Journal of *Marine Science and Engineering*

MDPI

Systematic Review

Maritime Pilotage and Sustainable Seaport: A Systematic Review

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Abstract: The long-term sustainability of seaports depends on various operational factors, including infrastructure efficiency, digital innovation, environmental management, and regulatory compliance, among which maritime pilotage plays a crucial role in ensuring safe navigation and minimizing environmental, economic, and social risks. This research employed the PRISMA-ScR framework to evaluate the environmental, economic, and social impacts of pilotage on the sustainability of seaports. The findings demonstrate efficient navigation and spill avoidance, which reduce emissions, safeguard marine biodiversity, and maintain water quality. Economically, it reduces delays, optimizes operational expenses, and increases port competitiveness by increasing maritime traffic. Moreover, pilotage improves navigational safety, local professional skill development, and community interactions via ecological conservation and operational efficiency. It also indicates how environmental initiatives benefit the economy, increase port competitiveness, and promote job security and community happiness. The results also emphasize the significance of pilotage in sustainable seaport operations by quantifying pollution reductions, cost savings, and safety. The result also suggests that successful pilotage enhances ports' viability and responsibility in global shipping networks while addressing environmental, economic, and social concerns.

Keywords: maritime; pilotage; seaports; sustainability; shipping

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Academic Editor: Simone Mancini

Received: 27 March 2025
Revised: 5 May 2025
Accepted: 8 May 2025
Published: 13 May 2025

Citation: Issa-Zadeh, S.B.; Garay-Rondero, C.L. Maritime Pilotage and Sustainable Seaport: A Systematic Review. *J. Mar. Sci. Eng.* **2025**, *13*, 945. https://doi.org/10.3390/jmse13050945

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1. Introduction

Ports are vital to international supply chains, and maritime commerce accounts for half of all global trade in value. According to the World Shipping Council's 2023 ranking, the top ten ports, such as Rotterdam, Shanghai, Long Beach, etc., affect 9.3% of the global economy, and marine commerce has an even more enormous influence on areas of the domestic economy [1]. In addition, seaports play a crucial role in global trade, necessitating sustainable practices to address environmental concerns, optimize operations, and meet social responsibilities [2]. Sustainable seaports include methods that reduce ecological harm, bolster economic resilience, and cultivate beneficial interactions with local people [3,4].

As a result, the shift towards sustainability enhances the ports' competitive edge and ensures compliance with international environmental standards and global objectives, including the United Nations Sustainable Development Goals (UN SDGs) [5,6]. Also, sustainable seaports serve as centers of innovation and economic advancement, crucial for attaining a balanced developmental strategy that advantages local and global stakeholders [7].

Additionally, the sustainability of seaport operations is a critical factor in overall seaport sustainability [6]. A crucial aspect of these operations within seaport boundaries is ship navigation, which maritime pilots conduct. Maritime pilotage entails the safe berthing, unberthing, navigating, and maneuvering of vessels in and out of ports, harbors, and other restricted or challenging waterways [8,9]. It plays a crucial role in the sustainability of seaports, as it directly affects environmental, economic, and social factors [10,11]. Proficient Maritime pilots navigate vessels through intricate waterways, minimizing the likelihood of accidents, oil spills, and other pollutant releases. This fosters cleaner seas and more robust marine ecosystems. Economically, practical pilotage saves fuel consumption, avoids delays, and optimizes vessel movements, consequently decreasing costs for shipping corporations and improving port competitiveness [12,13].

Furthermore, pilotage enhances community welfare by guaranteeing safe navigation and promoting local employment via specialized skill-based positions. The convergence of these advantages emphasizes the essential function of pilotage in attaining sustainable seaport operations, as discussed and highlighted in the Second International Maritime Organization Greenhouse Gases study (second IMO GHG study), IMO Initial GHG Strategy, and other relevant reports. It also highlights pilotage's capacity to promote innovation and change in maritime logistics and management by using new technology instruments and conducting safe and environmentally friendly operations [14,15].

The primary objective of this study is to examine how maritime pilotage contributes to the sustainability of seaports. While it is widely recognized that pilotage enhances safety by preventing accidents, collisions, and environmental incidents, and strengthens security by protecting port infrastructure from unlawful threats, this research goes further. It aims to systematically classify the specific ways in which pilotage supports sustainable port operations. This classification can help stakeholders and port authorities improve strategic planning and make evidence-based decisions. It also provides researchers with a clearer framework for advancing related studies. Based on this systematic review, which focuses on environmental, economic, and social dimensions, the core research question is "*How does maritime pilotage influence the environmental, economic, and social aspects of seaport sustainability*?".

This is accomplished by thoroughly analyzing and assessing current scholarly literature and pertinent international standards and legislative frameworks related to the research focus by utilizing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Scoping Review (PRISMA-ScR) methodology. This study's main limitation was the scarcity of literature, as mariners are practical professionals in the industry and typically do not engage in research. Additionally, most existing literature on maritime pilotage focuses on training and job conditions, presenting a significant challenge for authors in locating suitable, relevant, and scientifically credible sources on the topic.

