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Green innovation in ports: drivers, domains, and challenges

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The transition toward sustainable maritime development has placed ports at the forefront of global green transformation. As critical nodes in maritime supply chains, ports are under growing pressure to reduce emissions, optimize resource use, and adopt digital technologies. While numerous green practices have emerged in recent years, the literature on port green innovation remains fragmented, lacking a comprehensive synthesis of its drivers, application domains, and systemic challenges. To address this gap, this study conducts a systematic review guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, drawing on peer-reviewed publications from the Scopus and Web of Science databases. The analysis identifies three principal drivers of green innovation in ports: internal dynamics stemming from economic and technological capabilities, external pressures related to environmental regulation and policy, and societal expectations that steer transformation. Green innovation practices are classified into four functional domains: foundational measures, operational optimization, energy system transformation, and intelligent upgrading. In parallel, four major challenges are revealed: persistent ecological pressures, energy transition bottlenecks, fragmented regulatory frameworks, and operational trade-offs. This review contributes an integrated analytical framework that clarifies the conceptual landscape of port green innovation and offers actionable insights for research, policy, and strategic planning.

KEYWORDS
port, green innovation, meta-analyses, energy measures, environmental challenge

1 Introduction

As the core nodes of the global trade network, ports not only connect maritime transportation and land-based logistics, but also play a key role as hubs in international supply chains. More than 80.7% of global trade in goods is accomplished through maritime transportation (United Nations Conference on Trade and Development, 2023). The 2023 IMO GHG Strategy emphasizes the full decarbonization of maritime transport by or around 2050, with interim checkpoints for 2030 and 2040 (IMO, 2023). Ports, strategically situated at the interface between sea and land, undertake multiple functions such as cargo handling, transshipment, energy supply, and operational coordination. Concomitantly, ports are a key part of the green transition, as their operational efficiency and environmental performance have a direct impact on the sustainability of the entire shipping system. Although the proportion of direct emissions from ports in the shipping system is limited (Mustakim et al., 2025), ports act as integrated centers for vessel berthing, shore-based facilities, and hinterland transport, thereby playing a crucial role in overall greenhouse gas emissions and forming one of the major components of the maritime carbon footprint (Misra et al., 2017).

Research shows that more than 70% of shipping emissions occur within 400 kilometers of the coast (Zhen et al., 2020), making ports the focal points of combined externalities such as air pollution, greenhouse gases, and noise, severely impacting coastal ecosystems and public health. This has led to ports gradually shifting from traditional logistics platforms to innovation frontiers for green shipping. Green innovations centered on clean energy, digital technologies, and systems management are being widely deployed in port equipment, operational processes, and energy structures (Al Hasnat, 2025). Ports are no longer passive objects of pollution control, but active institutional platforms and technological testbeds for leading low-carbon transitions and environmental governance. This shift not only responds to increasingly stringent global environmental regulations, but also provides critical support for building a sustainable ocean economy.

With the deepening of sustainable development principles in global port management, the integration of environmental goals into core operational processes has increasingly become a key driver of innovation (Jaafar et al., 2021). In this context, "green innovation in ports", referring to environmentally friendly innovation activities that reduce waste and pollution emissions, and improve resource efficiency through new technologies, processes, services or products (Liao, 2018; Saether et al., 2021; Tang et al., 2018), has become particularly salient. It covers both technological breakthroughs, and institutional, strategic, and leadership transformations. Specifically, green strategies can be developed and implemented in a variety of forms, such as green development plans, environmental management processes, sustainable goal setting, and performance reporting. From a deeper systemic perspective, green innovation in ports can be understood as a typical 'transition concept', representing a comprehensive transformation that involves the interaction and synergistic evolution of the technological, economic, institutional, and ecological dimensions (Rotmans et al., 2001). This process is usually accompanied by path dependency and lock-in effects of pre-existing socio-technical systems, which in turn challenge existing institutional structures (Hanssen et al., 2014; Klitkou et al., 2015). Therefore, green innovation in ports is not only a result of technological evolution, but also a trigger for institutional reshaping and governance reform.

Despite growing scholarly attention to green innovation in ports, current research remains fragmented across technological, managerial, and policy domains. Most existing studies focus on single-case analyses or specific technologies, lacking an integrated understanding of how diverse innovation pathways interact across environmental, energy, regulatory, and operational dimensions. Moreover, few reviews systematically synthesize the drivers, enablers, and constraints of port green innovation from a multi-scalar and multi-stakeholder perspective. There is also limited comparative insight into cross-regional practices or forward-looking strategies that align digital transformation with sustainability goals. This study addresses these gaps by providing a structured synthesis of the literature, categorizing green innovation practices, identifying systemic challenges, and outlining actionable research and policy implications. Given the growing body of research in this field, a systematic review of the literature is essential to examine its main drivers, development domains, and challenges. This would provide a theoretical foundation and practical insights for future empirical and policy research.

This paper defines port green innovation as a multidimensional transformation process that integrates technological advancement, environmental stewardship, and institutional modernization within port systems. It extends beyond the adoption of isolated green technologies to encompass systemic innovation across energy infrastructure, digital intelligence, governance mechanisms, and operational practices. Unlike prior fragmented definitions, this study emphasizes the coordination between environmental objectives and economic functions, highlighting innovation pathways that support decarbonization, digitalization, and stakeholder integration in ports. This conceptualization provides a foundation for structured analysis and strategic policy design in the transition toward green and smart ports.

This study conducts a systematic review of green innovation in ports to address the identified gaps. Section 2 outlines the methodological framework, including data sources, screening criteria, and analytical procedures. Section 3 presents the main findings across three dimensions: drivers of green innovation, implementation measures, and ongoing challenges. Each subsection synthesizes current practices and theoretical insights. Section 4 concludes with future research directions grounded in the preceding analysis and discusses policy and managerial implications.

2 Methods and data

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to conduct a structured literature review (Liberati et al., 2009). The process was based on the 27-item PRISMA checklist and its four-phase flowchart. The review involved four sequential steps (see Figure 1): (1) Identification, (2) Screening, (3) Eligibility, and (4) Included.

2.1 Identification

In the first phase of the review, we conducted a multi-level search for titles, abstracts, and keywords across two major academic databases: Scopus and Web of Science, which are widely recognized for their comprehensive coverage of peer-reviewed literature. The search strategy followed a two-tier structure. In the first tier, we used a broad set of keywords related to green innovation, applying truncation symbols (e.g., asterisks "*") to capture different word

