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A Thematic Review of Port Services and Emission Reduction Strategies Using ATLAS.ti

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ABSTRACT: The maritime industry plays a dual role as a critical driver of global trade and a significant contributor to greenhouse gas (GHG) and air pollutant emissions, posing challenges to environmental sustainability. As key nodes in the global supply chain, ports face mounting pressure to adopt greener practices. This study synthesises insights from contemporary scientific research articles, highlighting best practices, successful case studies, and obstacles in implementing emission reduction strategies and environmentally friendly port services worldwide.
A two-step mixed-methods approach was utilised, combining a systematic review of literature with qualitative data analysis. The PRISMA methodology guided the selection of 27 peer-reviewed articles from the Web of Science Core Collection, spanning the period from 2015 to 2024. Subsequently, thematic coding and comprehensive analysis were conducted using Computer-Assisted Qualitative Data Analysis Software (CAQDAS) ATLAS.ti, enabling a structured synthesis of findings related to port services and emission reduction strategies.
Through this analysis, three critical themes emerged as essential for enhancing environmental sustainability in port operations: innovative technologies for emission reduction, data-driven optimization for port efficiency, and policies and governance for green ports. Drivers such as financial incentives, advanced technologies, and regulatory frameworks were identified, alongside barriers like economic feasibility, technical challenges, and organisational resistance. These themes reveal the interconnected nature of sustainability efforts and the need for collaborative strategies to overcome existing obstacles.
By identifying key drivers and challenges, this research offers valuable insights for advancing sustainable practices in port operations. The findings underscore the importance of aligning technological, operational, and policy-driven measures to foster environmental efficiency while mitigating emissions.
This study contributes to the growing body of knowledge on sustainable port operations, providing actionable insights for stakeholders and policymakers in the maritime industry to support the transition toward greener and more efficient port practices.

1 INTRODUCTION

The maritime transportation sector is one of the leading contributors to greenhouse gas (GHG) emissions and air pollution, accounting for approximately 3% of global GHG emissions annually [48]. Ports, as key hubs in the maritime supply chain, are significant sources of air pollution due to activities such as ship manoeuvring, cargo handling, and road transport within port areas.

Reducing carbon emissions is a fundamental goal for the transition towards more sustainable human societies, and it is reflected in official goals and political strategies of supranational authorities and intergovernmental bodies at the global level [9]. Given this context, it is necessary to consider the various strategies and initiatives aimed at mitigating the environmental impact of port activities. In present times, reducing emissions in port areas is a fundamental goal for the global maritime industry and policy agendas, driven by international frameworks like the International Maritime Organization (IMO)'s Initial Strategy on the Reduction of GHG Emissions from Ships [17], and regional initiatives such as the European Union's Green Deal [11]. In addition, initiatives like the EU Emission Trading System [10] and national-level subsidies for green port technologies such as environmental incentive and infrastructure subsidy [42] laid the groundwork for more comprehensive environmental management frameworks. These efforts are particularly critical for improving air quality in coastal urban areas and mitigating climate change impacts.

In this broader context, energy-related issues have acquired increasing centrality in the current agenda of sustainable port development and decarbonisation strategies [6]. Ports are increasingly focusing on energy transition measures such as renewable energy integration, energy-efficient technologies, and alternative fuels like liquefied natural gas (LNG) and hydrogen [41].

The concept of green ports has also been underlined as crucial to explain how ports can simultaneously reduce their environmental footprint and enhance operational efficiency and is particularly interesting in the domain of sustainability and governance.

Port administrations are an important player in this transition, as they are responsible for implementing emission control measures, such as onshore power supply (OPS) systems and cold ironing infrastructure, alongside regulatory compliance and operational improvements. The Intergovernmental Panel on Climate Change (IPCC) [18] and the World Port Climate Initiative (WPCI) [51] provide essential frameworks and guidelines for quantifying greenhouse gas (GHG) emissions in port operations. These standards enable ports to measure and monitor their environmental impact accurately, setting the foundation for effective emission reduction strategies [29]. Besides the frameworks, there are also technological intervention, such as Port of Valencia, where the implementation of renewable energy strategies reduced emissions by 17% [4]. Moreover, emission inventories have revealed that pollutants such as NOx, SOx, and PM10 significantly impact air quality in port cities [23]. In addition, ship operators play a critical role by adopting emission reduction technologies such as LNG-powered engines and exhaust gas cleaning systems.

In order to accelerate the transition towards greener ports, it is crucial to identify the key drivers of emission reduction strategies, such as policy incentives, collaborative frameworks, and technological advancements.

Numerous studies have highlighted efforts to integrate sustainable practices and green technologies into port operations. There are few research studies that discuss emission reduction measures in seaports from various perspectives: technological aspects onboard vessels and within land area [5], policy and management perspectives [2], various emission reduction measures in ports [50], and presentation of various models of implementation of solutions towards zero emissions [41].