Despite growing interest in port operation and management sustainability, few studies have studied how pilotage contributes to these goals. Pilotage training, fatigue, and safety are generally studied separately, ignoring their sustainability implications. Current frameworks lack measurable indicators linking pilotage methods to sustainability outcomes, denying stakeholders actionable information. This research aims to address this "research gap" by integrating the pilotage role into various elements of seaport sustainability.

On the other hand, this research innovatively positions maritime pilotage as a crucial factor in sustainable seaport operations, including environmental, economic, and social aspects. In contrast to other research, it directly correlates pilotage techniques with sustainability results and presents a complete framework that elucidates their interconnections. This approach addresses a deficiency in the literature and offers strategic insights for ports and stakeholders. Furthermore, this research can provide more meaningful insights for

port authorities, marine regulators, shipping corporations, environmental groups, and university scholars. Port authorities can use information to improve efficiency and sustainability. Policymakers may utilize the framework to create sustainable pilotage criteria. Shipping businesses may save money and comply with the environment, while academics and researchers may use the findings to develop sustainable maritime operations.

The following section comprehensively elucidates the "Methodologies and materials" used to create the conceptual framework and ascertain essential sustainability indicators. Section 3, the "Results" section, delineates the quantifiable effects of improved pilotage on emissions reduction, economic efficiency, and social wellbeing. Section 4, "Discussion", analyzes the significance of these results concerning current literature, emphasizing our study's contributions to the area. Finally, the "Conclusion" part encapsulates the principal observations, underscores the importance of pilotage in sustainable seaport operations, and proposes avenues for further study.

2. Materials and Methods

The authors utilized the PRISMA approach to organize and conduct literature reviews in this study. The flowchart in Figure 1 demonstrates that the review process consists of two distinct segments for gathering pertinent material. The initial segment comprises database and registry searches, and the authors have begun searching for relevant materials in Internet databases (Scopus and the Web of Science (WOS)). This segment is divided into three phases: identification, screening, and inclusion.

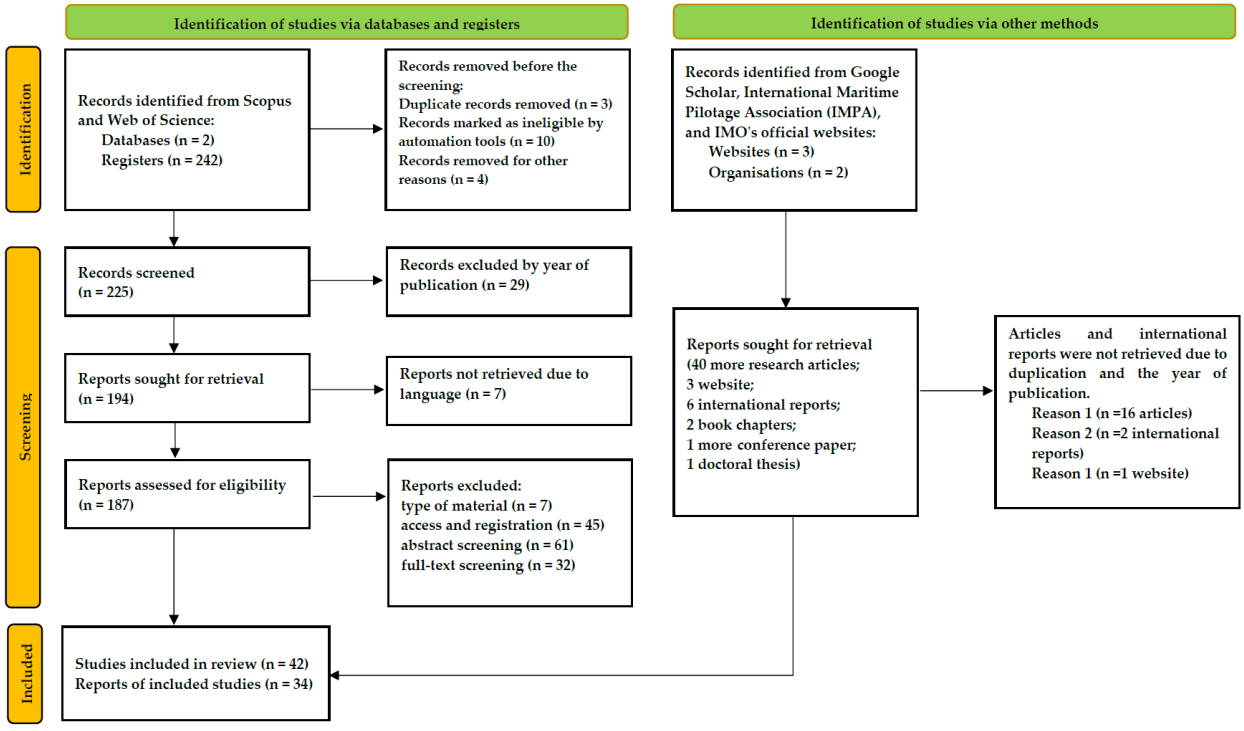


Figure 1. Methodology phases PRISMA-ScR literature review steps (flowchart retrieved from [16]).

