documents	102
	Annual Growth Rate (%)	51.12
	Document Average Age	1.82
	Average citations per doc	30.25
	References	7606
Document contents	Keywords Plus (ID)	278
	Author's Keywords (DE)	382
Authors	Authors	425
	Authors of single-authored docs	7
Authors collaboration	Single-authored docs	7
	Co-Authors per Doc	4.52
	International co-authorships (%)	40.2

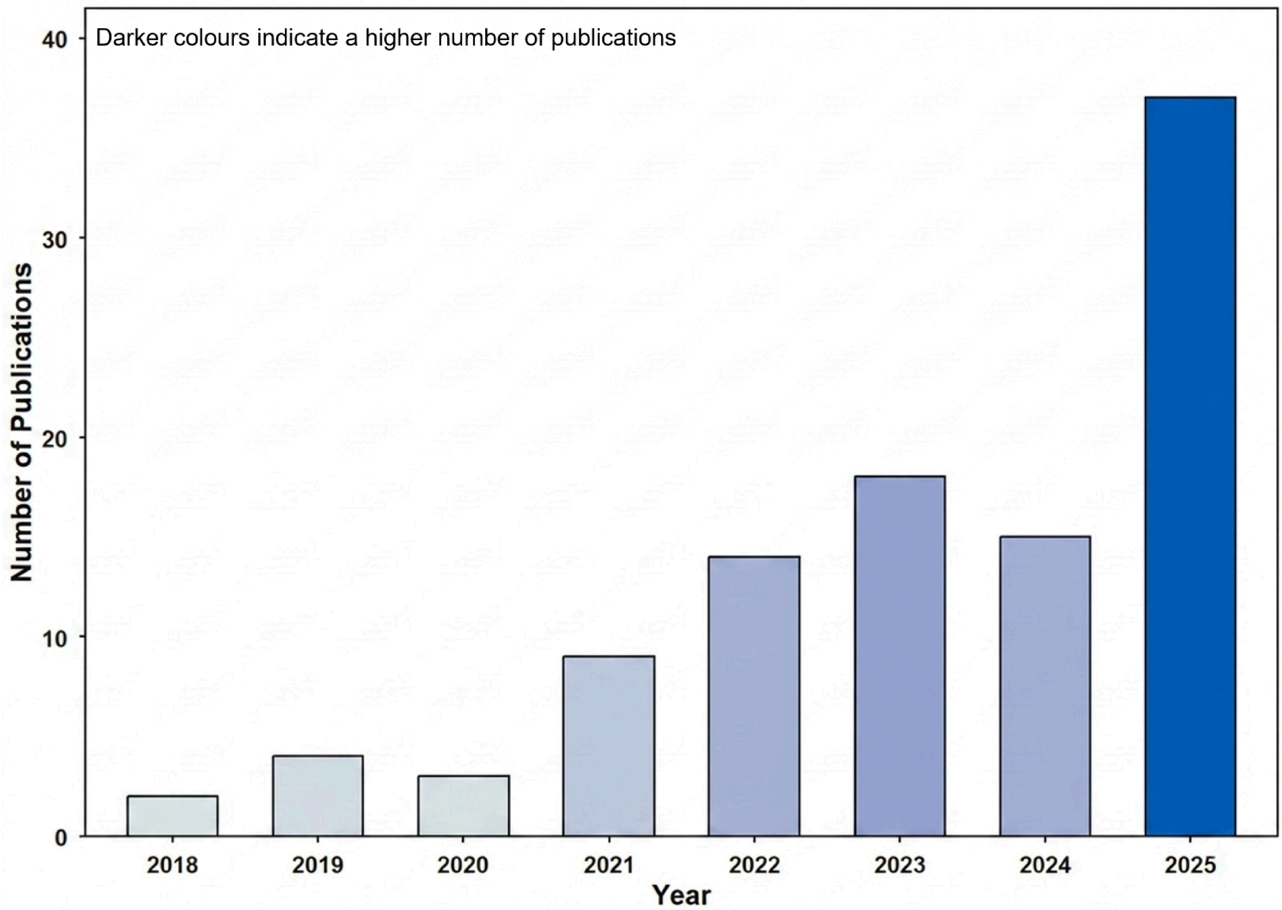

Figure 3. Academic publication trends.

The research output is dispersed across a range of journals, reflecting a field that is still consolidating. The *Journal of Marine Science and Engineering* is the leading source with 13 papers, followed by *Ocean Engineering* and *Renewable and Sustainable Energy Reviews*, each with 8 articles. Other active outlets include *Energies*, *Journal of Cleaner Production*, and *Sustainability*. The diversity of publication venues suggests that research on maritime sustainable measures remains highly interdisciplinary, encompassing perspectives from engineering, energy systems, and environmental sciences.

In terms of geographical distribution, China leads with 22 publications, followed by the United Kingdom, Italy, and several Northern European countries. However, Denmark, the Netherlands, and Sweden show higher average citations per article, indicating stronger research influence. These trends align with their early adoption of low-carbon initiatives and policy leadership in green maritime transport. The international co-authorship rate of 40.2% further highlights the global and collaborative nature of this emerging research field.

2.3. Thematic Analysis and Research Trends

To identify the central themes and research directions within the reviewed literature, a frequency analysis was conducted using the titles, abstracts, and author keywords of the 102 papers. The results are summarised in Table 2, while Figure 4 illustrates the co-occurrence relationships among all keywords, with different colours representing distinct keyword clusters.. Although the most frequently used terms naturally reflect the search parameters employed in data collection, the analysis still allows several observations to be made regarding recurring concepts and emerging areas within the field [38]. As a result, this analysis continues to be widely applied in systematic review studies within green maritime transport [41] to support the identification of key research themes. Firstly, the prominence of 'energy' across titles and abstracts indicates a growing research focus on energy transition and decarbonisation, largely driven by the need to comply with the IMO's emission reduction targets. Secondly, the frequent use of 'alternative fuels' suggests that this topic has become a central theme in recent studies, reflecting increasing attention to low- and zero-carbon alternative fuels as key enablers of emission reduction. Lastly, the frequent occurrence of 'technology' highlights the engineering focus of current research, which aims to develop and improve solutions for green maritime transport.

Table 2. Most frequent words in titles, abstracts, and author keywords (# denotes the number of occurrences).