However, the implementation of these initiatives remains at varying stages of development across different ports. This disparity underscores the need for more in-depth research to identify the challenges faced and the solutions adopted by the most advanced ports, offering valuable insights for accelerating sustainability in the sector.

This study is based on a critical literature analysis with the support of computer assisted qualitative data analysis software (CAQDAS) of recent scientific articles on port emissions and sustainability port services. Throughout the research, the authors focus on the main research question: What are the key drivers and challenges in enhancing environmental efficiency and implementing emission reduction strategies in port operations? Addressing this question involves investigating best practices, successful case studies, and obstacles in implementing various emission reduction strategies across global ports, encompassing technological, operational, and policy-driven measures.

The sections of the article are structured as follows: research methodology including the sampling strategy and qualitative data analysis method, research findings on the key drivers and challenges in achieving environmental efficiency in ports, and finally, discussion and conclusions presented along with limitations and further research.

2 RESEARCH METHODOLOGY

Aiming to investigate the key drivers and barriers to implementing various emission reduction strategies across global ports, the authors used a mixed-methods research design: A systematic selection of articles combined with qualitative data analysis CAQDAS. This approach ensures a structured synthesis of the articles while enabling to highlight insights across emission monitoring, sustainability policies, technological innovations, and port performance metrics.

2.1 *Data collection*

The data collection process involved a systematic selection of articles focusing on emission reduction strategies, operational solutions, technological innovations, and policy frameworks in port service operations. Articles were selected using the PRISMA 2020 methodology [15]. The initial search formula presented in Table 1 was used to select the articles based on their direct relevance to the research question, ensuring that the studies are aligned with the focus on enhancing environmental efficiency and sustainability in port operations. The next step was dedicated to timeframe selection. Only articles published within the last decade were included to ensure the use of recent and relevant data reflecting current practices and innovations in the port services operations and environmental sustainability. A further refinement of the selected publications was carried out to ensure the selection of peer-reviewed articles, appropriate for the qualitative analysis. The filtering process adhered to a systematic approach, narrowing the dataset to the open access studies. Finally, a title and abstract screening was conducted to exclude studies that did not perfectly align with the core research themes.

Table 1. Systematic refinement of the publications

Parameter	Content	Count
The initial search formula	TS = (("ship*" OR "vessel*") AND "emission*" AND ("port strategy" OR "port service" OR "port technology" OR "port monitoring" OR "port reducing" OR "Green port"))	97
Time frame selection	To focus on contemporary research, only publications from the last 10 years were retained. This step reduced the dataset by excluding 7 older studies.	90
Document type selection	Only articles and review articles were included in the analysis, further refining the dataset to 78 publications	78
Open Access	To ensure accessibility and transparency, open access publications were prioritised for detailed analysis.	28
Relevance Assessment	As a result of reviewing the abstracts, 27 publications were deemed highly relevant for qualitative analysis.	27

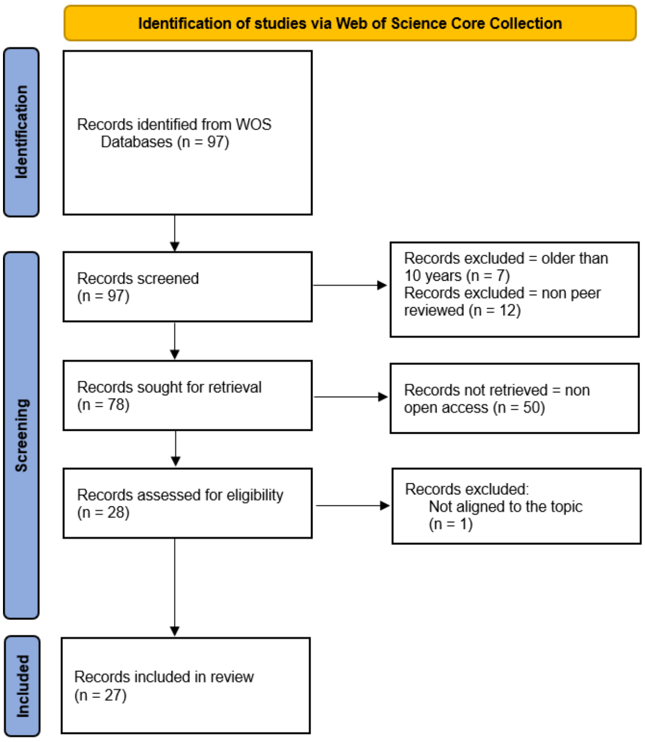

Figure 1. PRISMA flow diagram for systematic reviews

The 27 relevant publications were then subjected to an in-depth qualitative analysis using the Computer-Assisted Qualitative Data Analysis Software (CAQDAS) tool, ATLAS.ti v.25. This step enabled a deeper exploration of the key themes, drivers, and challenges in the field, laying the groundwork for a comprehensive understanding of sustainable practices in port emissions management. The qualitative analysis phase provided nuanced insights that complemented the bibliometric findings, bridging the gap between quantitative trends and detailed content interpretation.