Each phase may be divided into smaller steps, resulting in a compilation of relevant and cutting-edge research. The second segment includes supplementary literatures derived from the authors' skills, knowledge, and comprehension of the subject matter. The resources are gathered through the three specified phases of "identification, screening, and inclusion", comprising research articles, books, book chapters, information from official websites, and international regulations and reports, all chosen to fulfill the research's specific requirements

and ensure the material's relevance to the topic. The three mentioned phases of the first segment are as follows:

Identification: Due to the lack of scientific articles and work studies regarding marine pilotage, the authors decided to search only with the Keyword search for "marine pilot", OR "ship pilot", OR "maritime pilot" in WOS and Scopus and the paper's title, abstract, and keywords in the first refinement, which It ranked first in 242 results, and after the first filtering, which included factors such as duplicates and eligibility, the 225 results remained, as shown in the first part of the "Screening" section. It has to be mentioned that the word "pilotage" can also be considered to be found while searching the mentioned keywords.

Screening: This process, along with the eligibility assessment, is interrelated, as each screening stage brings up one or more considerations related to eligibility. Eligibility categories included the year of publication from 2000 to the end of 2025 (25 years), which led to 194 resources; further refining by language (only in English) led to 187 resources. Then, refining was performed by type of material (articles, conference papers, books, and conference reviews); in all, 104 articles, 66 conference papers, one book, five book chapters, and four review research papers were identified. The next step was refinement based on access and registration, and 134 research works were identified. Subsequently, abstract screening was performed, and refinement and adjustment were performed to account for important topics. Thus, 73 resources were found.

Including: comprehensive article screenings produced by 42 resources. In the concluding step, the authors initially endeavored to analyze and evaluate all 42 research works to understand the various effects of maritime pilotage on the sustainability of seaports and to categorize these impacts. Thereafter, VOSviewer (version 1.6.20) has also been utilized to support the classifications presented in this research study.

In this stage, the VOSviewer was used to classify the main keywords of the found literature. Then, with the help of these classes, the authors could find more relevant literature to support the arguments and provide a better overview of the issue. This VOSviewer-generated map depicts the co-occurrence of keywords from 42 literature review results. Keywords are organized into color-coded clusters, each indicating a separate study subject.

For example, the red cluster focuses on environmental impacts like carbon emissions and port operations, reflecting sustainability challenges. The green cluster emphasizes human factors and safety, including accidents, statistics, and risk control. The purple cluster narrows this focus to human error in marine accidents. The blue cluster centers on navigation and pilotage, addressing technical aspects of maritime maneuvering. The yellow cluster highlights optimization and scheduling, reflecting research on efficiency in maritime logistics. The pink cluster covers port operations and sustainability, emphasizing operational efficiency and environmental impact. Finally, the brown cluster touches on aerospace medicine, indicating potential interdisciplinary links. Central concepts like marine transportation, ships, and port operations appear to be inextricably linked, highlighting their fundamental importance. This map provides a strategic picture for identifying a better overview of related subjects, allowing authors to investigate well-established regions or focus on relevant issues for future literature discovery. Figure 2 illustrates the outcomes of employing VOSviewer concerning the 42 studies mentioned above [17].

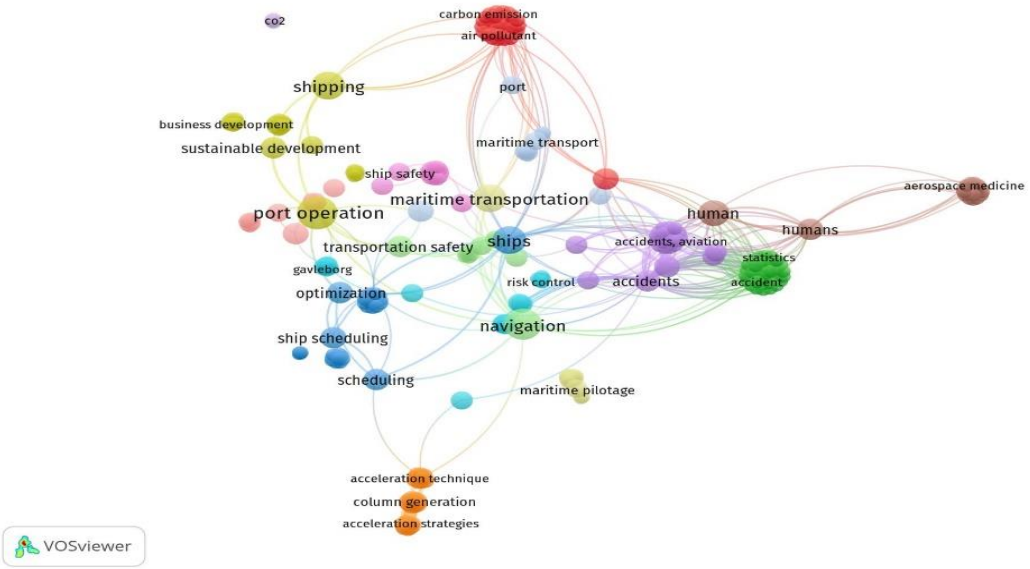


Figure 2. Keyword analysis by using VOSviewer.