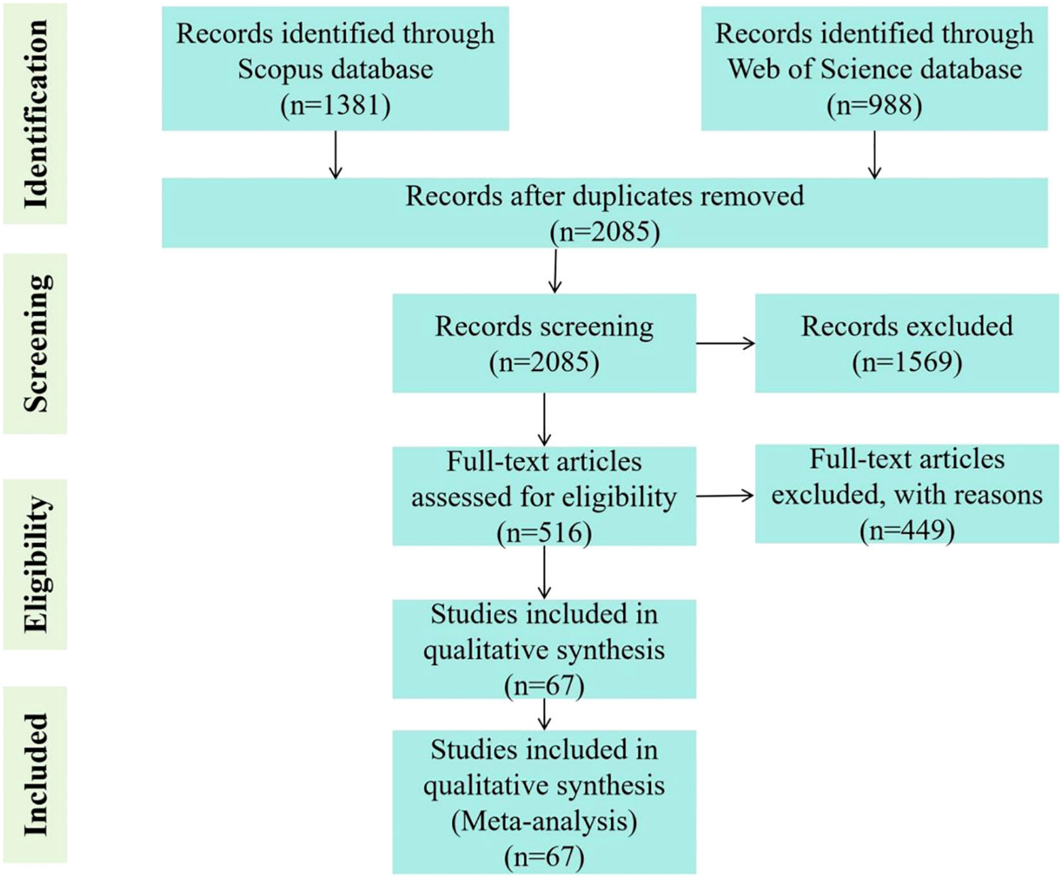

FIGURE 1
Systematic review flowchart.

endings and derivative forms. To enhance the relevance of retrieved articles, we applied filters to limit subject areas, document types, and languages[1] (see Table 1). The initial search yielded 45,564 records on June 20, 2025. After applying filters, this number was reduced to 32,754. A second-tier search was implemented by incorporating additional keywords specific to ports and maritime contexts, along with the same set of filters, given the volume remained too large for efficient screening. This method refined search yielded 1,381 articles, which were then used for further screening and eligibility assessment.

We applied the advanced search function in the Web of Science database, which enables the combination of search sets using Boolean operators and wildcards. We constructed eight separate search sets (see Table 2) on the basis, each corresponding to a cluster of keywords related to green innovation and port operations. In Set 9, Boolean expressions were defined to integrate these keywords and retrieve academic literature specifically focused on port green innovation. This search initially yielded 554 records.

We applied the same filtering criteria as in the Scopus search to ensure relevance and quality. These include restrictions on subject areas, document types, and language. The number of eligible studies was reduced to 391 after applying these filters. The refined dataset was then included in the PRISMA screening and eligibility assessment (see Table 3).

The search results from Scopus and Web of Science were 1381 and 988 articles, respectively; after duplicate articles were removed, the total was reduced to 2085 (see Figure 1).

2.2 Screening

A total of 2085 records were subjected to title and abstract screening to assess their relevance to the research topic. During this process, 1569 records were excluded based on the following criteria: 52 lacked author information, 59 were unrelated to green innovation, 247 did not pertain to ports or maritime contexts, and 1211 were not specifically concerned with green innovation in

1 Only English-language publications were considered for inclusion. For subject area filtering (as defined by Scopus and Web of Science), we limited the search to the following disciplines: Environmental Sciences, Energy, Engineering, Social Sciences, Economics, Econometrics and Finance, Business, Management and Accounting, Earth and Planetary Sciences, Decision Sciences, and Psychology. Regarding document types, we included only peer-reviewed journal articles, conference papers, book chapters, reviews, and books. These restrictions helped focus the analysis on scholarly and high-quality sources relevant to green innovation and port sustainability.

TABLE 1 Scopus search keywords and results.

Layer	Search keywords	Results			
		No limit[a]	Add[b] subject area limit	Add[c] document type limit	Add[d] language limit
First	TITLE-ABS-KEY (Green innovat* OR (Sustainab* environmental* innovat*) OR (Environmental management innovat*) OR (Emission innovat*) OR (Carbon innovat*) OR (Pollution innovat*)	45564	35134	34241	32754
Second	TITLE-ABS-KEY (Green innovat* OR (Sustainab* environmental* innovat*) OR (Environmental management innovat*) OR (Emission innovat*) OR (Carbon innovat*) OR (Pollution innovat*) AND TITLE-ABS-KEY (Maritime OR Port* OR Harbor OR Harbour)	1751	1456	1425	1381

[a]Number of manuscripts before setting limits.
[b]Number of manuscripts after setting limits on subject area.
[c]Number of manuscripts after setting limits on subject area and document type.
[d]Number of manuscripts after setting limits on subject area, document type, and language.

TABLE 2 Web of science search keywords and results (before setting limits).

Set	Results	Search operators and wildcards
#1	9994	TI=(Green innovat* or (sustainab* environmental* innovat*) or (environmental management innovat*) or (emission innovat*) or (carbon innovat*) or (pollution innovat*))
#2	94673	AB=(Green innovat* or (sustainab* environmental* innovat*) or (environmental management innovat*) or (emission innovat*) or (carbon innovat*) or (pollution innovat*))
#3	10590	AK=(Green innovat* or (sustainab* environmental* innovat*) or (environmental management innovat*) or (emission innovat*) or (carbon innovat*) or (pollution innovat*))
#4	6438	KP=(Green innovat* or (sustainab* environmental* innovat*) or (environmental management innovat*) or (emission innovat*) or (carbon innovat*) or (pollution innovat*))
#5	76303	TI=(Maritime OR port OR harbor OR harbor)
#6	3377906	AB=(Maritime OR port OR harbor OR harbor)
#7	39740	AK=(Maritime OR port OR harbor OR harbor)
#8	16398	KP=(Maritime OR port OR harbor OR harbor)

TI, Title; AB, Abstract; AK, Author keywords; KP, Keyword plus.

ports. Following this screening step, a total of 516 documents were retained for full-text eligibility assessment (see Table 4).

2.3 Eligibility

Eligibility represents the second-level screening phase, in which the full texts of the retained records were reviewed to assess their conformity with the study's inclusion criteria. During this phase, a number of articles were excluded based on the following main reasons (see Table 4): the study focused solely on ship-level innovation technologies; the research addressed energy innovation without any connection to ports; the article examined port sustainability without involving green innovation; the study focused on maritime transportation with no relevance to green innovation in ports; or the content was duplicated across sources.

2.4 Included

The final sample was reduced to 67 articles (see Figure 1), which represents a manageable and analytically meaningful dataset. The subsequent analysis focuses on these selected publications, including a breakdown of the authors' country affiliations (see Table 5).

A significant concentration of studies were published in 2021 (n=14) and 2020 (n=12), reflecting growing global attention to environmental concerns by institutions such as the United Nations and the IMO, which has stimulated academic interest in port-related green innovation. Among the journals, *Sustainability*, *Maritime Policy & Management*, and *the Journal of Marine Science and Engineering* were the top three publication outlets. In terms of author affiliations, China ranked first with 13 articles, followed by Norway and Italy with 5 each. Methodologically, most studies employed case studies, literature reviews, mathematical or statistical analysis, and survey-based approaches. Economic modeling and simulation were used less frequently, possibly due to heterogeneity among ports, the accessibility of case-specific data, and the practicality of narrative and integrative review methods when exploring port-related green innovation.

3 Green innovation in ports: drivers, domains and challenges

This section discusses three different phases of green innovation in ports (see Figure 2): 1) Manuscripts that discuss the drivers of

TABLE 3 Web of Science search results (after setting limits).

Combining sets	Results			
	No limit	Add subject area limit	Add document type limit	Add language limit
#9	988	925	920	863

TABLE 4 Records excluded in the screening and eligibility phase.

Phase	Reasons	Number of records excluded
Screening	No author name	52
	Irrelevant to green innovation	59
	Irrelevant to port	247
	Irrelevant to port green innovation	1211
	Sum	1569
Eligibility	Research on ship innovation technology	7
	Researching energy innovations not related to ports	180
	Research on port sustainability has not studied green innovation	134
	Study maritime transport	33
	Irrelevant to port green innovation	95
	Duplicates	0
	Sum	449
	Total Sum	2018

green innovation in ports are all categorized as "drivers" (see Figure 3), 2) manuscripts summarizing the achievements and goals of the port's green innovation are grouped in the "field" subcategory (see Figure 4), and 3) the problems encountered in green innovation in ports are classified as "challenges" (see Figure 5). Some articles may appear in two or even three subcategories.