	Titles		Abstracts		Author Keywords	
	Words	**#**	**Words**	**#**	**Words**	**#**
1	energy	27	energy	235	alternative fuels	16
2	shipping	26	fuels	189	decarbonization	14
3	maritime	25	fuel	177	decarbonisation	11
4	decarbonization	22	emissions	164	maritime transportation	9
5	fuels	20	maritime	159	ammonia	8
6	carbon	17	carbon	157	hydrogen	8
7	alternative	16	shipping	129	shipping	7
8	ships	16	alternative	119	biofuels	6
9	technology	15	hydrogen	98	lng	5
10	fuel	13	technologies	95	maritime transport	5

In particular, author keywords play an important role in bibliometric analysis, as they provide a concise representation of the main focus of each study and enable the identification of dominant themes and research trends within maritime sustainable measures [42]. Because the same concept may be expressed using different terms, a process of keyword standardisation is essential [43]. To enhance the precision of the keyword analysis, a data cleaning process was conducted. For example, (i) American English variations were unified into British English; (ii) related terms such as 'technique' and 'technologies' were merged into the single keyword 'technology'; (iii) variations like 'alternative marine fuels', 'marine alternative fuel', and 'new fuels' were standardised to 'alternative fuels'; (iv) generic terms such as 'shipping' and 'port' were excluded to focus on more specific thematic keywords. Following this standardisation process, the top 10 most frequent author keywords were visualised through a heatmap in Figure 5.

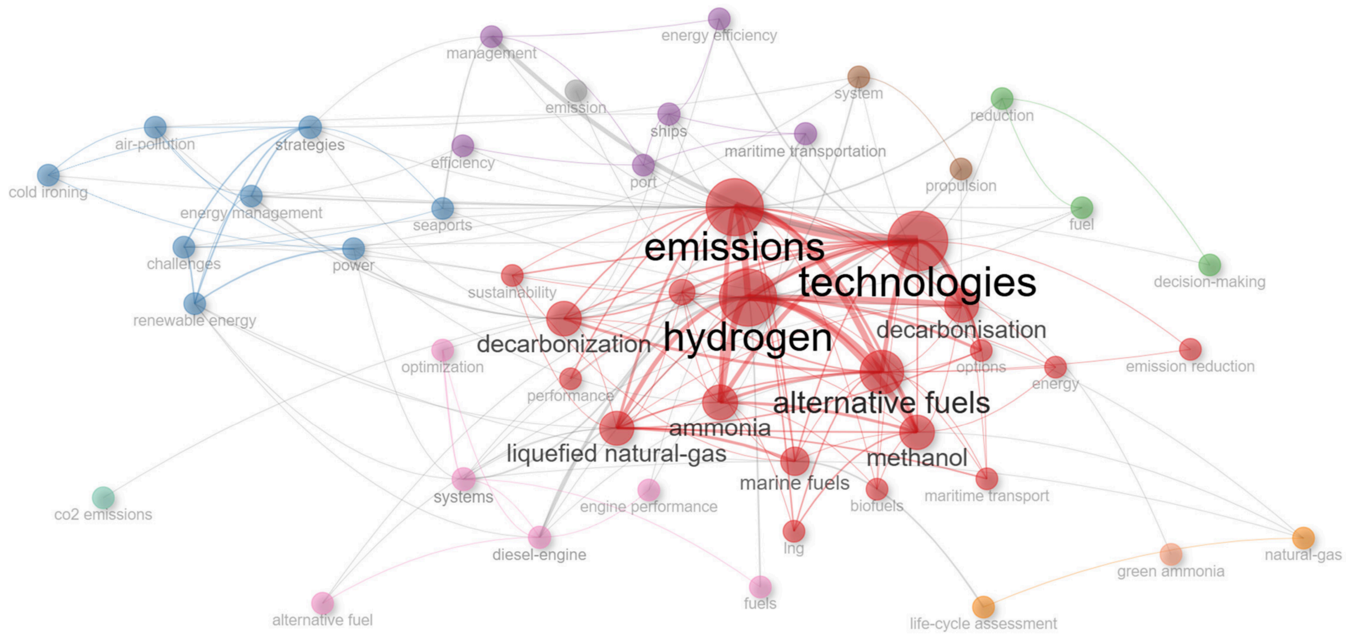

Figure 4. Co-occurrence network of all keywords. *Note: Generated using the bibliometrix R package (Aria and Cuccurullo, [40]).*