Subsequently, classifications, including environmental, economic, and social drives, were prepared. Additional relevant information was included in light of these classifications and the necessity to gather supplementary data while presenting findings. At this stage, the second segment of the PRISMA methodology was employed and refined following the identified need for investigation. Materials in this segment are carefully evaluated for their significance, relevance to the central research topic, and scientific integrity. Sources that are redundant or lack scientific substantiation are excluded. Figure 1 illustrates that this segment comprises three sequential steps: identification, screening, and inclusion.

In the identification phase, resources were gathered from two websites, including Google Scholar and the International Maritime Pilotage Association (IMPA), and IMO websites, resulting in the collection of over 40 research articles, three websites, six international reports, two book chapters, one conference paper, and one doctoral thesis. In the screening phase, 16 articles, two IMO reports, and one website were excluded based on some criteria such as duplication, year of publication, and not being applicable to generalize to all fields of the main issue. An additional 34 references were integrated into the initial pool, thus enhancing our study's foundational resource base, resulting in a total of 76 references. The comprehensive review of all references indicates that they can be categorized into six main groups as follows:

a. Sustainable Development and Carbon Emissions in Ports and Maritime Operations (24 references).
b. Maritime Pilotage, Safety, and Accident Analysis (19 references).
c. Digitalization, Technological Innovation, and Logistics in maritime and navigation operations (16 references)
d. Environmental Impact, Pollution Control, and Sustainability in the Seaports Area (11 references).
e. Policy and Legal Frameworks regarding maritime pilotage (4 references).
f. Miscellaneous websites (2 references).

3. Results

This section analyses the correlation between maritime pilotage and its diverse effects on port sustainability.

Prior to examining the connection at issue, it is imperative to emphasize its importance and provide a succinct description of the geographical boundaries of maritime pilotage operations. The authors' 2023 estimate indicates that emissions from marine operations comprise roughly 60% of overall emissions at a European seaport [18]. This conclusion is corroborated by many pertinent studies, including those conducted by Xia et al. (2021) and Hussain et al. (2022), as well as further studies concentrating on marine and shipping operations inside seaport confines, all of which highlight the significant magnitude and effect of these emissions [19,20].

Following this, maritime operations within a seaport boundary commence at the point designated as "START," continue in the direction of the arrows, and culminate at the "SAILING" point, as depicted in Figure 3. These operations are broadly categorized into two primary groups. The first category encompasses maneuvering activities, such as berthing, unberthing, and shifting, all of which necessitate the presence of a maritime pilot onboard. The second category pertains to vessels stationed alongside or in a hoteling scenario involving loading, discharging, bunkering, and workshop operations. Meanwhile, many seaports are adopting Cold Ironing (CI) and Shore Power Supply (OPS) systems, significantly reducing emissions from ships docked at jetties to near-zero levels [21,22]. Consequently, this issue highlights that a substantial proportion of emissions is generated during ship maneuvering, emphasizing the critical role of emissions occurring while maritime pilots are onboard. For instance, according to research conducted by the authors of this study in 2023, at the Port of Valencia in Spain, the emissions generated from these maneuvering operations accounted for nearly 56% of the total emissions produced by the port in 2016 [18].

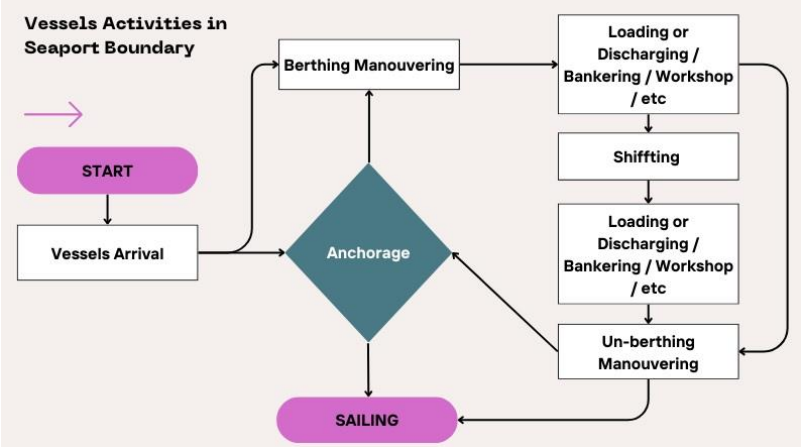


Figure 3. The entire maritime operations of a vessel in a seaport [23].

Furthermore, according to IMO rules, documents about marine pilotage are addressed under Chapter 5 of the International Convention for the Safety of Life at Sea (SOLAS), entitled "*Safety of Navigation*" [24]. In contrast, according to IMO resolution A.960 regarding pilotage, maritime pilotage is essential for enhancing maritime safety and safeguarding the marine environment [25].