Authors used ATLAS.ti v.25, to systematically organise, code, and analyse data extracted from the selected scientific articles on emission reduction strategies in ports. Like any other CAQDAS program, ATLAS.ti, does not actually analyse data; it is simply a tool for supporting the process of qualitative data analysis [13]. The authors chose ATLAS.ti for its robust capabilities in handling complex qualitative datasets, enabling the identification of themes, relationships, and patterns across diverse sources. The software facilitates a transparent and replicable coding process, which is essential for ensuring the reliability and validity of the analysis. Its advanced features allow for a comprehensive exploration of connections between codes, offering insights into the key drivers, challenges, and opportunities for enhancing environmental efficiency in port operations. Rather than taking control away from the researcher, ATLAS.ti enables authors to solve a range of methodological challenges, such as working with large data-sets and supporting deeper levels of analysis than is possible by hand [33]. In addition, the software provides the "ability to express relationships between codes, concepts, and themes in a range of different ways, and often these cannot be represented in a hierarchical list" [40].

2.2 *Data preparation*

The data included in the preparation process to be analysed in this study consists of the titles, abstracts, and key sections from 27 peer-reviewed articles selected during the bibliometric and systematic literature review phase. The selected articles were imported into ATLAS.ti v25. Each document was pre-processed to ensure clarity and uniformity, with metadata such as publication year, authors, and themes recorded for contextual reference. The text was cleaned to remove irrelevant content to focus solely on the research objectives.

A hybrid coding approach was adopted, combining deductive, inductive techniques and Artificial Intelligence suggestions. For deductive coding the authors developed a set of predefined codes based on the research objectives: "Emission reduction strategies", "Data-driven solutions", " Energy efficiency technologies", and "Policy". Additional codes, inductive, were generated during the analysis as new themes emerged from the data, ensuring flexibility in capturing unexpected insights. The features of ATLAS.ti were utilised, with AI-assisted code generation employed and subsequently reviewed and filtered by the authors.

Each article was systematically reviewed to identify text segments relevant to the research questions. These segments were highlighted and coded using ATLAS.ti. Codes were organised into families to represent broader categories or themes, such as "Technological drivers" or "Policy challenges." The relationships between codes were explored using the network mapping tool, enabling a deeper understanding of how different factors interact to influence emission reduction efforts.

2.3 *Analysis and interpretation*

Thematic analysis was conducted to identify recurring themes and patterns across the articles. Queries were run in ATLAS.ti to explore co-occurrence of codes and to highlight areas of convergence and divergence among the studies. For instance, the co-occurrence of "Policy frameworks" and "Technological innovations" was examined to understand how regulations drive the adoption of green technologies. The NCT method: Noticing, Collecting, and Thinking, proposed by Friese [13], lets analysis move among the three vertices (noticing important information, associating those findings and interpreting them in an intelligent manner), allowing the methodological process to be creative, flexible and resourceful [28]. The network feature of ATLAS.ti software was used to illustrate how the codes surrounding work-related problems were further discussed in the theme creation process [32]. Codes that all contributed to, or impacted the port services emissions, and the port efficiency and sustainability were drawn into a network and connected to each other. This was not an automatic method [43]. The software creates no connections or names the links. The software only provides the authors with space for conceptual thought.

3 RESEARCH RESULTS

The results highlight various factors that significantly influence environmental efficiency in port operations, promoting sustainability and reducing emissions within port areas. These factors are comprehensively summarised in Table 2.

Table 2. Distribution of quotations (n=103) according to codes (11) of influential factors

Codes	Quotations	%
Theme 1. INNOVATIVE TECHNOLOGIES FOR EMISSION REDUCTION		
Energy efficiency technologies (LED lighting, energy-efficient cranes, solar panels)	9	8.74
Alternative fuels (LNG, biofuels, hydrogen, clean fuel)	9	8.74
Emission reduction strategies (Cold ironing, shore power, scrubbers)	16	15.53
Automation and digitalisation (Automated cranes, smart port, automated container terminals)	10	9.70
Theme 2. DATA-DRIVEN OPTIMIZATION FOR PORT EFFICIENCY		
Optimisation techniques (Berth scheduling algorithms, quay crane allocation models)	3	2.91
Data-driven solutions (Big data, AI, digital twins, predictive maintenance, traffic flow optimisation, decision-making, sensors)	7	6.80
Performance metrics (Vessel turnaround time, fuel efficiency metrics)	7	6.80
Theme 3. POLICIES AND GOVERNANCE FOR GREEN PORTS		
International regulations (IMO's MARPOL Annex VI, EU Green Deal)	7	6.80
National and regional policies (Subsidies, incentives, green port initiatives)	14	13.59
Stakeholder collaboration (Public-private partnerships, port authority initiatives)	7	6.80
Environmental sustainability (Local air quality, community health, social impact)	14	13.59
Total: 11	Total: 103	100

The codes were structured into three overarching themes: (1) Innovative technologies for emission reduction, (2) Data-driven optimization for port efficiency, and (3) Policies and governance for green ports. These themes, identified as critical by the authors, address the key challenges of enhancing environmental sustainability and operational efficiency in port operations while mitigating emissions. Each theme is linked to the codes based on their co-occurrence, providing a comprehensive framework for analysis. Figure 2 synthesises these findings, illustrating the key themes and their interconnections.