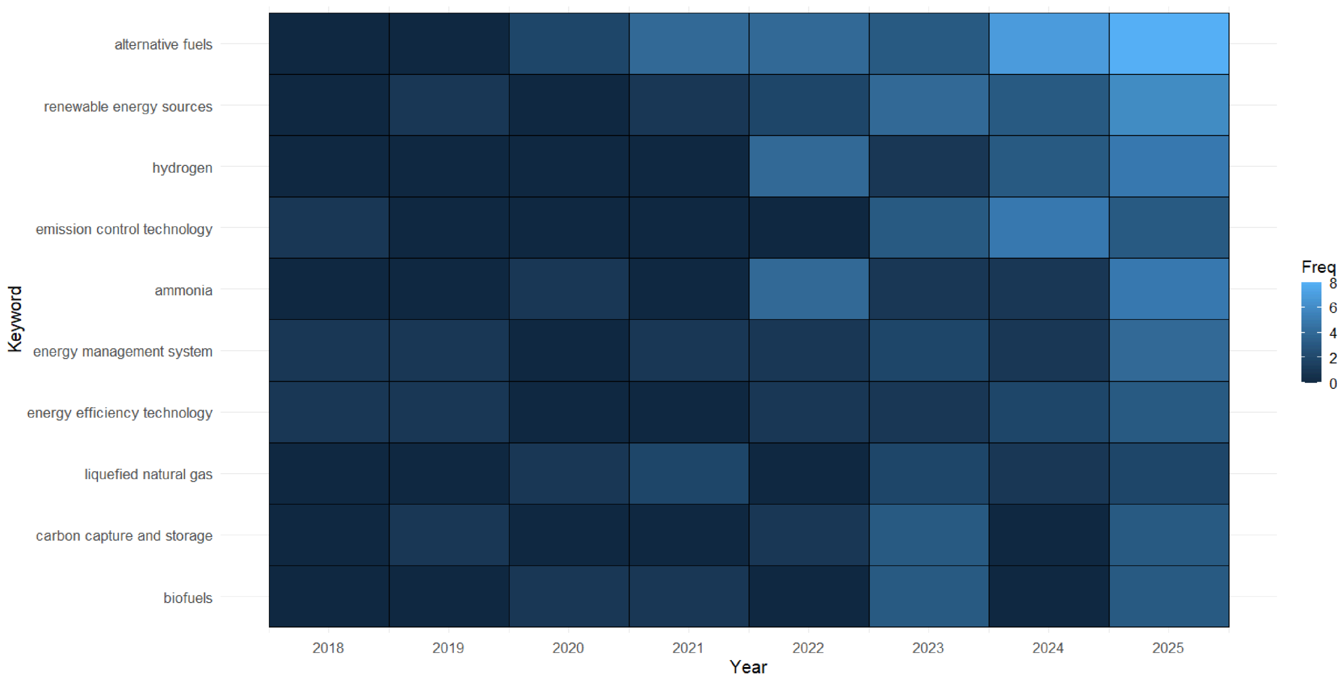

Figure 5. Top 10 high occurrence keywords heatmap.

Figure 5 presents the year distribution of the top 10 keywords from 2018 to 2025, illustrating how research attention related to sustainable measures in maritime transport has evolved over time. Overall, the results show that most keywords occurred more frequently in the later years of the study period, although their annual frequencies varied. This pattern indicates increasing, but uneven, research attention to emission reduction across the maritime transport sector. In the earlier phase from 2018 to 2020, research attention was primarily anchored in vessel-level performance improvement and emission mitigation. Energy efficiency technology and emission control technology appear consistently throughout this period, reflecting a sustained focus on improving ship operational efficiency and reducing onboard emissions. At the same time, alternative fuels and renewable energy sources were already present, although at relatively moderate levels. This suggests that early research did not exclusively concentrate on conventional ship technologies, but rather developed along parallel tracks combining efficiency improvement and emerging fuel transition pathways.

From 2022 onwards, the diversification of research topics becomes more evident, particularly in relation to alternative fuels. Keywords such as liquefied natural gas (LNG), methanol, hydrogen, ammonia, and biofuels show increasing frequencies, with alternative fuels displaying a pronounced upward trend after 2022. By 2024 and 2025, alternative fuels emerge as the most frequently occurring keyword, highlighting the growing emphasis on fuel transition as a central pathway for green maritime transport. An especially notable trend is observed for renewable energy sources, which show a sharp increase in frequency from 2022 onwards. This increase is closely associated with port-related applications, reflecting rising research interest in integrating renewable energy into port operations. By 2025, renewable energy sources record the second highest frequency among all keywords, following alternative fuels. This trend suggests an expanding recognition of ports as active contributors to emission reduction, rather than passive service nodes within green maritime transport.

2.4. Thematic Analysis

Thematic analysis plays a central role in bibliometric reviews, as noted by Aria and Cuccurullo [40], since it enables researchers to capture the conceptual structure of a research domain. By examining how keywords co-occur across studies, this approach helps to identify major themes and their interconnections. Each theme is characterised by two dimensions: density, which reflects its internal development, and centrality, which represents its relevance within the overall research field. When plotted on a thematic map, density is shown on the vertical axis and centrality on the horizontal axis.

Following the framework proposed by Aria and Cuccurullo [40], the thematic map is divided into four quadrants based on these two dimensions, as presented in Figure 6. Motor themes (high density and high centrality) are both mature and influential in shaping the field. Niche themes (upper left) are well-developed but relatively isolated, whereas basic themes (lower right) are broad and cross-cutting, serving as a conceptual foundation for further studies. Finally, emerging or declining themes (lower left) have lower density and centrality, indicating areas of ongoing or diminishing research interest.

The motor themes highlight the central role of fuel transition in shaping current research on maritime sustainable measures. The strong presence of alternative fuels, together with hydrogen and ammonia, indicates that research attention has largely converged on fuel-based solutions as the most promising pathway for deep emission reduction. These fuels are increasingly discussed not only in terms of their emission reduction potential, but also with respect to technical feasibility, safety, and infrastructure readiness. This suggests that the literature is gradually shifting from exploring fuel options in principle to examining how such fuels can be realistically deployed within green maritime transport.

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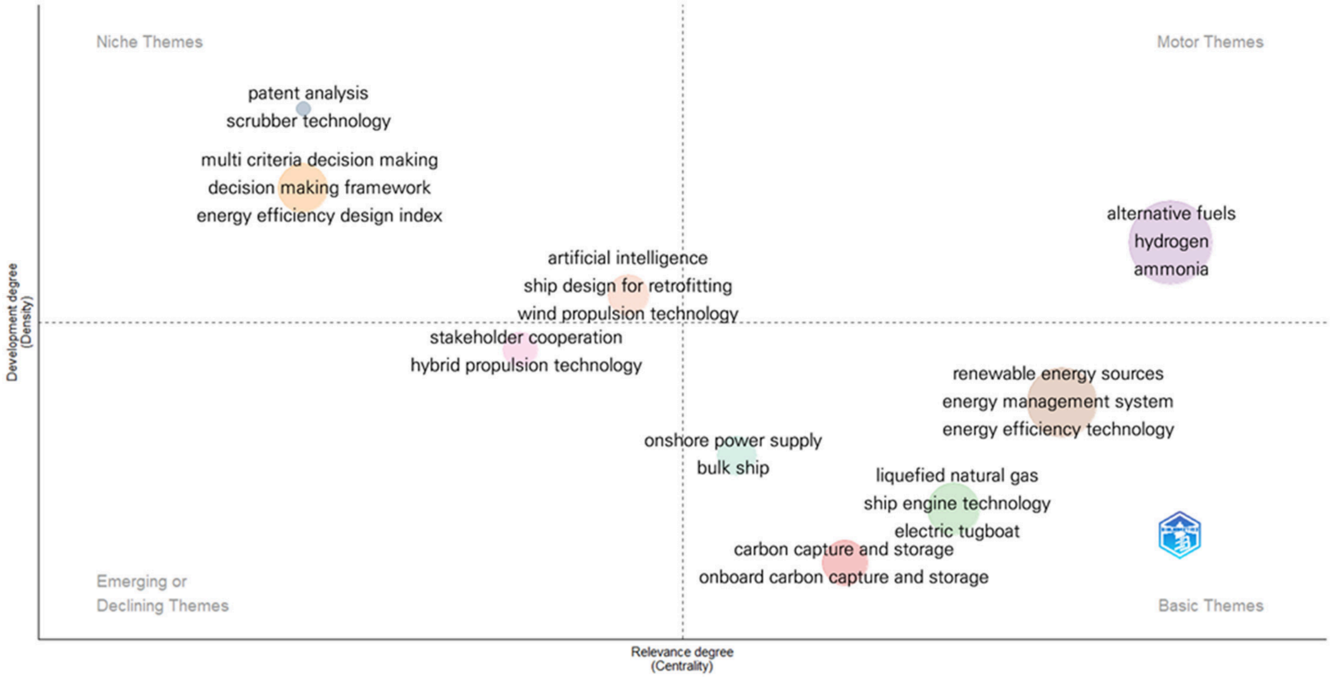