Following the issues raised about the magnitude of emissions while pilots are conducting their maritime operations, as well as the emphasis of international regulations and conventions, it can be concluded that these safety measures have an impact on the infrastructure surrounding seaports, such as channels, canals, breakwaters, jetties, facilities, and neighboring ecosystems, as well as the pilot's operations impacts on social community and economy in the surrounding area. According to the author's review, these consequences may be classified into three principal dimensions: *environmental*, *economic*, *and*

social. An exhaustive examination and study of current literature facilitated the discovery of these elements, establishing the foundation for a conceptual framework. Each fundamental dimension can be further categorized into distinct sub-dimensions, illustrating their significance and operational characteristics.

3.1. Environmental Sustainability

Maritime pilotage is essential for enhancing the environmental sustainability of seaports by facilitating safe and efficient navigation through waterways and basins within a port authority's jurisdiction while reducing environmental impact [26,27]. Figure 4 provides a structured overview of the keyways by which marine pilotage enhances environmental sustainability. These routes include several effects formed by contextual elements, such as the geographical position of the port, accessible technical infrastructure, and the operating duration of pilotage activities. This study limits its focus to the primary indicators illustrated in Figure 4, despite the potential for other sub-indicators to further elucidate the link between pilotage and sustainability, especially those attuned to local environmental, technological, and regulatory contexts. The choice to concentrate solely on these fundamental components guarantees analytical clarity. It upholds methodological consistency, acknowledging that sub-indicators' heterogeneity across diverse port environments may add complexity beyond the present study framework.

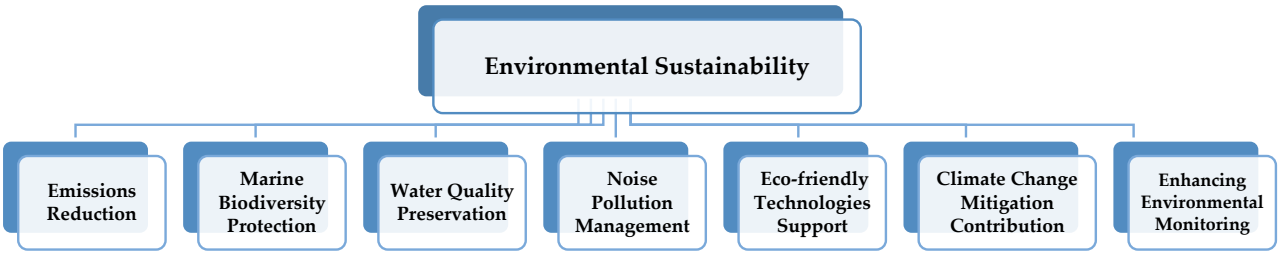


Figure 4. Maritime pilotage key indicators on seaports' environmental sustainability.

A. Reduction in Emissions

To achieve efficient maneuvering, pilots optimize ship navigation to reduce engine idling and maneuvering time, which also leads to reduced fuel consumption. This reduction in fuel consumption directly reduces engine exhaust gas from ships, which in turn mitigates emissions of GHGs such as carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM). These emissions are directly contributing to global warming and climate change. Consequently, this reduction improves air quality in port areas [28,29]. Research by M. Baldauf et al. (2018) argues that implementing sustainable navigation practices, which involve eco-efficient routing strategies and the optimization of engine and maneuvering techniques, minimizes unnecessary actions and further reduces emissions during docking and undocking [7]. These dimensions can directly influence the sustainability of ports.

B. Marine Biodiversity Protection

Accident prevention is of the utmost importance to ensure the long-term viability of seaports. Skilled pilots limit the likelihood of collisions and groundings. When that is impossible, they handle the situation as best they can, following established emergency protocols and authority-approved contingency plans that consider various factors, including environmental ones. Based on the findings of the research by L. Nedelcu et al. (2022) and also other research by T. R. Walker et al. (2018), through these actions, pilots may reduce the negative impact of potential accidents on sensitive marine habitats, such as coral reefs and mangroves [30,31].

Additionally, pilots can regulate ballast water discharge by directing vessels to avoid unauthorized releases, thus reducing the risk of invasive species entering marine ecosystems [31,32]. Moreover, pilotage can mitigate spills by substantially decreasing the probability of oil spills or hazardous material leaks, which can harm marine biodiversity. These results are aligned with the findings of a research study by M. Cabrini et al. (2019) and R. P. Schoeman et al. (2020) [33,34].

C. Water Quality Preservation

Pilots eliminate the risk of accidental pollutant discharges into seaport waters by ensuring that vessels follow established navigation routes, thus reducing contamination hazards [34,35]. Pilots' functions encompass guided waste management, ensuring compliance with waste disposal standards, and preventing the illegal discharge of sewage, chemicals, and plastics into the sea, consistent with the research conducted by R. Zhang (2020) [36]. Furthermore, in line with the study conducted by J.K. Abbott et al. (2019), pilot-assisted operations help minimize bottom sediment disturbances during anchoring and maneuvering, which helps maintain cleaner and healthier water conditions [37].