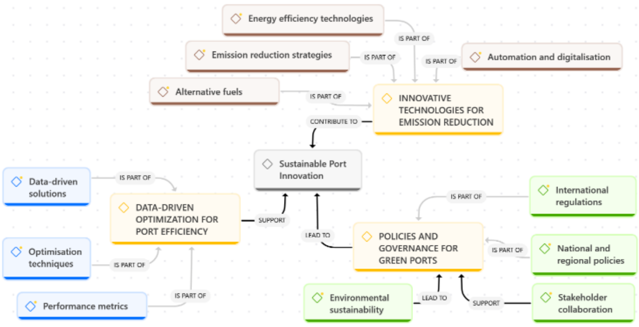

Figure 2. Key themes and interconnections

The research progressed to the next stage, utilising Atlas.ti software analysis tools to establish associations between quotations, codes, and memos. This phase also involved synthesising the results using the network formation feature, with the objective of emphasising key drivers for enhancing environmental efficiency in port operations and understanding the challenges faced in implementing emission reduction strategies.

3.1 *Innovative technologies for emission reduction*

The theme "Innovative technologies for emission reduction" represents more than 40% of the quotations and includes the following innovative technologies contributing to emission reduction, as synthesised by the codes: energy efficiency technologies, emission reduction strategies, the use of alternative fuels, and automation and digitalisation within port operations. Figure 3 summarises this theme, highlighting the drivers and challenges or barriers encountered.

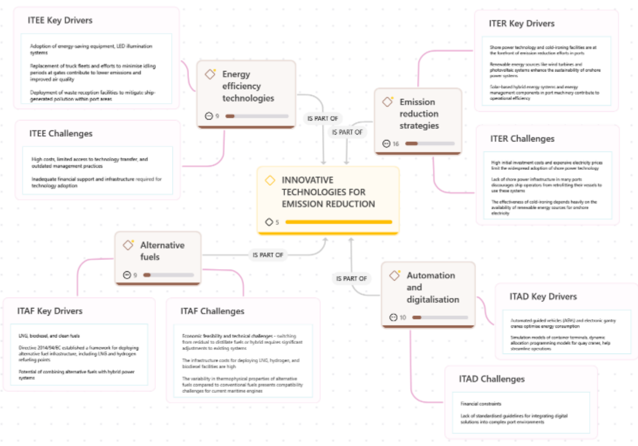

Figure 3. Innovative technologies for emission reduction - key drivers and challenges

3.1.1 *Energy efficiency technologies*

Innovative technologies for energy efficiency are transforming port operations by reducing emissions and promoting sustainability. Financial and technical incentives provided by port authorities enable the adoption of energy-saving equipment, such as LED illumination systems, which significantly cut energy consumption by leveraging occupant position and daylight dispersal [22]. Additionally, the replacement of truck fleets and efforts to minimise idling periods at gates contribute to lower emissions and improved air quality. Advanced technologies like AI, big data, and IoT offer robust support for intelligent shipping and green port construction [52], enhancing operational efficiency and environmental performance. The deployment of waste reception facilities also plays a pivotal role in mitigating ship-generated pollution, advancing sustainable practices within port areas [46].

Despite the potential of energy-efficient technologies, their adoption faces significant barriers, particularly in underdeveloped nations. High costs, limited access to technology transfer, and outdated management practices hinder the implementation of environmentally friendly solutions like RTG cranes [14]. Ports in these regions struggle with inadequate financial support and infrastructure, which exacerbates disparities in technology adoption [21]. Moreover, external measures such as enhancing inland waterways and hinterland connections require administrative and logistical support, which may be lacking in less developed areas [20]. These challenges highlight the urgent need for coordinated efforts to bridge technological and financial gaps to enable widespread adoption of energy-efficient innovations.

3.1.2 *Alternative fuels*

Alternative fuels such as liquefied natural gas (LNG), biodiesel, and clean fuels have emerged as significant drivers in reducing emissions in maritime operations. The 2014 Directive 2014/94/EC established a framework for deploying alternative fuel infrastructure, including LNG and hydrogen refuelling points, to minimize oil dependence and mitigate environmental impacts [8]. Studies [16] have highlighted the potential of combining alternative fuels with hybrid power systems to enhance sustainability and emission reduction. Biodiesel fuels, due to their renewable nature and reduced pollution impact, are increasingly regarded as viable options for sustainable transport sectors [52]. Moreover, innovative energy measures such as electrification and smart technologies, including artificial intelligence and blockchain, further drive advancements in this area [26].