Figure 6. Thematic map. *Note: Generated using the bibliometrix R package (Aria and Cuccurullo, [40]).*

The basic themes include systemic infrastructure such as renewable energy sources and energy management systems, which provide the essential framework for integrating green technology into ship and port operations. At the same time, practical technology solutions like LNG, ship engine technology, and electric tugboats remain indispensable. The inclusion of LNG here is particularly noteworthy, suggesting it has matured from a novel fuel into a foundational transitional bridge. Furthermore, carbon reduction technologies such as onboard carbon capture and storage (OCCS) and the onshore power supply (OPS) emphasise the growing importance of efficiency beyond the ship approach. Crucially, these measures represent technologies that cannot be implemented by either ships or ports in isolation. Instead, they require a high degree of technical and operational synchronisation between both sectors to be effective. While these themes have lower density compared to motor themes, their high centrality confirms they are the essential building blocks of a truly integrated green maritime transport.

The niche themes, such as patent analysis, scrubber technology, and multi-criteria decision-making, suggest that these topics are highly specialised or technically closed niches. For instance, scrubber technology represents a mature engineering field, yet its lower centrality indicates it is increasingly viewed as a localised or interim compliance measure rather than a global long-term trend. Similarly, the application of artificial intelligence (AI) for ship design retrofitting and the development of wind propulsion technology represent cutting-edge engineering silos. While these topics are internally well-developed, they have yet to penetrate the broader, mainstream maritime transport literature, remaining specialised frontiers that offer unique but specific technical contributions.

The emerging or declining themes point to research areas that remain relatively underdeveloped within the current literature. The appearance of stakeholder cooperation highlights increasing recognition that effective emission reduction requires coordination among multiple actors. Similarly, hybrid propulsion technology reflects interest in combining different technological pathways. However, their positioning suggests that challenges related to institutional alignment, operational complexity, and integration have limited the expansion of these topics into more established research streams. Notably, themes related to cross-sector coordination and stakeholder interaction are not always clearly visible in mainstream bibliometric results. This is because they often span across different domains rather than forming tightly connected clusters. However, these themes are critical for system-level transition. As green maritime transport increasingly depends on coordinated and hybrid approaches, greater attention to such cross-sector interactions is needed.

2.5. Discussion and Implications of the Bibliometric Analysis

The bibliometric analysis of the literature on sustainable measures for green maritime transport presents a comprehensive overview of an increasingly dynamic and technologically driven research field. The overall increase in publications since 2018 reflects rising academic attention following the adoption of the IMO's initial GHG reduction strategy. This acceleration indicates that sustainability has become a central focus of maritime research, as the sector seeks practical and scalable solutions to achieve net-zero objectives [44].

The geographic distribution of research output reveals a strong concentration in technologically advanced maritime nations, particularly China, the United Kingdom, and several European countries such as Sweden, Italy, and Norway. These countries have demonstrated proactive engagement in green maritime transport through policy initiatives and research investment, which is consistent with the findings of Wan et al. [28] and Jugović et al. [45]. The international co-authorship rate of 40.2% indicates a relatively strong level of cross-border collaboration, yet this cooperation remains largely concentrated among a limited group of leading nations (e.g., China, the United Kingdom). This pattern suggests the need to expand collaborative networks and encourage broader participation from emerging maritime regions to achieve more globally representative progress in sustainability research.

The thematic analysis shows that research on maritime sustainable measures is strongly centred on alternative fuels. This emphasis reflects how fuel transition has become both a policy and an economic priority, as these measures are directly aligned with international regulatory goals such as the IMO's and the EU's emission reduction targets, while fuel expenses represent the largest share of a vessel's operating costs [46]. As a result, the adoption of cleaner fuels is seen as a necessary but economically demanding pathway, encouraging research focused on balancing environmental goals with cost efficiency in maritime operations. At the same time, the emergence of themes such as stakeholder cooperation points to future research directions and the need for integrated, cross-sectoral collaboration in green maritime transport.

Despite the growing research interest and the promising directions identified in this analysis, the literature on maritime sustainable measures remains fragmented across different technologies, operational practices, and application contexts. While alternative fuels continue to dominate the research landscape, other sustainable measures have received comparatively less attention despite their potential contributions to green maritime transport. Moreover, existing studies tend to focus on individual measures or specific technology groups, providing limited insight into how different measures can contribute to the maritime transition over time. Accordingly, the next section classifies these measures according to their expected implementation horizons to support the transition towards green maritime transport.

3. Sustainable Measures Across Implementation Horizons

Following the literature selection process, a systematic review was conducted to identify and examine sustainable measures developed across the maritime transport sector. In the shipping sector, these measures are traditionally classified into three categories: operational, technical, and market-based measures (e.g., carbon taxes and emissions trading schemes) [41,47]. However, this classification is not always clear-cut, as market-based instruments often incentivise the adoption of operational and technical measures, with slow steaming the easiest way to reduce energy consumption and thus emissions. Since policy instruments such as taxes and emissions trading schemes fall outside the scope of this study, they are not considered further. Furthermore, the bibliometric analysis presented above highlights the growing prominence of alternative fuels and energy-related measures, justifying their treatment as a distinct category.

As the maritime sector transitions towards greener and more sustainable operations, ports play an increasingly important role in supporting emission reduction efforts [48]. Unlike shipping, where many sustainable measures are implemented directly on vessels, port-related measures often involve fixed infrastructure, terminal operations, and energy supply systems [49,50]. Accordingly, sustainable measures in ports are classified into three categories: operational measures, infrastructural measures, and alternative fuels and energy measures [51–54]. As with shipping, some overlap between these categories is inevitable.