D. Noise Pollution Management

According to research conducted by M. Lajaunie et al. in 2023, underwater noise significantly affects marine species and ecosystems, and this impact is currently under investigation [38]. Enhancing navigation speed and vessel positioning allows pilots to contribute to reducing underwater noise from ships, which can disrupt marine organisms, especially migratory species and cetaceans. Additionally, N.D. Merchant et al. (2014) argued that ship noise and port development significantly impact marine mammals [39]. In this regard, green marine pilotage can manage localized noise by adjusting its operations to reduce sound in environmentally sensitive areas, thereby contributing to the conservation of aquatic species.

E. Support for Eco-friendly Technologies

Several studies have underlined the teamwork of pilots and port authorities in setting green port infrastructure innovations into use. Adopting systems like Onshore Power Supply (OPS), Cold Ironing (CI), and Automated Mooring Systems (AMS), which together lower emissions during important ship movements like docking, berthing, and unberthing, has been made possible by this cooperation. Pilots and port authorities guarantee the smooth incorporation of these technologies, supporting more efficient and sustainable port operations [39–41].

Likewise, trained and expert pilots employ environmentally sustainable pilotage techniques that incorporate green technologies, such as smart glass and remote piloting, as discussed by Ostendorp et al. (2015) and Janne Lahtinen et al. (2020), which can ultimately be regarded as supportive of eco-friendly technologies [42,43].

F. Contribution to Climate Change Mitigation

Pilotage helps seaports reduce their overall carbon footprint by minimizing fuel use and GHG emissions. In addition, efficient and environmentally sustainable pilotage complies with international environmental standards, such as the IMO's MARPOL (maritime pollution) regulations, the IMO GHG strategy, and local or regional standards. This adherence contributes to climate change mitigation, as discussed in the research by T. H. Joung et al. in 2020 and K. Yeremenko et al. in 2022 [44,45].

G. Enhancing Environmental Monitoring

The monitoring system is essential for sustainable development in seaport areas, as evidenced by the research findings of K. Yeremenko and also Abramowicz–Gerigk et al. in

2024 [45,46]. Aligned with this objective and referencing the study by Alamoush et al. (2021) on the influence of seaports in reducing emissions from shipping within port boundaries, primarily governed by pilotage operations, it can be asserted that pilots provide critical data on environmental risks during operations, thereby enhancing the monitoring of environmental conditions in port areas [47]. Insights from pilotage operations inform ports about designing sustainable infrastructure, including navigational channels that reduce environmental disruption.

3.2. Economic Sustainability

Pilotage facilitates sustainable practices by using green technology, streamlining logistics, and therefore minimizing emissions while ensuring the safe and efficient navigation of vessels in intricate port regions, mitigating the chances of accidents and environmental harm. As detailed in the preceding paragraph, these approaches improve operating efficiency while reducing environmental impacts. Collectively, these initiatives enhance economic development and promote equilibrium between industrial requirements and economic resources. Economic sustainability, as the second key aspect of maritime pilotage's impact on seaport sustainability, encompasses various components detailed in Figure 5 and described in the following sections. Economic sustainability, recognized as the second primary dimension through which maritime pilotage enhances overall seaport sustainability, includes several critical drivers, as depicted in Figure 5 and discussed in the following paragraphs. Each primary driver is linked to particular sub-factors, including the reduction of vessel turnaround time, enhanced appeal for larger vessels owing to reliable pilotage services, and the mitigation of environmental penalties or legal liabilities. The sub-factors are context-dependent and can vary considerably based on specific ports' operational, regulatory, and geographic characteristics. This study seeks to classify the fundamental economic drivers applicable across various port settings, avoiding focusing on localized or port-specific details. It aims to develop a general framework for understanding the economic contributions of pilotage to port sustainability by concentrating on shared economic mechanisms.

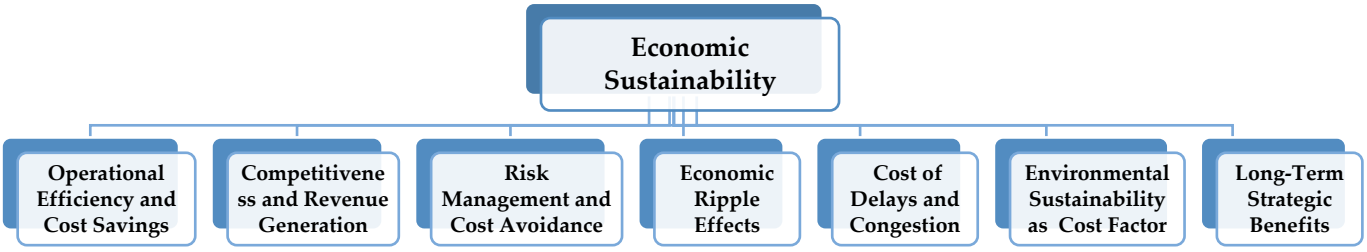


Figure 5. Maritime pilotage key indicators on seaport's economic sustainability.