While they hold great potential, the implementation of alternative fuels is facing several barriers, including economic feasibility and technical challenges. For instance, switching from residual to distillate fuels or utilizing hybrid fuel blends requires significant adjustments to existing systems [3]. The infrastructure costs for deploying LNG, hydrogen, and biodiesel facilities remain high, limiting their widespread adoption. Additionally, the variability in thermophysical properties of these fuels compared to conventional fuels presents compatibility challenges for current maritime engines [30]. Lastly, the focus of existing mitigation strategies often excludes comprehensive integration, leaving gaps in addressing alternative fuel deployment holistically.

3.1.3 *Emission reduction strategies*

Innovative strategies like shore power technology and cold-ironing facilities are at the forefront of emission reduction efforts in ports. Shore power technology significantly reduces CO_2 emissions by supplying electric power to vessels during berthing, eliminating the need for auxiliary diesel engines [27]. This approach not only benefits the environment but also aligns with the green port strategy, as it reduces energy consumption by up to 75% and offers long-term economic advantages [22]. Renewable energy sources like wind turbines and photovoltaic systems enhance the sustainability of onshore power systems, making them a cornerstone of low-carbon port initiatives. Additionally, technologies like solar-based hybrid energy systems and energy management components in port machinery contribute to operational efficiency and reduced energy use during port activities [22]. For example, storing and utilising energy during hoist-down and hoist-up movements can significantly save power.

Despite their potential, emission reduction strategies face significant barriers. High initial investment costs and expensive electricity prices limit the widespread adoption of shore power technology, especially in underdeveloped regions [27]. The lack of shore power infrastructure in many ports discourages ship operators from retrofitting their vessels to use these systems [1]. Furthermore, the effectiveness of cold ironing depends heavily on the availability of renewable energy sources for onshore electricity. Financial constraints, including the capital required for pre-development and operational phases of green port projects, further impede implementation [21]. Ports in underdeveloped nations struggle with limited access to advanced technology and resources, widening the gap between regions in adopting emission reduction strategies.

3.1.4 *Automation and digitalisation*

Automation and digitalisation offer transformative potential for improving port efficiency and reducing emissions. Technologies like automated guided vehicles (AGVs) and electronic gantry cranes optimise energy consumption by managing resources based on real-time data and minimising energy usage [22]. Simulation models of container terminals, including dynamic allocation programming models for quay cranes, help streamline operations, reducing bottlenecks and operational inefficiencies [34]. Additionally, advanced discrete choice models like the Multinomial Logit Model (MNL) provide frameworks for decision-making in resource allocation and behaviour prediction, enhancing planning accuracy in automated systems [12].

Although highly promising, the adoption of automation and digitalisation encounters significant barriers, mainly due to financial constraints. The cost of upgrading facilities and implementing technologies such as clean trucks and automated cranes remains a challenge, especially for underfunded ports [46]. Moreover, the lack of standardised guidelines for integrating digital solutions into complex port environments can lead to inefficiencies [37].

3.2 *Data-driven optimization for port efficiency*

The theme "Data-driven optimization for port Efficiency" was the least represented, accounting for 16.51% of the quotations. It is summarised by the following codes: data-driven solutions, optimisation techniques, and performance metrics onboard ships and within port operations. Figure 4 provides a comprehensive overview of this theme.

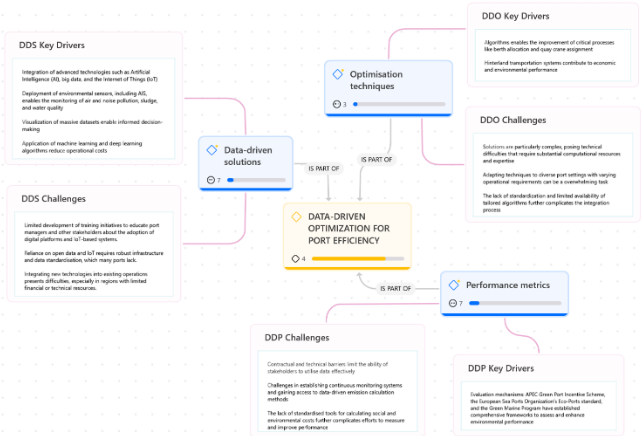

Figure 4. Data-driven optimization for port efficiency - key drivers and challenges

3.2.1 *Optimisation techniques*

Optimization techniques are important for enhancing the efficiency and sustainability of port operations. The use of advanced algorithms, such as hybrid parallel genetic algorithms, enables the improvement of critical processes like berth allocation and quay crane assignment [34]. These techniques ensure more effective resource utilization, reducing delays and operational inefficiencies. Additionally, designing hinterland transportation systems and implementing efficient inland logistics planning contribute significantly to economic and environmental performance, steering ports closer to achieving green port status [3]. These advancements highlight the potential of optimization to streamline operations while promoting sustainability in port management.

Despite the evident benefits, significant challenges hinder the full implementation of optimization techniques. Nonlinear solutions in multi-objective and large-scale scenarios are particularly complex, posing technical difficulties that require substantial computational resources and expertise [26]. Moreover, adapting these techniques to diverse port settings with varying operational requirements can be a daunting task. The lack of standardization and limited availability of tailored algorithms further complicates the integration process, making optimization a critical yet challenging area for research and development.