Several review studies have identified measures aimed at reducing emissions in shipping and enhancing the sustainability of ports, although the two sectors are generally examined separately (see Section 4.3 for further discussion). This review does not seek to replicate the detailed analyses provided by previous studies. Instead, interested readers are referred to Bouman et al. [35], Iris and Lam [52], and Fadaie et al. [20], among others, for a comprehensive discussion of the relevant sustainable measures.

More importantly, beyond their sectoral application, these measures also differ in terms of their implementation timeframe. This temporal dimension is particularly relevant because the transition towards sustainable maritime transport is a gradual, multi-stage process rather than a single-step transformation. Some measures can be applied through operational improvement, maintenance, and energy efficiency management, whereas others require technological retrofitting, new infrastructure, alternative fuel supply chains, or wider energy-system transformation. As discussed in Section 1, the IMO GHG Strategy sets out a staged decarbonisation pathway for the maritime industry towards 2030, 2040, and 2050 [4]. A time-based perspective is therefore useful for linking individual measures to the sequence and pace of transition expected in practice.

In this study, the individual measures (see Table 3) are classified according to their dominant implementation horizons. This does not mean that a measure is relevant only within one period. Rather, it refers to the period in which the measure is expected to diffuse more widely and make its main contribution under current transition conditions. As this study is based on a systematic literature review, no separate empirical analysis or external expert judgement was employed. The classification was developed, reviewed, and validated by the authors. For each measure, the classification was determined through an overall assessment of technological maturity and commercial readiness [13], retrofit or design complexity [26,55], dependence on fuel [56], bunkering [57], grid [58], or digital infrastructure [59–61], required investment [29], and the degree of safety [44,62], regulatory [63], and inter-organisational coordination involved [64]. These criteria were considered collectively rather than applying a single criterion to each measure. Where studies associated the same measure with different implementation horizons, these variations generally reflected differences in the aspects emphasised by individual studies, such as technological maturity, economic feasibility, or safety, rather than directly conflicting evidence. The relevant evidence was therefore synthesised across these aspects to determine the dominant implementation horizon for each measure. Accordingly, the assigned horizons should be interpreted as indicative rather than fixed, as the timing and effectiveness of sustainable measures may vary depending on geographical context, vessel type, lifecycle integration, investment capacity, infrastructure readiness, and fuel market development [29,56,65].

Table 3 presents the classification of sustainable measures in green maritime transport by implementation horizon.

As shown in Table 3, short-term measures (towards 2030) are dominated by operational optimisation and immediately deployable efficiency actions. In shipping, these mainly include voyage and navigation measures, maintenance and monitoring, onboard energy efficiency management, mature emission-control options, and already deployable fuel or supplementary energy measures. In ports, the short-term is centred on terminal and facility efficiency, ship-port interface measures, AI and Internet of Things (IoT) applications, LNG bunkering, solar energy, energy management system (EMS), and alternative fuel or electrification of vehicles and cargo handling equipment (CHE) where commercial options are increasingly available. These measures were placed in the short-term because they can generally be implemented through existing assets, routine retrofits, or commercially available equipment [75], without waiting for major changes in fuel supply chains or port-wide energy architectures [76,77].

Medium-term measures (towards 2040) are more strongly associated with technological integration, retrofitting, electrification, and infrastructure upgrading. In shipping, this includes hull and hydrodynamic design improvements, propulsion efficiency technologies, waste heat recovery (WHR), battery and hybrid power systems, fuel cell (FC)-based systems, supercapacitors, wind-assisted propulsion, and transitional fuels such as methanol. In ports, this horizon includes terminal automation, blockchain, 5G, digital-twin (DT), selected bunkering and low-carbon infrastructure measures, harbour craft fuel transition, large-scale wind energy, and microgrids. These measures are technically credible today, but their wider diffusion depends on vessel-specific engineering, higher capital expenditure, interoperable digital and power systems, or broader port-side planning [52,58,78]. In this sense, they are better understood as scaling measures rather than immediate measures.

Long-term measures (towards 2050) are those linked to deep decarbonisation and wider energy-system transformation. In shipping, these include electrofuels, hydrogen, ammonia, OCCS, and nuclear propulsion. In ports, they include hydrogen and ammonia bunkering, carbon capture and storage (CCS) infrastructure, and less mature marine renewables such as wave and tidal energy. These measures were assigned to the long-term because their large-scale contribution depends on zero- or near zero-carbon fuel production at scale, dedicated storage and handling systems, carbon transport and storage chains, and further progress in safety regulation and institutional acceptance [13,29,44,70]. In addition, wave- and tidal-based applications remain much less deployable at scale than solar and wind in current marine energy systems [17,44,61,79]. This horizon also implies a broader role for ports as future energy hubs, not only cargo interfaces [49,50,53].

Figure 7 illustrates this implementation pathway. The transition begins with measures that improve operational efficiency and reduce avoidable energy use, then progresses through retrofitting, electrification, and infrastructure-dependent system integration, and finally moves towards energy and carbon pathways consistent with full decarbonisation. However, these horizons should not be interpreted as discrete phases in which one set of measures is replaced by another. Short-term measures remain important beyond 2030, while medium- and long-term measures will overlap as technologies mature, infrastructure expands, and regulatory conditions become clearer. The value of the classification lies in showing a cumulative transition pathway rather than a strict sequence of substitution.

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Table 3. Time-based implementation horizon classification of sustainable measures.

Sector	Main Category	Subcategory	Measure	Implementation Horizon		
				Short-Term (Towards 2030)	Medium-Term (Towards 2040)	Long-Term (Towards 2050)
Shipping	Operational	Voyage & Navigation	Weather Routing	V		
			Slow Steaming	V		
			Trim and ballast optimisation	V		
			Just-in-Time	V		
		Maintenance & Monitoring	Hull Maintenance	V		
			Propeller Maintenance	V		
			Remote Monitoring System	V		
		Energy Efficiency Optimisation	Efficient Lighting System	V		
			Efficient Engine Operating Load	V		
			Fleet Management Optimisation	V		
	Technological	Hull & Hydrodynamic Design	Air Lubrication System		V	
			Ballast Water Reduction		V	
			Bulbous Bow Retrofit		V	
			Hull Form Optimisation		V	
			Lightweight Shipbuilding		V	
		Propulsion Efficiency Improvement	High-efficiency Propeller		V	
			High-efficiency Rudder		V	
			Energy-saving Devices		V	
		Engine & Power Technologies	Waste Heat Recovery		V	
			Fuel Cell Power Systems		V	
			Battery Power Systems		V	
			Hybrid Power Systems		V	
			Supercapacitor		V	
		Emission Control & Reduction	Selective Catalytic Reduction	V		
			Exhaust Gas Recirculation	V		
			Scrubber	V		
			Onboard Carbon Capture and Storage			V
	Alternative Fuels & Energy	Alternative Fuels	LNG	V		
			LPG		V	
			Methanol		V	
			Ethanol		V	
			Biofuels	V		
			Electrofuels			V
			Hydrogen			V
			Ammonia			V
		Alternative Energy Propulsion	Wind-assisted Propulsion		V	
			Solar-assisted Propulsion	V		
			Nuclear Propulsion			V