3.1 What are the factors driving green innovation in ports?

Green innovation in ports is shaped by a combination of internal drivers and external pressures. Understanding these forces is essential for promoting sustainable transformation. Internal drivers stem from economic dynamics, technological advancement, and strategic planning, which together generate momentum for upgrading infrastructure, improving efficiency, and fostering low-carbon development. External pressures arise from environmental regulation, international commitments, and public scrutiny, which compel ports to adopt greener practices and comply with evolving standards. In addition, shifts in social values, stakeholder engagement, and collaborative governance provide a normative foundation for innovation. These factors influence not only the motivation to innovate but also the pathways and institutional arrangements through which green transformation occurs. This section categorizes the drivers of port green innovation into three domains based on a systematic literature review: economic and technological, environmental and policy-related, and social and behavioral. Each domain contributes distinct yet interconnected impulses to the innovation process. The following subsections examine these domains in turn to clarify how they interact to support or constrain the development of green port systems.

3.1.1 Factors in the economic and technological domains provide endogenous impetus for green innovation in ports

This study examines the internal forces within the economic and technological domains that drive green innovation in ports. The twin pressures of economic transformation and technological change have been continuously providing endogenous impetus for green innovation in ports over the years. Against the backdrop of increasingly stringent global carbon emission reduction and sustainable supply chain requirements, ports are enhancing their green competitiveness by reducing carbon footprints and environmental externalities (McGinley, 2014). For small and medium-sized ports, assuming environmental responsibility and enhancing digital efficiency have become key pathways to upgrading service capabilities (Meyer et al., 2023). Ports with a long-term strategic orientation are more inclined to proactively deploy green initiatives (Saether et al., 2021) and invest in the development and application of green technologies (Hanssen et al., 2014). Innovations in systems and business models also energize green innovation. By designing novel cooperative mechanisms such as green-oriented concession agreements or establishing offshore energy contracts (Del Giudice et al., 2021; Olaniyi et al., 2018), ports can effectively mobilize operators and stakeholders to engage in green practices (Notteboom and Lam, 2018). Further, the construction of green port facilities is also influenced by the evolution of ship technology standards, and ports need to continuously adopt new equipment compatible with low-carbon technologies to remain aligned with these standards (Roy et al., 2020; Twrdy and Zanne, 2020).

The diffusion of green technologies has not relied solely on isolated breakthroughs but has also been driven by collaborative

TABLE 5 Descriptive statistics (n = 67).

Year of publication	n	Source title	n	Author country	n
2025(as of 20 June 2025)	7	*Sustainability*	9	China (Mainland)	13
2024	6	*Maritime policy & management*	4	Norway	5
2023	2	*Journal of marine science and engineering*	4	Italy	5
2022	5	*WIT Transactions on the built environment*	3	Germany	4
2021	14	*Ocean & coastal management*	3	Greece	3
2020	12	*WMU journal of maritime affairs*	2	Swedish	2
2019	4	*Computational science and its applications-ICCSA*	2	Spain	2
2018	5	*IEEE Access*	2	USA	2
2017	5	*International journal of production research*	2	Others	31
2015	2	*Transactions on the built environment*	2		
2014	4	*Transport and telecommunication journal*	2		
2013	1	Others	32		

experimentation and knowledge sharing across actors. By piloting new technologies, ports have created innovative ecosystems with information flows and co-development (Cariou, 2018). Human capital and managerial competence have likewise played indispensable roles in driving green transformation (Meyer, 2023). As the cost of renewable energy declines and low-emission technologies mature at an accelerated pace (Damman and Steen, 2021), ports are becoming better equipped to build green technology industrial chains (Koelemeijer et al., 2013), and are increasingly playing the role of collaborative hubs in regional innovation networks (Senarak, 2020). More importantly, the constant inflow of new forms of productivity has substantially enhanced the endogenous innovation capacity for the green transformation of ports (Nie et al., 2025). In sum, expected economic returns, institutional incentive design, collaborative technological progress, and innovation capacity building have together formed the internal pillars of green innovation in ports.

In summary, the literature consistently highlights the complementary role of economic motivation, technological capability, and institutional design in fostering endogenous innovation. While some studies emphasize long-term strategic orientation and infrastructure investment, others stress the role of collaborative ecosystems and digital transformation. Despite contextual differences across port types and scales, a common theme emerges: internal innovation momentum depends on the alignment of economic incentives, technological readiness, and managerial competence. These elements together form a foundational pillar for green transition in the port sector.

3.1.2 Factors in the environmental and policy domains provide exogenous impetus for green innovation in ports

This study focuses on the environmental and policy dimensions as sources of exogenous drivers for green innovation in ports. The environmental impacts of ports are increasingly receiving widespread attention from policy makers and the public (Wang and Notteboom, 2015). These impacts can be divided into three categories: first, the port's own operations (e.g., yard handling, cargo loading and unloading, energy use); second, emissions and pollution from berthed vessels; and third, the pressures on traffic and land use arising from the multimodal transport systems that support port functionality (Aksoy and Durmusoglu, 2020). For example, engineering activities such as land reclamation, new and expanded infrastructure, and facility operations and equipment renewal can lead to ecological disturbance, waterfront degradation, and pollutant discharge (Chen et al., 2018; Twrdy and Zanne, 2020). Consequently, environmental problems such as air pollution, noise nuisance, solid waste accumulation, species invasion, and waterfront congestion arise (Hasanspahic et al., 2021; Pellegrini et al., 2020; Nogué-Algueró, 2020), and even the decision of shipping companies to call at ports may be affected (Franchi and Vanelslander, 2021).

In this context, environmental regulation has become an important driving force for green innovation in ports, and the evolution of regulatory policies is forcing proactive engagement of ports in the low-carbon and sustainable transition (Raza, 2020; Bjerkan et al., 2021). Governments at all levels and international organizations are exerting progressively stringent compliance pressures on port operations by setting environmental standards, implementing carbon taxes, and limiting pollution emissions (Jiang et al., 2024). Regulators can mandate that ports adopt green technologies to reduce negative externalities (Darnall, 2009), and incentivize green innovation through funding, standard setting, and process guidance (Johnstone and Labonne, 2009; Doran and Ryan, 2016). Countries are also reshaping the institutional ecology of green port development by adopting the "command-and-control" and "market incentives" environmental regulatory approaches, combined with industrial clustering and policy coordination (Deng et al., 2022). In addition, incorporating green performance indicators into port concession agreements (Platias et al., 2025) empowers ports to institutionalize actionable pathways for green innovation through performance reviews, incentive subsidies, and emissions trading. Pollution control has thus shifted from a reactive response to an opportunity for proactive innovation and has become an important driver of new green port strategies (Mahmud et al., 2024).

In summary, environmental degradation and the tightening of regulatory frameworks have jointly exerted significant external pressure on ports to pursue green innovation. Unlike internal drivers rooted in profit incentives or strategic planning, these exogenous forces are largely shaped by ecological urgency,