3.2.2 *Data-driven solutions*

The integration of advanced technologies such as Artificial Intelligence (AI), big data, and the Internet of Things (IoT) has become a significant driver for data-driven solutions in ports. The deployment of environmental sensors, including vessel traffic systems and Automatic Identification Systems (AIS), enables the monitoring of air and noise pollution, sludge, and water quality, enhancing ecological oversight [46]. These tools offer unprecedented opportunities for intelligent ship identification and maritime traffic flow supervision, with widespread adoption reported in various countries [52]. The visualization of massive datasets further empowers researchers and stakeholders by mapping the state, subjects, and boundaries of study areas, thus fostering a comprehensive understanding of port operations and enabling informed decision-making. Moreover, the application of machine learning and deep learning algorithms is laying the foundation for greater autonomy in intelligent ships, reducing operational costs while improving efficiency and safety.

While the rapid technological advancements have been made, significant challenges still obstruct the full implementation of data-driven solutions in ports. One major barrier is the limited development of training initiatives aimed at educating port managers and other stakeholders about the adoption of digital platforms and IoT-based systems [8]. Without a shift in awareness and behavioural attitudes, the potential of these technologies remains underutilised. Additionally, the reliance on open data and IoT requires robust infrastructure and data standardisation, which many ports lack. Further, integrating these technologies into existing operations presents significant difficulties, especially in regions with limited financial or technical resources. Even platforms like the web-based Port-MIS, which aim to streamline port operations, highlight the need for broader adoption and harmonisation across the sector [53]. These challenges point to the necessity of strategic training, infrastructure investment, and policy alignment to overcome existing barriers.

3.2.3 *Performance metrics*

Performance metrics play a crucial role in improving environmental sustainability and operational efficiency in port operations. The adoption of advanced technologies, such as the Automatic Identification System (AIS), has significantly enhanced the estimation of ship emission inventories, providing accurate data for monitoring and decision-making [31]. Similarly, evaluation mechanisms like the APEC Green Port Incentive Scheme, the European Sea Ports Organization's Eco-Ports standard, and the Green Marine Program have established comprehensive frameworks to assess and enhance environmental performance [26]. These indicators not only secure the ecological balance of port environments but also contribute to their economic growth. Furthermore, industry and academia's focus on intelligent maritime monitoring and ship behaviour recognition underscores a growing commitment to improving maritime safety and reducing environmental risks [52].

Despite advancements, several barriers hinder the effective use of performance metrics in port operations. Contractual and technical barriers limit the ability of stakeholders to utilise data effectively, such as optimising ship speeds en route [45]. Additionally, ports like Busan Port face challenges in establishing continuous monitoring systems and gaining access to data-driven emission calculation methods [53]. The lack of tools for calculating social and environmental costs further complicates efforts to measure and improve performance [3]. Furthermore, the implementation of innovative fuel monitoring systems remains limited in scale [24], indicating a need for broader adoption and integration across the industry.

3.3 *Policies and governance for green ports*

The final theme, "Policy and governance for green ports", holds significant importance, accounting for 40% of the quotations. This theme encompasses the following codes: international regulations, national and regional policies, stakeholder collaboration, and environmental sustainability. Figure 5 provides a detailed summary of it.

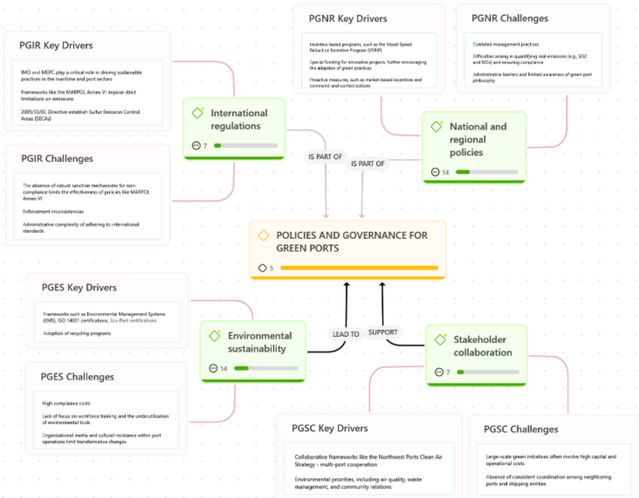

Figure 5. Policies and governance for green ports - key drivers and challenges

3.3.1 *International regulations*

International regulations, spearheaded by organisations such as the International Maritime Organization (IMO) and the Marine Environment Protection Committee (MEPC), are driving sustainable practices in the maritime and port sectors. Frameworks such as MARPOL Annex VI impose strict limitations on emissions of SOx, NOx, and particulate matter, which have been effective in curbing air pollution [45], [12]. Additionally, amendments such as the 2005/33/EC Directive establish Sulfur Emission Control Areas (SECAs), mandating the use of low-sulphur fuels to reduce harmful emissions. These international standards not only aim to improve air quality but also encourage the adoption of cleaner fuels and green technologies, fostering environmental sustainability globally [8]. The global sulphur limit of marine fuels demonstrates the ongoing commitment of regulatory bodies and flag states to reducing emissions, which aligns with broader global climate goals [45], [19].