Table 3. *Cont.*

Sector	Main Category	Subcategory	Measure	Implementation Horizon		
				Short-Term (Towards 2030)	Medium-Term (Towards 2040)	Long-Term (Towards 2050)
Port	Operational	Terminal Efficiency Improvement	Terminal Automation		V	
			Terminal Operating System	V		
			Equipment Maintenance	V		
		Facility Efficiency Improvement	Lighting	V		
			Heating, Ventilation, and Air Conditioning	V		
			Building Energy Management System	V		
			Reefer Container Management	V		
		Ship-Port Interface	Ship Turnaround Time Reduction	V		
			Vessel Speed Reduction	V		
			Virtual and Just-in-Time Arrival	V		
		Digitalisation	AI	V		
			Blockchain		V	
			IoT	V		
			5G Technology		V	
			Digital-Twin		V	
	Infrastructural	Alternative Fuel Bunkering	LNG Bunkering	V		
			LPG Bunkering		V	
			Methanol Bunkering		V	
			Hydrogen Bunkering			V
			Ammonia Bunkering			V
		Low-Carbon Infrastructure	Carbon Capture and Storage			V
			Onshore Power Supply		V	
			Automated Mooring System		V	
			Modal Shift		V	
	Alternative Fuels & Energy	Alternative Fuels & Electrification	For Harbour Craft		V	
			For Vehicles	V		
			For Cargo Handling Equipment	V		
		Renewable Energy	Solar Energy	V		
			Wind Energy		V	
			Wave Energy			V
			Tidal Energy			V
		Energy Management	Microgrid		V	
			Energy Management System	V		

Source: Developed by the author based on the literature [29,56,66–74].

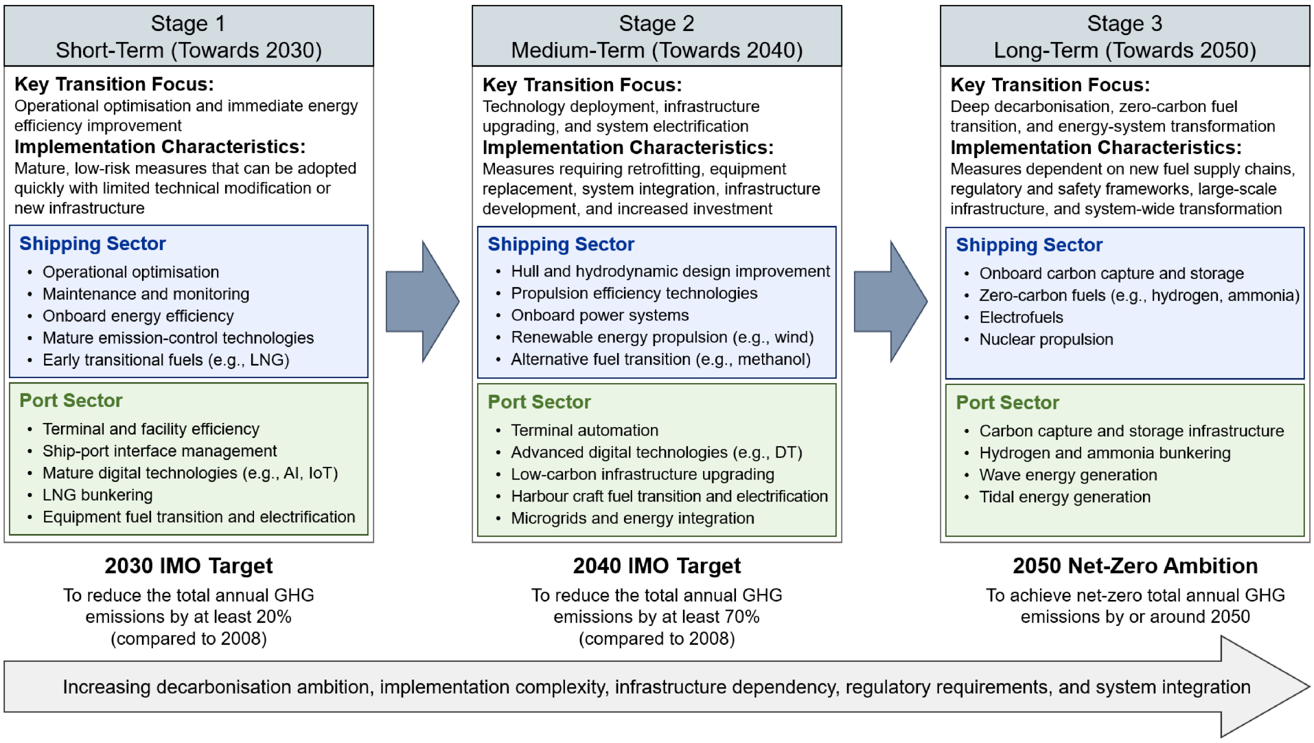

Figure 7. Time-based implementation pathway of sustainable measures towards green maritime transport.

4. Discussion and Implications

The implementation horizon classification developed in Section 3 provides a broader perspective on how sustainable measures may contribute to the transition towards green maritime transport over time. Rather than representing isolated technological options, the identified measures collectively illustrate a cumulative transition process in which operational improvements, technological innovations, infrastructure development, and energy-system transformation evolve in parallel. The findings suggest that some measures can be deployed immediately because they are already technologically mature and commercially available, whereas others require longer preparation periods involving retrofitting, infrastructure investment, fuel supply development, regulatory adaptation, and stakeholder coordination. From this perspective, the classification serves not only as a framework for organising sustainable measures, but also as a practical guide for prioritising near-term actions, scaling medium-term solutions, and preparing long-term pathways under continuing technological, commercial, and regulatory uncertainty.