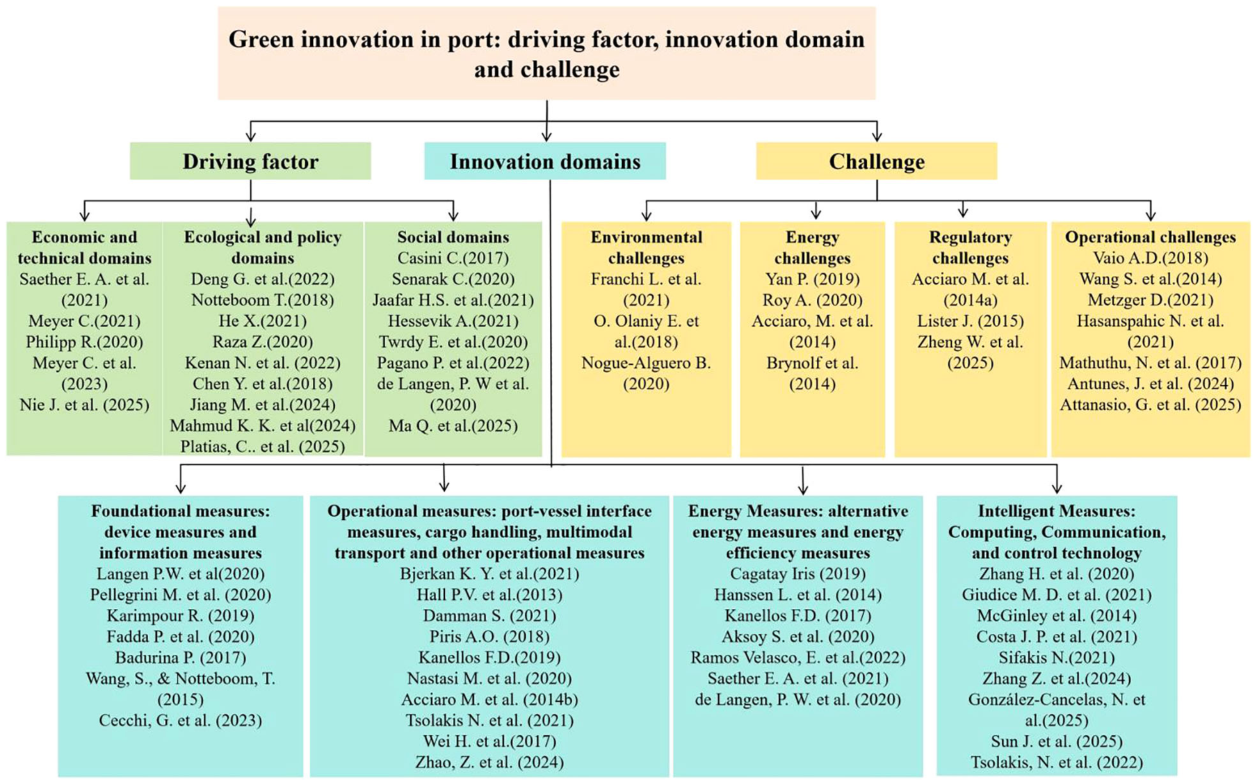

FIGURE 2
Classification of green innovation research in ports.

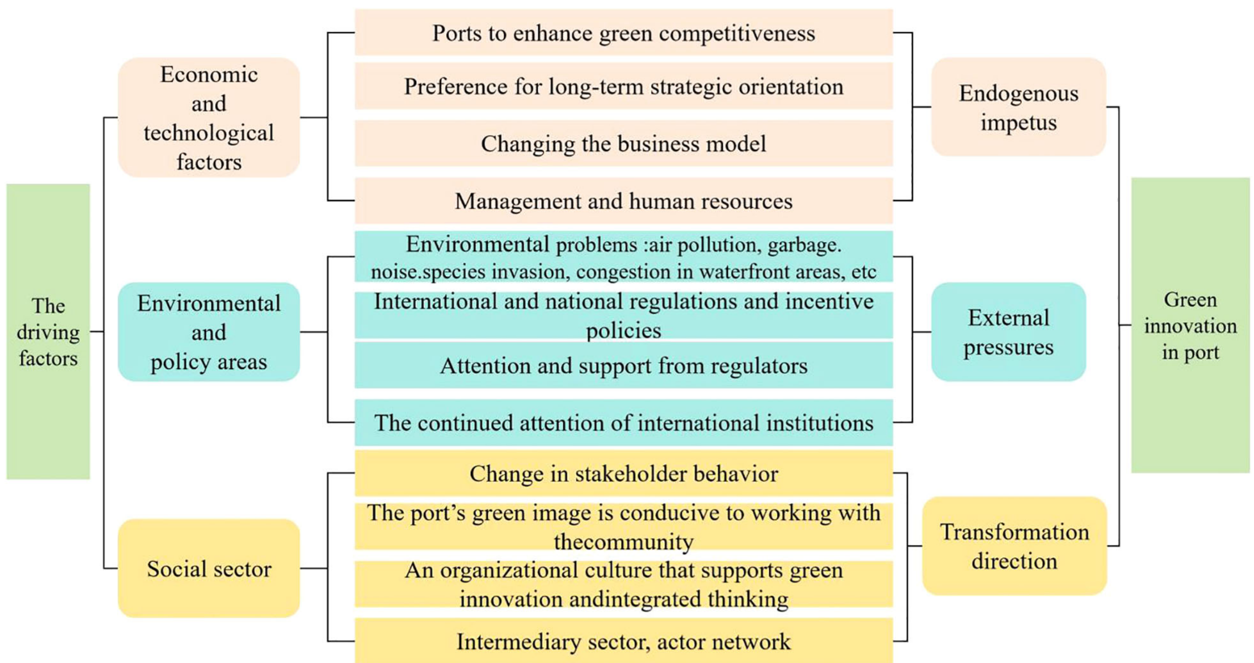

FIGURE 3
Drivers of green innovation in ports.

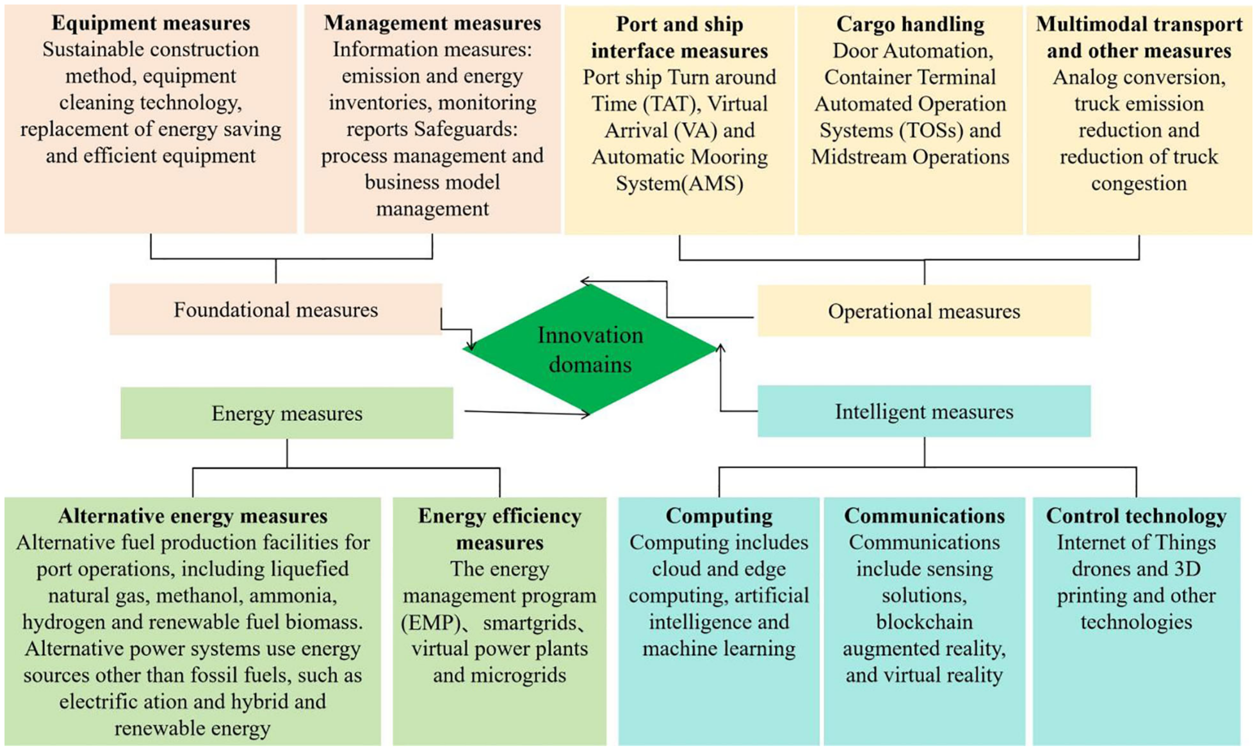

FIGURE 4
Port green innovation domains.