A. Operational Efficiency and Cost Savings

Research by Pantjadjatmika et al. in 2024 indicates that pilots ensure the safe navigation of vessels through challenging and congested waterways, hence reducing the likelihood of accidents that might incur substantial costs for ports and shipping companies [48]. On the other hand, research by Oktafia et al. in 2017 stated that marine pilots are essential for port services, as they greatly influence the objective of zero waiting time [49]. This research demonstrates that efficient vessel maneuvering by pilots reduces berth occupancy time, increasing throughput and overall port operational efficiency, thereby enhancing economic performance [49].

In conclusion, a decision support system utilizing an optimization model can effectively manage ship fuel consumption, as J. Gonzales et al. noted in 2021 [26]. Furthermore, pilots' expertise in local conditions enhances route planning, minimizing unnecessary

engine power usage and reducing fuel consumption. This reduction can benefit port authorities by decreasing fuel costs for service vessels such as tugboats, pilot boats, etc. [50].

B. Competitiveness and Revenue Generation

It is possible to claim that efficient pilotage services improve a port's image for dependability and safety, attracting more shipping lines and increasing income [51]. Additionally, recent findings by the authors of this study, along with P. Ariantoko et al. (2023), suggest that ports offering superior pilotage services have the potential to position themselves as leading logistics hubs, thereby gaining a significant competitive advantage over other regional ports. This strategic positioning can translate into greater influence within the maritime logistics network and foster long-term financial sustainability [52,53]. Dependable pilotage reduces transit expenses, enhancing the seaport's appeal for international commerce and subsequently augmenting the economic activity produced by the port [54].

C. Risk Management and Cost Avoidance

The 2013 study by Chauvin et al. indicates that pilots' local experience reduces the probability of accidents, groundings, and environmental disasters, thereby averting significant liability for ports, shipping companies, and insurers, which is one of the critical cost factors for shippers and their decision-making processes [55]. Moreover, as highlighted by Ashraf et al. (2020) and K.H. Chai (2008), the strict adherence of vessels to established navigational regulations, as enforced by pilots, plays a critical role in safeguarding port infrastructure, including piers and berths, from potential damage. This proactive approach significantly reduces the frequency and cost of maintenance and repairs, thereby enhancing the long-term operational efficiency of port facilities [56,57].

D. Economic Ripple Effects

Efficient pilotage enhances the port's operational ecosystem, directly supporting jobs in pilotage services and indirectly benefiting logistics, customs, and related businesses. Moreover, heightened shipping traffic resulting from dependable pilotage fosters supplementary economic activities, including warehousing, trucking, and manufacturing, thereby enhancing local economies [58]. Ports offering superior pilotage services are crucial to regional trade networks, significantly impacting local and national economies. They facilitate establishing additional companies and markets in the surrounding areas, thereby creating further economic opportunities [59].

E. Cost of Delays and Congestion

Pilotage facilitates prompt vessel movements, thereby minimizing bottlenecks and related expenses, including demurrage (a fee charged to charterers, shippers, or consignees for exceeding the agreed-upon time for loading, unloading, or returning cargo containers or vessels) and delays in cargo handling. Efficient port operations facilitated by pilotage improve supply chain predictability, thereby minimizing economic losses for businesses dependent on just-in-time logistics [58,59].

F. Environmental Sustainability as a Cost Factor

Research indicates that environmental penalties and fines can affect a port's attractiveness to clients, thereby influencing the port's economic revenue [60,61]. Consequently, ship pilots' proficiency in mitigating incidents such as oil spills reduces environmental cleanup expenses and related penalties, which are essential for sustaining the financial viability of the port. These financial costs can be categorized into two types impacting port authorities: shipping lines and ship owners. In this context, environmental penalties can be reduced by utilizing pilots and their expertise. Pilots assist vessels in adhering to stringent

environmental and operational regulations, thereby preventing penalties and maintaining the financial viability of the port.

G. *Long-Term Strategic Benefits*

Ports exhibiting elevated safety and efficiency standards owing to sustainable pilotage services are more inclined to attract sustained stakeholder investments [62]. Moreover, ports that guarantee operational stability are often included in trade agreements, promoting enduring economic advantages for the area.

3.3. Social Sustainability

Maritime pilots play a pivotal role in the social sustainability of seaports by ensuring the safety, efficiency, and inclusiveness of port operations. Their specialized expertise minimizes accidents, protecting human lives, coastal communities, and marine ecosystems. By fostering stable employment opportunities and promoting professional growth, pilotage contributes to job satisfaction and economic stability within local communities.

Additionally, pilots enhance public trust by maintaining transparent and effective operations, actively engaging with stakeholders, and participating in community outreach programs [63]. These contributions strengthen relationships between seaports and their surrounding areas, creating a sense of shared purpose and resilience while supporting equitable and sustainable development in maritime regions [64]. Figure 6 illustrates a conceptual model depicting maritime pilotage's diverse effects on seaports' social sustainability. Each identified driver exerts a potential influence that can be assessed using specific indicators. These indicators may be subdivided into sub-indicators, offering a more detailed impact evaluation. It is essential to recognize that the choice and relevance of these sub-indicators are context-dependent, differing based on the specific operational, geographical, and socioeconomic attributes of each seaport. The identification and analysis of these sub-indicators exceed the scope of this study and are suggested for future research initiatives aimed at localized sustainability assessment frameworks.