These findings are broadly consistent with previous review studies, while extending their scope and practical interpretation. Bouman et al. [35] identified operational improvements, technological development, and alternative fuels as major pathways for reducing emissions from shipping, which corresponds with the principal shipping categories identified in this review. Similarly, the importance of terminal efficiency, energy management, electrification, and renewable energy in the port sector is consistent with the findings of Iris and Lam [52]. The growing prominence of alternative fuels and energy-related measures is also consistent with the trends identified by Fadaie et al. [20]. However, previous reviews have generally examined shipping and port measures separately or focused on the characteristics and emission reduction potential of particular measures. The present review builds on this literature by integrating measures across both sectors and interpreting them according to their dominant implementation horizons towards 2030, 2040, and 2050. This comparison indicates that the findings reinforce established sustainable measure categories while providing an additional temporal perspective for implementation planning.

From a sustainability perspective, these measures have implications across the dimensions of environment, society, and economics. The environmental dimension, which is the main focus of this study, is reflected in their potential to reduce GHG emissions, air pollutants, and fossil fuel dependence. The social dimension includes occupational health and safety, workforce skills, public acceptance, employment implications, and the effects of maritime emissions on port communities. The economic one concerns investment requirements, operating costs, commercial viability, and the competitiveness of shipping and port operations. These dimensions are interconnected, as environmentally effective measures may face delayed adoption if they are financially unviable, socially unacceptable, or dependent on skills and safety arrangements that are not yet available. The following discussion examines the broader implications of this transition process from the perspectives of market drivers, structural barriers, and stakeholder collaboration.

4.1. Market Drivers and Investment Requirements

The classification highlights that the transition towards green maritime transport is influenced not only by technological availability but also by economic feasibility. While many sustainable measures have already reached commercial maturity, their large-scale deployment remains strongly dependent on investment conditions and market incentives.

The findings suggest that measures expected to contribute to deep decarbonisation are generally associated with greater financial commitments than operational and efficiency-oriented measures. Technologies such as alternative fuels and bunkering systems, carbon capture infrastructure, renewable energy integration, and advanced propulsion systems often involve high capital expenditure, uncertain returns on investment, and long asset lifecycles. Consequently, their adoption is strongly influenced by investment conditions, expected returns, and broader market dynamics.

Although market-based measures were excluded from the classification framework of this review, they remain important enablers of maritime decarbonisation [80]. Carbon pricing mechanisms, such as EU Emissions Trading System (EU ETS), create financial signals that improve the competitiveness of low- and zero-carbon technologies by reducing the relative cost advantage of conventional fossil fuels [36]. Similarly, financial incentives, green financing mechanisms, and public investment programmes can reduce investment risks and support the commercial deployment of emerging technologies.

The importance of such market drivers becomes particularly evident for alternative fuels. Green ammonia, green hydrogen, electrofuels, and associated bunkering infrastructure currently remain more expensive than conventional marine fuels and existing fuel supply systems [81]. As the relative economics of these technologies improve through carbon pricing, policy incentives, or technological learning, investment decisions become increasingly favourable. In this way, market drivers influence not only the adoption of individual technologies but also the overall pace of maritime decarbonisation.

The findings indicate that economic instruments will play an increasingly important role in accelerating the diffusion of sustainable measures, particularly those associated with deep decarbonisation pathways. Rather than serving as alternatives to technological solutions, market drivers help create the conditions under which such technologies can achieve widespread adoption [82].

4.2. Structural Barriers to Deep Decarbonisation

Despite the growing number of sustainable measures identified in the literature, significant barriers continue to constrain the transition towards full maritime decarbonisation.

The findings of this review indicate that many measures associated with deep emission reduction depend on factors extending beyond individual technological development.

A major challenge is the interdependence between vessels, ports, energy suppliers, and regulatory institutions. Alternative fuels provide a clear example. Ports are often reluctant to invest in hydrogen or ammonia bunkering infrastructure without sufficient demand from vessels, while shipping companies are hesitant to invest in alternative fuel vessels without confidence that fuel supply infrastructure will be available [83,84]. Similar challenges can be observed in relation to shore power systems, carbon capture infrastructure, and renewable energy integration, where successful implementation depends on complementary investments across multiple stakeholders.

This situation creates a well-documented chicken-and-egg dilemma that slows technological diffusion and increases investment uncertainty [57]. Under such conditions, stakeholders often prioritise measures that offer immediate economic benefits and lower implementation risks while postponing investment in more transformative solutions. Although this approach can generate important environmental improvements, it may also delay progress towards the long-term decarbonisation objectives established by the IMO.

The barriers identified here are therefore not purely technological. Rather, they reflect broader institutional, financial, and organisational challenges. Even where technical solutions are available, uncertainty regarding fuel availability, infrastructure readiness, regulatory stability, and long-term market conditions can discourage large-scale investment decisions. Without mechanisms that reduce uncertainty and distribute risks more evenly across stakeholders, many promising sustainable measures may struggle to achieve widespread adoption.

Consequently, achieving deep decarbonisation will require stable regulatory frameworks, coordinated infrastructure planning, and policy mechanisms capable of reducing uncertainty and encouraging long-term investment [85]. Addressing these barriers will be essential for enabling the maritime sector to move beyond incremental efficiency improvements and towards more transformative decarbonisation pathways.

4.3. Stakeholder Collaboration and System Integration

The review further demonstrates that green maritime transport should be understood as a system-level transition rather than a collection of isolated technological improvements. Although individual sustainable measures are often implemented within either shipping or port operations, their effectiveness increasingly depends on interactions among multiple stakeholders across the wider maritime transport system.

Shipping companies, port authorities, terminal operators, energy suppliers, technology providers, logistics operators, cargo owners, and policymakers all influence the development and implementation of sustainable measures [86–88]. While some measures can be implemented primarily through internal organisational decisions, many others depend on varying degrees of coordination, information exchange, and joint planning among different actors. Terminal operators influence the adoption of sustainable cargo handling equipment, terminal automation, and operational efficiency measures, while energy suppliers determine the availability and cost of low-carbon fuels and electricity. Logistics operators can facilitate operational coordination and information sharing across maritime supply chains, whereas cargo owners can stimulate demand for lower-emission transport through their procurement decisions and contractual requirements.