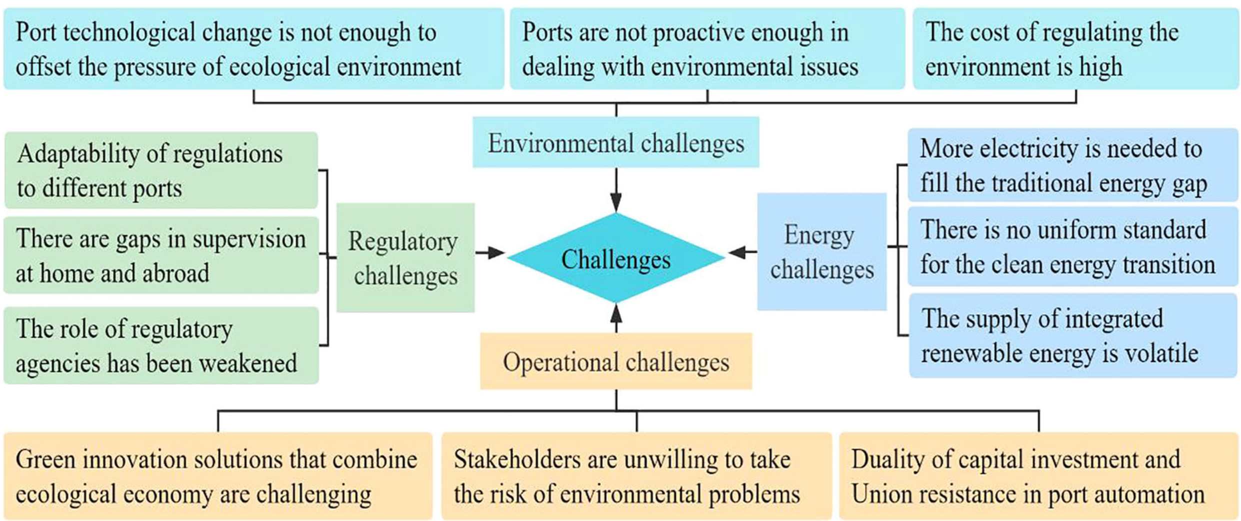

FIGURE 5
Port green innovation challenges.

societal expectations, and multilevel policy interventions. The reviewed literature consistently underscores the critical role of environmental standards, institutional design, and compliance mechanisms in accelerating the port sector's transition toward low-carbon, sustainable development.

3.1.3 Factors in the social domains provide transformative direction for green innovation in ports

This study explores the role of social dynamics in steering green innovation in ports. Green innovation in ports is not only driven by the technological and institutional dimensions, but also strongly influenced by behavioral and cognitive shifts in the social domain. The behavioral transformation of diverse stakeholders, including governments, businesses, and communities, is a prerequisite for achieving green innovation (Tseng and Pilcher, 2019), as they can actively participate in the innovation process by providing knowledge, resources, and institutional support (Turnheim and Geels, 2019). Only innovative strategies that fit the institutional environment of the port and meet the diverse needs of the participants can be effective in practice (Acciaro et al., 2014a). Shaping a green image for the port plays a significant role in enhancing community acceptance (Casini, 2017), which helps to strengthen the implementation basis and social legitimacy of green policies (Bergqvist and Egels-Zandén, 2012). Simultaneously, fostering a green-oriented organizational culture (Jaafar et al., 2021) and establishing effective intermediary institutions (Bjerkan et al., 2021) can facilitate knowledge flow and coordination of interests, providing stable support for green innovation in ports.

Regional cooperation and standardization mechanisms further amplify the effect of social collaboration. Under the European Union (EU) framework, ports have formed cross-regional innovative services in areas such as ship navigation, electronic freight, mobility, and sustainable growth (Pagano et al., 2022). The Port of Amsterdam, for example, has built a multi-layered green collaboration system through integrated logistics infrastructure and services, input-output linkage, industrial symbiosis, and other mechanisms (de Langen et al., 2020). Port integration strategies have been viewed as institutional tools to break free from homogenized competition and promote green transformation (Ma et al., 2025). Importantly, the concept of "responsible innovation" necessitates ports to evaluate the actual impacts of technology deployment on stakeholders, and to improve their awareness of and responsiveness to potential environmental risks (Heij and Knapp, 2012; Yan and Ravesteijn, 2019). Ports have thus been able to transform themselves from traditional trade facilitators to system orchestrators for green innovation (Senarak, 2020), while the synergized networks of various stakeholders have alongside contributed to the sustainable green transformation of ports (Hessevik, 2021).

In summary, social factors function as a transformative catalyst by mobilizing stakeholder behavior, reshaping institutional norms, and fostering cooperative mechanisms. Compared to endogenous economic incentives and exogenous regulatory pressures, social drivers emphasize shared values, legitimacy, and participatory governance. Together, these dimensions create a socially embedded foundation for long-term, inclusive, and responsible green innovation in ports.

Figure 3 presents the main drivers of green innovation in ports, categorized into three domains: economic-technological, environmental-policy, and social. Economic-technological drivers reflect internal dynamics such as market transformation, technological progress, and innovation capacity. Environmental-policy drivers represent external pressures from regulations, environmental standards, and policy incentives. Social drivers emphasize the role of stakeholder behavior, organizational culture, and collaborative governance. These domains interact to form a comprehensive driving framework, combining endogenous momentum and exogenous forces to support sustainable port transformation.

3.2 What are the main domains of green innovation in ports?

Green innovation in ports manifests across multiple functional domains that together constitute a systemic transformation pathway. These domains are not isolated; rather, they reflect interlinked layers of operational, technological, institutional, and strategic change. This section classifies the main areas of port green innovation into four categories. First are foundational measures, which lay the groundwork through green equipment upgrades and institutional reforms. Second are operational measures, targeting the optimization of port logistics, ship-port interfaces, and cargo handling processes. Third are energy measures, which focus on the adoption of low-carbon fuels, energy efficiency improvements, and renewable energy integration. Lastly, intelligent measures emphasize the deployment of digital and smart technologies such as IoT, AI, and blockchain to enable data-driven environmental management. Each category embodies distinct mechanisms and tools yet collectively supports the overarching goal of ecological sustainability and resilience in port systems. The following subsections examine these domains in detail.

3.2.1 Foundational measures

Foundational measures constitute the infrastructural and institutional basis for green innovation in ports. This category centers on how environmental objectives are embedded into port planning, facility upgrades, and management frameworks. These foundational efforts are critical because they establish the physical and organizational preconditions for broader sustainability transitions. This subsection distinguishes two key dimensions of foundational measures based on the literature: the technological advancement of equipment and the refinement of institutional management. Together, these dimensions reflect how ports build long-term capacity for low-carbon, eco-efficient operations through both material and procedural innovation.

1. Equipment Measures: Integration of Green Technologies and Ecological Infrastructure.

Green innovation with respect to port equipment involves improving operational efficiency and environmental performance in an eco-friendly manner. For example, the adoption of sustainable construction techniques and eco-design concepts supports the development of green infrastructure (Pagano et al., 2022; Odum and Odum, 2003). Through collaboration with stakeholders, ports have promoted ship waste recycling (Karimpour et al., 2019), deployed liquefied natural gas (LNG) fueling systems (Wang and Notteboom, 2015), and introduced plasma gasification technology to convert carbon-based waste into clean syngas (Fadda et al., 2020). Innovative applications such as sediment environmental management (Pellegrini et al., 2020), noise reduction (Nastasi et al., 2020), and microbial barrier remediation systems (Cecchi et al., 2023) are replacing the traditional physico-chemical treatments to enhance ecological resilience and achieve pollution control. In addition, replacing old energy-consuming equipment with efficient and clean equipment also contribute to green technology upgrading in ports.

2. Management Measures: Emphasizing Information Transparency and Institutional Safeguards.

Port management measures include information disclosure mechanisms and institutional safeguard arrangements. The former mainly refers to the compilation of emissions inventories and energy registers, environmental monitoring, and annual reports, which enhance transparency and accountability in port operations. Energy inventories, in particular, cover direct and indirect carbon emissions within the port's control, and help to pinpoint energy efficiency management priorities (Di Vaio and Varriale, 2018). The latter includes process management and business model management. Process management involves the promotion of a green management system by the port through the application of a balanced scorecard and the digital management of interface operating processes (Del Giudice et al., 2021). Business model management includes the design of green port fee structures, the setting of green concession agreements (Bjerkan et al., 2021), business model innovations for green fuels (e.g., liquefied biogas) (Philipp, 2020), and an environmental performance-oriented port tax system (Hasanspahic et al., 2021). All of these together reflect the institutional progression of green innovation.

The reviewed literature shows that foundational measures address both the technological and institutional dimensions of port systems. Technological improvements in equipment contribute directly to environmental performance, while institutional arrangements such as information disclosure, incentive structures, and digital management enhance governance capacity. These two aspects are closely interlinked and mutually reinforcing. Foundational measures not only establish the basic conditions for implementing green innovation but also create a scalable platform that supports the development of more advanced and integrated sustainability practices across other domains.