Although highly significant, international regulations encounter implementation challenges, particularly in enforcement and compliance. A notable issue is the absence of robust sanction mechanisms for non-compliance, which limits the effectiveness of policies like MARPOL Annex VI [19]. While many seaports voluntarily adhere to these regulations, enforcement inconsistencies reduce their impact. Moreover, the high cost of transitioning to low-sulphur fuels and clean technologies presents a financial burden for shipping companies and ports, especially in developing regions.

3.3.2 *National and regional policies*

National regulations and policies are among the most important factors in advancing green port initiatives and sustainability practices. Incentive-based programs, such as the Vessel Speed Reduction Incentive Program (VSRIP), demonstrate effective strategies by offering financial rewards for emission-reduction measures [54]. For example, ships participating in designated emission reduction zones can receive significant dockage refunds, fostering compliance. Additionally, pilot projects initiated by the Ministry of Transport of China have boosted confidence in energy conservation and emission reduction through special funding for innovative projects, further encouraging the adoption of green practices [25]. As highlighted in the China's Guiding Opinions on Building World-Class Ports [36], the national frameworks are required for the alignment of national requirements with policy incentives. Governance frameworks for green and smart port encourage ports to take responsibility to elevate greening to a new height and enhance social responsibility [7]. Establishing high-quality inland waterway transport infrastructure to connect seaports with the hinterland serves as a key enabler within national policies, providing a competitive advantage in the port services market while aligning seamlessly with sustainable port strategies and with global sustainability goals [20]. Proactive measures, such as market-based incentives and command-and-control policies, also enable ports to comply with environmental regulations and adopt advanced abatement technologies [45], thereby fostering sustainability and reducing environmental risks.

While these drivers support the greening of ports, significant challenges remain in implementing national regulations. A lack of financial support and outdated management practices hinder the ability of many ports to comply with stringent sustainability requirements [49]. High costs associated with infrastructure upgrades, development or retrofitting, further exacerbate the issue, especially in less affluent regions [19]. Monitoring and enforcement mechanisms also remain a critical challenge, with difficulties arising in quantifying real emissions (e.g., SO2 and NOx) and ensuring compliance [8]. Moreover, administrative barriers and limited awareness of green port philosophy among stakeholders present obstacles to achieving broader adoption of sustainable practices [7]. These issues underline the need for collaborative efforts, enhanced funding mechanisms, and stronger regulatory enforcement at the national level.

3.3.3 *Stakeholder collaboration*

Effective partnerships among stakeholder contributes to green port development and environmental sustainability. From the perspective of long-term sustainable development, the active engagement of ocean carriers with ship manufacturers, port authorities, central and local governments, and other stakeholders facilitates a deeper understanding of green port issues and keeps stakeholders informed of development trends [47]. By fostering these partnerships, ocean carriers can effectively adopt and implement mitigation strategies to support long-term sustainable development. Collaborative frameworks like the Northwest Ports Clean Air Strategy demonstrate the potential of multi-port cooperation to implement unified environmental strategies, such as set up clear pollution reduction targets in various pollution sources, such as ocean going vessels, harbour vessels, cargo handling equipment, trucks, rail [38]. Moreover, ports like Santos emphasize environmental priorities, including air quality, waste management, and community relations, ensuring a holistic approach to sustainability [3]. Access to EU funds and pro-ecological investment initiatives further enables port managers and other relevant stakeholders to implement innovative projects and improve infrastructure in coastal regions [19].

Establishing collaborative partnerships for financial support remains a significant hurdle, as large-scale green initiatives often involve high capital and operational costs. Even so, a strategic framework for financial support that provides mutual benefits to all parties involved is urgently needed [1]. The absence of consistent coordination among neighbouring ports and shipping entities can delay progress, particularly in areas requiring substantial investment [31]. In addition, stakeholder collaboration may face significant barriers and challenges, particularly in aligning financial and policy priorities among diverse government units, such as the Ministry of Transportation and Communication, Ministry of Economic Affairs, and the Environmental Protection Administration [47]. However, achieving consensus on budget allocation and financing mechanisms poses a considerable challenge, as such decisions often involve difficult trade-offs.

3.3.4 *Environmental sustainability*

Environmental sustainability in ports is driven by the implementation of green practices, regulations, and certifications. Ports like Kaohsiung, Keelung, and Taichung in Taiwan have achieved Eco-Port certifications, highlighting the effectiveness of policy formulation and targeted implementations for pollution reduction [46]. Green initiatives such as the use of clean-burning low-sulfur fuels, environmentally friendly materials, and waste-to-energy strategies significantly contribute to enhancing sustainability and competitiveness [39]. Furthermore, frameworks such as Environmental Management Systems (EMS) and ISO 14001 certifications provide structured approaches for environmental monitoring and improvement [3], [8]. The adoption of recycling programs and advanced monitoring systems, like those implemented by TIPC, ensures long-term environmental quality and effective management of pollution sources [45].