Examples identified throughout this review include Just-in-Time (JIT) and virtual arrival, shore power systems, alternative fuels and associated bunkering infrastructure, carbon capture networks, and renewable energy integration. These measures require cooperation across organisational boundaries because their benefits cannot be fully realised through unilateral action. The increasing adoption of digital technologies, including blockchain, 5G networks, and DT, further reinforces the importance of integrated decision-making and information sharing throughout the maritime transport system. Consequently, the success of future maritime decarbonisation efforts will depend on the ability of stakeholders to align strategies, share risks, and coordinate long-term investments across the maritime transport system.

The people dimension also requires greater consideration during the implementation of sustainable measures. The adoption of alternative fuels, electrification, automation, and digital technologies may change existing working practices and create new requirements for technical training and occupational safety, particularly when handling fuels such as hydrogen and ammonia or operating high-voltage equipment. Automation and digitalisation may also alter employment roles, making workforce reskilling important for ensuring a socially inclusive transition. At the same time, reductions in NOx, SOx, and PM can improve air quality and health conditions for workers and communities surrounding ports, while early engagement with employees and local communities can strengthen public acceptance of new infrastructure and technologies [53].

From a practical perspective, the findings indicate that future decarbonisation strategies should move beyond technology-specific approaches and adopt a more integrated systems perspective. The transition towards green maritime transport will depend on the capacity of stakeholders to establish collaborative governance arrangements and coordinate implementation activities across shipping, port, and wider maritime supply chain sectors. Strengthening such collaboration is therefore likely to become one of the most important enabling conditions for achieving the maritime sector's net-zero ambitions.

5. Conclusions

This study systematically reviewed sustainable measures developed for green maritime transport across both shipping and port sectors. Using a PRISMA-based review and bibliometric analysis, the study identified a broad range of operational, technological, infrastructural, and alternative fuel and energy measures aimed at reducing emissions and supporting the maritime transition.

The findings show that research attention has increasingly shifted towards alternative fuels, renewable energy, and technology-driven solutions following the IMO's decarbonisation strategy. To provide a more practical perspective on implementation, the identified measures were classified according to short-, medium-, and long-term implementation horizons. Measures towards 2030 are primarily associated with operational optimisation, maintenance, energy efficiency, and commercially available technologies. Measures towards 2040 involve wider retrofitting, electrification, technological integration, and infrastructure upgrading, while measures towards 2050 depend more strongly on alternative fuel supply chains, carbon management systems, and broader energy-system transformation. The findings also demonstrate that shipping and port measures need to develop in parallel, particularly where vessel technologies depend on complementary bunkering, electricity, digital, or carbon handling infrastructure. The transition towards green maritime transport should therefore be viewed as a cumulative and integrated process rather than a sequence in which one group of measures simply replaces another.

The proposed implementation horizon classification contributes to the literature by integrating shipping and port perspectives within a structured temporal framework. Compared with classifications that primarily organise measures by sector or technology type, it provides an additional understanding of the likely timing, sequencing, and complementary development of sustainable measures. In practical terms, this perspective may assist shipping and port actors, wider maritime supply chain stakeholders, and policymakers in prioritising near-term actions, coordinating medium-term investment and infrastructure development, and preparing for longer-term fuel and energy transitions under evolving technological, economic, and regulatory conditions.

As with any empirical study, several considerations are relevant to the interpretation of the findings. First, the database search was limited to Scopus and WoS, although additional publications and reports were identified through snowballing and other search methods. Relevant studies indexed in other databases may therefore have been omitted. Second, maritime technologies, fuel markets, infrastructure, and regulatory frameworks are evolving rapidly. The proposed implementation horizons should therefore be interpreted as indicative rather than fixed forecasts and may require revision as these conditions evolve. Their applicability may also vary according to geographical context, vessel type, investment capacity, and infrastructure readiness. In fact, geographical context and the associated regulatory frameworks are indeed important considerations. Our analysis and implementation timelines are aligned primarily with the International Maritime Organization strategy, given that the IMO serves as the global regulator of international shipping. At the regional level, however, policy frameworks can accelerate the pace of transition. As noted in the Introduction, European Union regulations provide a clear example of how regional measures can strengthen decarbonisation incentives. Furthermore, regional market-based mechanisms, such as carbon taxes or emissions trading systems (e.g., the EU Emissions Trading System, EU ETS), impose additional costs on greenhouse gas emissions. As discussed in Section 4.1, these economic and market signals are likely to influence not only the uptake of individual technologies but also the overall rate of maritime decarbonisation.

At the same time, it is important to emphasise that the technologies and operational measures identified through the literature and the analysis we presented above are generally applicable across different policy and regional contexts. Shipping is inherently a global industry, with vessels operating across multiple jurisdictions and therefore subject to a combination of international, regional, and national regulatory requirements. Consequently, policy and regional settings do not alter the technical effectiveness of the identified measures. Rather, they affect their economic attractiveness and cost-effectiveness, which in turn influences the timing and extent of their adoption.

Future research should periodically update the evidence base to capture developments in maritime technologies, fuel markets, infrastructure, and regulation. Empirical studies involving shipping companies, ports, energy suppliers, cargo owners, and policymakers could validate the proposed horizons across different geographical, vessel, and port contexts. Further research should also examine how individual measures can be combined within integrated decarbonisation pathways and assess their environmental, social, and economic implications, including their effects on emissions, financial viability, workforce requirements, safety, and port communities. Such studies would provide a stronger evidence base for supporting long-term decision-making in green maritime transport.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su18189560/s1: Table S1: Complete search strings used in Scopus and Web of Science; Table S2: List of publications and reports included in the systematic literature review.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse Gas
IMO	International Maritime Organization
EU	European Union
CO_2	Carbon Dioxide
NOx	Nitrogen Oxides
SOx	Sulphur Oxides
PM	Particulate Matter
PRISMA	Preferred Reporting Items for Systematic reviews and Meta Analyses
WoS	Web of Science
DOI	Digital Object Identifier
LNG	Liquefied Natural Gas
OCCS	Onboard Carbon Capture and Storage
OPS	Onshore Power Supply
AI	Artificial Intelligence
EU ETS	European Union Emission Trading System
IoT	Internet of Things
EMS	Energy Management System
CHE	Cargo Handling Equipment
WHR	Waste Heat Recovery
FC	Fuel Cell
DT	Digital-Twin
CCS	Carbon Capture and Storage
JIT	Just-in-Time

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