3.2.2 Operational measures

Operational measures represent a core dimension of green innovation in ports by embedding environmental considerations into the day-to-day processes of cargo flow, vessel coordination, and hinterland logistics. This subsection categorizes operational innovation into three interconnected areas: ship-port interface optimization, automation of cargo handling, and the transformation of multimodal transport systems. Together, these measures reflect how technological advancement and intelligent coordination reshape traditional port operations toward lower emissions and higher efficiency.

1. Ship-port interface optimization: Improving efficiency and reducing idle emissions:

By optimizing berthing schedules and berth resource allocation, ports can effectively shorten ship turnaround time (TAT) and reduce energy consumption and emissions during idle periods (Kontovas and Psaraftis, 2011). Virtual Arrival (VA) systems dynamically adjust berthing times based on real-time shipping data, which can improve ship punctuality and save about 12-20% of energy (Gibbs et al., 2014). Automated mooring systems (AMS) allow ships to complete berthing without ropes, significantly reducing TAT and pollution emissions, and have been estimated to reduce carbon emissions from berthing by 97% (Ortega Piris et al., 2018; Tichavska et al., 2019). In addition, innovations in inland-port to seaport container systems have improved logistics efficiency and space utilization (Zhao et al., 2024).

2. Automation of Cargo Handling: System Upgrades and Smart Scheduling:

Cargo handling is a major source of carbon emissions in ports, and automation and intelligent technologies have become mainstream solutions for emission reduction in this process. Technologies such as smart gates and terminal operating systems (TOS) have been widely deployed to improve operational efficiency and reduce unnecessary transport (Gelareh et al., 2013; Lee et al., 2015; Hervás-Peralta et al., 2019). The use of autonomous surface vessels (Zheng et al., 2017) and mid-stream operations has further reduced pressure on berthing resources. In terms of crane operation scheduling, studies have proposed mixed-integer programming models considering carbon regulation (Kenan et al., 2022), multi-objective optimization approaches (Kanellos, 2019), and bi-objective location-resource allocation models (Wei and Sheng, 2017) to minimize emissions while maintaining throughput efficiency.

3. Green Multimodal Transport: Advancing Alternative Modes and Traffic Regulation in Parallel:

Optimizing the multimodal transport structure in the port hinterland is key to reducing overall transport emissions. Shifting cargo by rail, barges, or short-sea shipping provides both economic and environmental benefits compared to road transport (IMO, 2018; Mamatok and Jin, 2017). Ports can support this green transition by investing in multimodal transport enterprises and optimizing lease agreements (Kotowska, 2016). The promotion of electric trucks (Kanellos, 2017) and the establishment of policies for clean truck mandates (Clott and Hartman, 2013) are also important. To mitigate carbon emissions caused by port traffic congestion, ports have also deployed digital traffic management tools such as truck reservation systems, smart gates, and permit mechanisms (Hall et al., 2013; Accenture and SIPG, 2016).

In summary, operational measures have brought tangible progress in lowering emissions and enhancing efficiency within port logistics systems. Each component, including ship-port coordination, intelligent cargo handling, and modal shift in hinterland transport, addresses specific operational challenges while contributing to a shared objective of sustainable transformation. These initiatives collectively improve resource utilization, support environmental performance, and enable ports to respond more effectively to dynamic demands across global supply chains.

3.2.3 Energy measures

This subsection focuses on the energy dimension of green innovation in ports, which is fundamental to reducing emissions, enhancing efficiency, and achieving low-carbon transformation. The reviewed literature identifies four primary pathways in this domain: deployment of alternative fuels, development of green electricity systems, implementation of energy management mechanisms, and integration of intelligent energy infrastructure. These pathways reflect a coordinated shift toward cleaner, smarter, and more resilient energy structures in ports. The following analysis outlines key approaches, technologies, and institutional arrangements contributing to the evolution of port energy systems. The goal is to enable a cleaner and smarter transformation of the port energy system through emission reduction, efficiency improvements, and system coordination (Acciaro et al., 2014b; Styhre et al., 2017).

1. Alternative Fuel Systems: Low-Carbon Energy Deployment and Substitution:

Alternative fuels herald a port's green transition, and are introduced chiefly by constructing relevant infrastructure to provide clean fuels such as liquefied natural gas (LNG), methanol, ammonia, hydrogen, and biomass for operational equipment and berthed vessels. Studies have shown LNG to be about 10% more energy efficient per kilometer, and lead to about 25% lower CO_2 emissions than conventional fuels (Yun et al., 2018). Methanol possesses a lower risk of methane leakage under low load operation (Asia-Pacific Economic Cooperation (APEC), 2014), and hydrogen and ammonia are emerging as potential alternatives for ship fuels (Bicer and Dincer, 2017). Despite supply constraints (Winnes et al., 2015), biofuels can be an important complement during the energy transition phase (Metzger, 2021). In addition, Organic Rankine Cycle (ORC) technology has been used to build renewable shore power systems to enhance energy recovery efficiency (Aksoy and Durmusoglu, 2020).

2. Green Electricity Systems: Coordinated Electrification and Hybrid Energy Adoption:

Alternative power systems enhance the cleanliness of port operating segments by reducing dependence on fossil fuels. Electrification of shore power, rail-mounted cranes, and ship-to-shore cranes have significantly reduced emissions during berthing (Alasali et al., 2018). Renewable energy sources including wind (Ramos Velasco et al., 2022), solar (Hanssen et al., 2014), marine energy (Saether et al., 2021), and geothermal energy (de Langen et al., 2020) are becoming increasingly popular in ports. In terms of mobile equipment, rechargeable battery systems are being adopted for container handling equipment (CHE) (Dhupia et al., 2011), and port vehicles are widely used in a variety of hybrid forms, such as fuel-electric, diesel-hydraulic, and plug-in electric hybrid (CARB/EPA, 2015). This combination of technologies enhances the low-carbon resilience of the port's energy mix.

3. Energy Management and Optimization: System Control and Key Performance Indicator (KPI) Integration:

Port energy management programs (EMPs) improve overall energy efficiency performance by monitoring and coordinating energy flows. Typical practices include the integration of electricity consumption data into KPI systems for port operations, achieving joint optimization of energy use, and logistics efficiency (Acciaro et al., 2014b; Di Vaio and Varriale, 2018). Energy storage systems are effective in balancing electrical loads during peak periods of equipment operation, such as recovering electrical energy during CHE lifting operations (Antonelli et al., 2017). Smart grids, on the other hand, effectively mitigate supply and demand fluctuations by fine-tuning grid stability through sensors and information systems (Yigit et al., 2016; Kanellos, 2017).

4. Smart energy systems: Virtual power plants (VPPs) and microgrid integration mechanisms:

In the field of smart energy systems, VPPs achieve intelligent optimization of energy generation and dispatch by integrating distributed energy resources and storage units, thus improving system flexibility and security. Microgrids, on the other hand, build small-scale energy systems that can operate independently or are grid-connected, increasing renewable energy penetration and energy autonomy (Roy et al., 2020). Based on this, a distributed demand response (DR) strategy that integrates renewable generation, flexible loads and intelligent dispatch mechanisms can transform ports into multi-energy complementary energy nodes (Kanellos, 2017).

In summary, energy-related innovation measures demonstrate a transition from isolated fuel substitution efforts toward comprehensive energy system redesign. The integration of renewable energy, digital control systems, and decentralized infrastructures has enabled ports to enhance energy flexibility and environmental performance. Despite differences in technological maturity and regional implementation, these innovations collectively support the strategic positioning of ports as hubs of low-carbon transformation. The convergence of alternative energy sources and intelligent energy management forms a critical pillar of the green port agenda.

3.2.4 Intelligent measures

This subsection explores intelligent measures as a core domain of green port innovation, focusing on the role of next-generation information technologies in enabling environmental responsiveness and operational efficiency. Smart ports are composed of three key technology modules (Alamoush et al., 2020), namely computation, communication, and control (Min, 2022), which support the enhancement of their operational intelligence, environment sensing capabilities and resource optimization efficiency (Xiao et al., 2021). The following analysis outlines key advancements and their relevance to sustainable port development.