Implementing environmental sustainability initiatives in port areas faces several barriers despite their recognised importance. Financial constraints remain a significant hurdle, as green practices adoption often require substantial investment. For example, drayage operations inherently rely on a large fleet of heavy-duty vehicles operating in concentrated areas, which impact the local air quality [44]. Transitioning to cleaner vehicle technologies, such as electric or alternative fuel-powered trucks, requires substantial upfront investment, and operators may resist due to the financial burden. Workforce-related issues, including a lack of training and limited access to advanced environmental tools, impede progress [8]. Lastly, organisational inertia and resistance to deep cultural and procedural changes act as significant obstacles to achieving meaningful environmental reforms [35]. Particularly in port operations, entrenched practices and complex stakeholder dynamics often hinder the adoption of environmentally sustainable solutions.

4 DISCUSSIONS AND CONCLUSIONS

The overarching objective of this study was to identify the key drivers for enhancing environmental efficiency in port operations and to examine the challenges associated with implementing emission reduction strategies. Employing a systematic selection of articles guided by the PRISMA methodology, coupled with qualitative data analysis using the CAQDAS tool Atlas.ti, the study ensures a structured and comprehensive synthesis of insights. The research focuses on three critical themes — innovative technologies for emission reduction, data-driven optimization for port efficiency, and policies and governance for green ports — each essential for addressing the dual challenges of enhancing environmental sustainability and operational efficiency in port services. The findings, presented through visual graphs and detailed analyses, underscore the interconnectedness of these themes and their collective role in fostering sustainable port operations while mitigating emissions. Key drivers and barriers identified within each theme are explored in depth, offering valuable insights for stakeholders aiming to advance green port initiatives.

Innovative technologies such as energy-efficient systems, alternative fuels, and automation have shown significant potential in reducing emissions and improving environmental outcomes. However, barriers such as financial constraints, limited infrastructure, and lack of standardised guidelines highlight the need for collaborative efforts to bridge technological gaps and ensure equitable adoption of green technologies across different regions.

Data-driven optimization emerged as the least represented category in this study, reflecting its relatively nascent stage of adoption in port operations. Despite this, the integration of advanced technologies, including artificial intelligence, big data, and IoT, offers transformative potential for monitoring and optimising port efficiency. Challenges such as inadequate training initiatives, infrastructure limitations, and data standardisation issues underscore the importance of strategic investment in capacity-building and technology development. Performance metrics further highlight the importance of accurate data collection and analysis for informed decision-making. Adoption of data-driven solutions requires a concerted effort to harmonise technological innovations with policy support.

Policies and governance are the most important for facilitating the adoption of environmentally sustainable practices in ports. International frameworks such as MARPOL Annex VI and regional policies like the EU Green Deal provide a strong foundation for emissions regulation and green initiatives. However, challenges in enforcement and compliance, particularly in developing regions, impede their effectiveness. The absence of consistent stakeholder coordination among neighbouring ports and shipping entities can delay progress. Furthermore, environmental sustainability frameworks offer structured approaches for monitoring and managing port activities. At the same time, transitioning to cleaner practices and technologies requires substantial upfront investment, and stakeholders may resist due to the financial burden. Addressing gaps in funding, organisational inertia, and stakeholder alignment will be key to realising the full potential of green ports.

In conclusion, the successful implementation of green and energy-efficient solutions in port operations is driven by key enablers such as financial incentives, technological advancements, national and internationals policies, and collaborative frameworks. However, widespread adoption continues to face significant barriers, including economic feasibility and technical challenges. A major obstacle is the insufficient development of training programs aimed at equipping port managers and stakeholders with the necessary skills to adopt digital and data-driven platforms effectively. Addressing this gap has the potential to transform this barrier into a key driver for advancing sustainability and operational efficiency in port operations. Furthermore, the reliance on open data necessitates the establishment of robust infrastructure, standardised protocols, and frameworks for collaborative data utilisation—resources that are currently unavailable in many ports. Additionally, organisational inertia and resistance to cultural and procedural changes present substantial challenges, impeding the integration of environmentally sustainable solutions within port operations.

This study has a few limitations that should be acknowledged. The primary limitation lies in the restricted number of sources, as the data collection was primarily conducted using a single platform, Web of Science. While this platform is a resource for academic literature, its exclusivity may have limited the diversity of perspectives and publications included in the analysis. Furthermore, accessibility issues arose, as several relevant articles were not open access and were consequently excluded during the systematic literature review. These exclusions may have led to the omission of potentially valuable insights, which could have enriched the findings.

Further research should focus on identifying region-specific challenges and opportunities to implement sustainable practices in port operations. Expanding the research to include interviews with industry representatives and policymakers across diverse geographical contexts would provide a more nuanced understanding of the barriers and drivers influencing green port initiatives globally.

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