1. Computational technology: Building core capabilities for intelligent decision-making:

The computing module mainly includes cloud computing, edge computing, artificial intelligence (AI), and machine learning systems. Cloud platforms can provide low-cost and highly scalable remote data processing capabilities for port management (Wang et al., 2010), while edge computing reduces latency and energy consumption by processing close to the data source, and improves the efficiency of port response to dynamic events (Min, 2022). In data-intensive port operations, the PIXEL project provides massive data processing and analysis capabilities for different types of ports (Pita Costa et al., 2021). AI algorithms and machine learning have been widely used in scenarios such as maritime traffic risk analysis, ship route optimization, weather forecasting and emission prediction, significantly improving the environmental adaptability and decision-making intelligence of port operations (Wang et al., 2021; Zhang et al., 2024). Ports such as Singapore and Rotterdam have pioneered AI-based data-driven scheduling systems (Parolas, 2016; de la Peña Zarzuelo et al., 2020).

2. Communications technologies: Building an infrastructure network for data sharing and real-time collaboration:

The communication module relies on technologies such as sensor systems, blockchain, and augmented reality. Sensors are embedded in Global Positioning System (GPS), near-field communication, and shore-based monitoring networks to accurately capture ship, cargo, and environmental status data (Zhang et al., 2020). Blockchain serves as an information sharing and tamper-proof platform for smart documents, vehicle scheduling, and safety monitoring (Wang et al., 2021). The integrated "Digital Twin + Blockchain" model has shown potential in reducing costs of maritime documentation management and enhancing transparency. In port traffic management, combining blockchain with vehicle-to-everything technologies has been shown to increase vehicle throughput by 70% and reduce carbon emissions by 57.74 kg/hour (González-Cancelas et al., 2025). Communication technologies provide key support for green collaboration and multi-party data integration.

3. Control technologies: Achieving intelligent execution for green operations and environmental response:

Control technologies mainly include Internet of Things (IoT), unmanned systems, and autonomous control devices. IoT is widely used in scenarios such as electronic seals and smart meter reading to achieve real-time monitoring and dynamic scheduling of resource usage (Siror et al., 2011). Surface Unmanned Aerial Vehicles (UAVs) and remotely piloted vehicle systems are used for monitoring marine pollution, picking up floating garbage, and conducting safety inspections in harbor areas (Sun et al., 2025; Min, 2022), with mature applications already in place in ports such as Mawan in China (Wang et al., 2021). Automated Guided Vehicles (AGVs) with multi-objective path planning models can significantly optimize scheduling efficiency at container terminals (Tsolakis et al., 2022). In addition, the application of 3D metal printing in ship equipment maintenance also opens up a new path for circular economy, and green operation and maintenance.

In summary, smart measures provide strong infrastructure support for green transformation of ports through data-driven operations, system coordination, and process automation. This not only improves operational efficiency, but also builds a new paradigm of intelligent green port through energy efficiency management and pollution monitoring.

In sum, intelligent measures embed digital intelligence into port systems by integrating computational, communicative, and control technologies. These innovations support green transformation through enhanced environmental sensing, predictive analytics, and automated execution. Despite differences in technological maturity and application scale, all reviewed approaches contribute to a common trajectory: the development of smart, efficient, and low-emission port ecosystems. The synergy among digital tools forms the backbone of intelligent green ports and unlocks new opportunities for data-driven sustainability governance.

Figure 4 illustrates the four main domains through which ports advance green transformation: foundational, operational, energy, and intelligent measures. Each domain corresponds to a distinct pathway—ranging from infrastructure upgrades and management reforms to clean energy systems and digital technologies. Together, they form an integrated framework that supports low-carbon operations, enhances resource efficiency, and enables smart environmental governance across port systems.

3.3 What are the present and future challenges?

Amid growing momentum for green innovation, ports face a complex landscape of implementation challenges that go beyond technical feasibility. This subsection systematically synthesizes key difficulties encountered in the transition toward sustainable port systems. Drawing on the reviewed literature, four major dimensions of challenge are identified: environmental, energy-related, regulatory, and operational. These dimensions reflect both external constraints and internal tensions across port systems. Environmental pressures persist despite technological progress, often compounded by regulatory uncertainty and institutional inertia. At the energy level, the port's evolving role from passive consumer to active energy hub introduces infrastructural, financial, and coordination challenges. Regulatory fragmentation and institutional misalignment between international frameworks and national practices further hinder coherent governance of green port agendas. At the operational front, the pursuit of ecological, economic, and technological goals frequently leads to trade-offs and coordination failures. Together, these interlinked challenges underscore the need for integrated strategies, risk-sharing mechanisms, and stakeholder-inclusive governance. The following subsections elaborate on each challenge category in detail to provide a more nuanced understanding of the barriers that constrain the realization of green innovation in ports.

3.3.1 Environmental challenges: the twin dilemma of ecological pressures and institutional imbalances

Environmental challenges constitute a persistent and systemic barrier to green innovation in ports. As maritime activities expand, the ecological burden and regulatory complexity associated with emissions, waste, and ecosystem disruption continue to intensify. This subsection focuses on the dual pressures posed by environmental degradation and institutional imbalance. It explores how technological progress alone remains insufficient when confronted with the cumulative impacts of ecological stressors and the uneven enforcement of environmental policies. In particular, it emphasizes the need for deeper institutional integration and alternative development models to support the ecological transition of ports.

Despite the continued advancement of green technologies in ports, difficulties in offsetting the environmental loads associated with the growth of maritime transportation persist (Nogué-Algueró, 2020). Emissions, pollution, and ecological disturbances continue to accumulate, placing higher demands on ports for environmental management. In parallel, environmental regulation is often accompanied by high compliance costs, which can erode profits, especially for small and medium-sized ports. Additionally, fuel price volatility exacerbates the uncertainty of alternative energy investments, and the experimental and dynamic adjustments of the regulatory mechanisms make implementation challenging for ports and the relevant stakeholders to coordinate (Olaniyi et al., 2018).

In this context, the concept of "blue degrowth" has been proposed as a responsive counter-paradigm that advocates the mitigation of systemic shocks to ecosystems from the expansion of global maritime transport through the localization of regional production and sustainable cooperation between port systems (Nogué-Algueró, 2020). This reflection emphasizes that environmental challenges are not only technical, but also involve economic incentives, institutional harmonization and a fundamental transformation of port development models. Without adequate institutional support, green innovation in ports is unlikely to meet the complex demands of ecological transition.

In summary, the environmental dimension of port innovation reveals a paradox where technological advancements fail to fully alleviate ecological stress, largely due to institutional gaps and regulatory complexity. High compliance costs, market uncertainties, and fragmented governance undermine the scalability of green technologies. The "blue degrowth" perspective highlights the need to move beyond techno-centric approaches, calling instead for structural realignment in economic incentives, regulatory coordination, and port development models. Addressing environmental challenges thus requires a comprehensive framework that integrates ecological integrity with institutional coherence.

3.3.2 Energy challenges: structural shift from transit node to energy mainstay

Energy-related challenges represent a critical frontier in the transition toward green ports. As ports move from passive energy users to active energy coordinators, the complexity of their role within the energy system has grown substantially. This subsection identifies the structural tensions in port electrification, fuel substitution, and energy system integration. It categorizes the core constraints related to infrastructure readiness, technological volatility, and governance gaps, aiming to reveal why energy transformation in ports remains difficult despite policy ambition and technical progress.

Traditionally, ports have functioned merely as transit nodes within the energy chain, with energy practices confined largely to meeting direct operational needs (Acciaro et al., 2014b). However, the electrification of green ports has significantly increased their energy consumption, requiring a shift from their being passive recipients to active coordinators. Against the backdrop of an increasingly complex energy system, there is a critical need for ports to develop long-term transition agendas to address facility modifications, power demand expansion, and system stability issues (Hanssen et al., 2014).

The diffusion of LNG, for example, is limited by insufficient infrastructure, lack of uniform operating standards, high capital investment, and unclear risk-sharing mechanisms (Brynolf et al., 2014). Shipowners, fueling service providers, and investors are often trapped in a "strategic deadlock", each waiting for others to take the lead in bearing transformation costs (Wang and Notteboom, 2015). Concurrently, systemic integration of renewable energy sources faces challenges such as low inertia, high volatility, and unclear management of load diversity and policy incentives, all of which may undermine the operational stability and investment attractiveness of port energy systems (Roy et al., 2020).

In conclusion, energy challenges underscore a structural transformation in the port's functional role, from a logistical hub to an energy-integrated platform. The stagnation in alternative fuel diffusion and renewable energy integration reflects not only technological immaturity but also institutional inertia and fragmented coordination across stakeholders. Without robust governance frameworks to align incentives, distribute risks, and stabilize systems, the realization of energy-smart green ports will remain limited. Bridging this gap requires synchronized technological, infrastructural, and institutional innovation.

3.3.3 Regulatory challenges: multilayered institutional fragmentation and governance failures

Regulatory frameworks form the institutional backbone of green port transitions. However, the implementation of environmental innovation is often hindered by fragmented governance structures, inconsistent policy instruments, and overlapping jurisdictions. This subsection critically examines the challenges arising from multi-level regulatory complexity, highlighting how the absence of unified legal mandates and limited global enforcement capabilities restrict ports' ability to adopt consistent and coordinated green strategies.

Green innovation in ports is highly dependent on effective institutional safeguards, but current maritime governance presents a complex pattern of multi-jurisdictional, multi-level, and multi-centered governance, leading to significant differences in the regulatory systems followed by ports (Lister, 2015). In the absence of comprehensive national legislations, ports are often compelled to develop their own incentive mechanisms based on international norms to facilitate the transition towards renewable energy systems (Acciaro et al., 2014b). Regulatory updates at the international level, such as the shore power program and emissions reduction initiatives promoted by the International Maritime

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Organization (IMO), while providing a framework to support the construction of green ports, also constitute one of the main institutional challenges at present (Wan et al., 2025).

However, at the global level, the enforcement and harmonization of the maritime regulatory system remains inadequate. For example, since 2004, the Ballast Water Management Convention has long failed to reach the threshold for ratification, reflecting delays and inaction in institutional alignment among states. It has been challenging to achieve substantial consensus between the IMO and governments on key topics such as Greenhouse Gases (GHG) governance, division of roles, attribution of responsibilities, and basic principles (Hackmann, 2012), and even when reached, the consensus tends to be significantly watered down at the implementation level (Lister, 2015).

To summarize, regulatory fragmentation reflects both structural and procedural deficiencies in global maritime governance. While international institutions such as the IMO provide normative guidance, their limited enforcement power and weak alignment with national policies undermine operational consistency and stakeholder commitment. The persistence of legal gaps, diverging port-level incentives, and diluted international consensus continues to constrain the institutional environment necessary for green innovation. Strengthening vertical and horizontal regulatory integration remains essential for advancing a coherent and enforceable green port agenda.

3.3.4 Operational challenges: structural contradictions in efficiency, technology and harmonization of interests

Operational challenges represent one of the most intricate barriers in port green transitions, as they involve reconciling environmental ambitions with efficiency, technological feasibility, and stakeholder acceptance. This subsection focuses on the tensions emerging at the operational level, including trade-offs between ecological goals and logistics performance, the under-realization of digitalization potential, and conflicts stemming from automation-related disruptions. It analyzes how these interlocking issues shape the feasibility of green innovation initiatives within complex port systems.

Green innovation programs that balance ecological performance with economic benefits are particularly challenging to implement in the green transition phase (Hasanspahic et al., 2021). For example, while ships sailing at reduced speeds have high emission reduction potential, the resultant reduction in transportation time efficiency will impact their economic competitiveness (Cheaitou and Cariou, 2019; Metzger, 2021). Lack of awareness among port stakeholders of the link between their behavior and environmental performance, and the general unwillingness to take risks on environmental sustainability issues have led to frequent resistance and failure of green projects in the absence of effective risk management mechanisms (Di Vaio and Varriale, 2018; Mathuthu et al., 2017).

Although most ports have embraced digitalization as a core strategy for green innovation, its technological potential is yet to be fully realized (Del Giudice et al., 2021). The construction of smart ports requires heavy investment, while dealing with operational bottlenecks like container storage saturation and traffic congestion in port areas (Antunes et al., 2024). It is thus essential to foster multi-dimensional coordination to simultaneously achieve the objectives of efficiency, safety, and sustainability. This requires the deep integration of digital technologies throughout port systems to enable intelligent, integrated operations and maintenance (Attanasio et al., 2025).

Lastly, while port automation can help improve operational efficiency and resource mobilization, it can also lead to social challenges such as job losses, capital-intensive investments, and resistance from labor organizations, making it a "double-edged sword of technology" in the green transition process (Tsolakis et al., 2022). Therefore, green innovation at the operational level is in urgent need of the establishment of systemic balancing mechanisms that reconcile technological advancement, cost-effectiveness, and stakeholder interests.

In sum, operational challenges lie at the intersection of efficiency constraints, technological limitations, and stakeholder misalignment. While digitalization and automation offer significant potential for greener port operations, their successful implementation is hindered by financial, organizational, and social frictions. The absence of integrated risk-sharing, adaptive governance, and participatory mechanisms undermines the transformative capacity of green innovation. Overcoming these obstacles requires a systemic approach that balances innovation-driven upgrades with institutional support and stakeholder consensus.

Figure 5 presents a synthesized framework of the core challenges confronting green innovation in ports across four interconnected dimensions: environmental, energy, regulatory, and operational. Environmental challenges stem from the persistent gap between ecological pressures and institutional capacity. Energy challenges reflect the shift from traditional consumption roles to system-wide coordination. Regulatory challenges are characterized by fragmented multi-level governance and institutional misalignment. Operational challenges involve trade-offs between efficiency, technological deployment, and stakeholder interests. Collectively, these challenges illustrate the systemic complexity and multi-scalar nature of transitioning ports toward green innovation pathways.

4 Conclusions

In order to systematically identify the key mechanisms by which green innovation in ports may be achieved, and the obstacles in its path, this study followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines to screen 67 academic publications, and categorized their content into three dimensions: driving forces, innovation domains, and types of challenges. The findings indicate that green innovation in ports is driven by three types of factors: economic and technological, environmental policy pressure, and shifts in social cognition. Innovation practices are mainly concentrated in four major domains: infrastructure, operational systems, energy pathways, and smart technologies. Despite considerable progress, green innovation still faces multiple challenges such as persistent environmental pressures, slow transformation of the energy system, imbalanced regulatory synergies, and complex operational coordination. Given the multi-stakeholder nature of port systems, the green transformation requires enhanced synergy and risk-sharing.

This study offers concrete guidance for advancing green innovation in ports. First, port authorities should integrate digital platforms with electrified cargo handling and shore power systems to optimize energy use and reduce emissions. Second, scalable infrastructure such as virtual power plants, microgrids, and autonomous logistics should be promoted to enhance flexibility and efficiency. Third, institutional mechanisms should be improved by establishing standardized green assessment criteria, introducing incentive-compatible concession agreements, and enhancing international regulatory alignment. Policymakers should support clean fuel infrastructure including hydrogen, ammonia, and LNG through targeted subsidies and tax incentives while leveraging blended finance to reduce investment risks. Multi-stakeholder coordination platforms are essential to overcome strategic inertia among ports, fuel suppliers, and shipowners. Finally, automation should be accompanied by workforce retraining and inclusive transition strategies to mitigate social risks. These recommendations provide an actionable pathway for building intelligent, low-carbon, and resilient ports.

There are some limitations to this study. Despite the standardized literature screening system, green innovation in ports covers a wide range of domains and there may be keyword omissions. In addition, this paper focuses primarily on applied literature on green technologies, which has not yet been systematically incorporated into patent databases or technical standards analyses. Future research could deepen the understanding of green innovation mechanisms and performance by integrating multi-source data and adopting mixed-method approaches.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft. YC: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft. SX: Data curation, Formal Analysis, Writing – original draft. GW: Conceptualization, Data curation, Formal Analysis, Methodology, Writing – original draft. LW: Conceptualization, Formal Analysis, Visualization, Writing – original draft. CX: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Project administration, Writing – original draft.

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Conflict of interest

Author GW was employed by the company Zhoushan Xiao'ao Maritime Service Base Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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