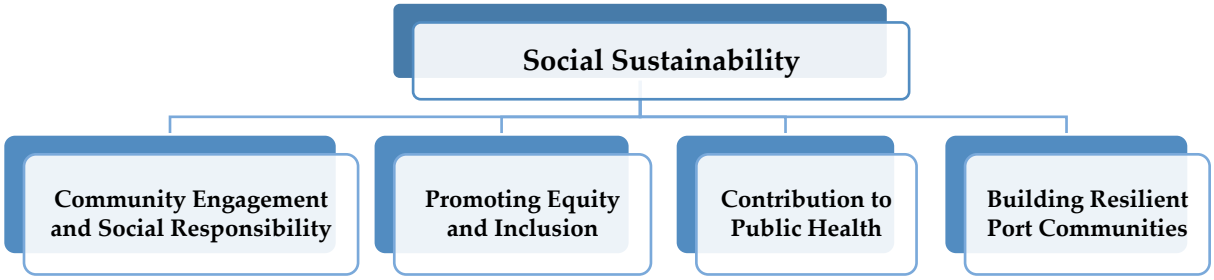


Figure 6. Maritime pilotage key indicators on seaport's social sustainability.

A. *Community Engagement and Social Responsibility*

Transparent and efficient pilotage services foster confidence among port officials, local communities, and stakeholders [53]. Furthermore, their activities frequently include training initiatives that enhance local communities, promoting skill acquisition and diversity in maritime careers. They regularly engage in training programs, educational outreach, and disaster preparedness drills [65].

Furthermore, they enhance the relationship between seaports and their adjacent communities through safety, economic contributions, and collaborative initiatives. These initiatives exemplify the community engagement and social responsibility that maritime pilotage offers to a seaport and its surrounding area [66].

B. Promoting Equity and Inclusion

According to the findings of a 2022 study conducted by Praetorius et al. regarding the training and characteristics of maritime pilotage, the authors believed that ensuring safe access to seaports for ships of all sizes supports equitable trade and economic opportunities for various regions and industries [67]. This can be considered a form of promoting equity and inclusion in the sector mentioned and the region. Furthermore, in areas where maritime traditions are firmly ingrained, pilotage contributes to the preservation of these cultural activities, boosting the sense of community identity and pride through the preservation of these traditions [68]. Ultimately, the research conducted by Andresen et al. in 2007 indicates that a career in pilotage may provide job satisfaction and benefits to the local communities and cultures in the surrounding area [69].

C. Contribution to Public Health

B. Brooks et al. (2016) highlighted in their research that a key mission of maritime pilotage is to guarantee the safe navigation of vessels within seaport areas and beyond [12]. Ensuring safe navigation minimizes the risk of oil spills and other contaminants that may adversely affect water quality, fisheries, and public health [70]. In addition, according to Paulauskas et al., in 2020, congestion and delays were reduced, and air quality improved by lowering emissions from idle vessels [28]. This directly impacts the health of the communities in the surrounding area.

D. Building Resilient Port Communities

Research by X. Liu (2023) and D. R. Hunter (2011) underscores the critical role of pilots in emergency scenarios, highlighting their specialized expertise in navigating vessels to safety amid adverse weather conditions [71,72]. Based on other research, this protects port infrastructure and saves human lives, directly impacting the community's reliance. Such dynamics may be seen in many places where ports, rivers, channels, and waterways are near local neighborhoods, emphasizing the importance of their function [69,70]. Furthermore, based on Delphine et al, (2019), it is possible to argue that their participation in the design of port expansions ensures that new projects consider the welfare and safety of the community [73].

4. Discussion

Based on the materials mentioned above, the function and impact of maritime pilotage, along with the involvement of maritime pilots in navigating vessels through seaport regions, channels, and canals, regardless of whether their employment is compulsory or optional, are crucial for minimizing accidents, improving navigation efficiency, and mitigating issues related to time, expenses, fuel usage, and environmental effects. The complex interactions and relationships between the different factors that marine pilotage affects deserve a more in-depth analysis. In addition, these dynamics can be seen and studied from various perspectives, which sheds light on how they are connected and how their effects overlap. In the following paragraphs, the interactions and relationships are interpreted briefly.

4.1. Interactions and Relationships

Environmental ↔ Economic: Maritime pilotage catalyzes transformative sustainability in seaports by integrating environmental stewardship with economic resiliency. In addition to immediate eco-efficiency, piloting methods affect systemic cost frameworks by preserving assets over the long run; optimal navigation minimizes vessel deterioration, prolonging lifespans, and postponing capital investments [74]. Considering that the marine pilot alone is not accountable for implementing low-emission technology and compliance with IMO environmental regulations, investing in green pilotage solutions reduces regula-

tory fines under frameworks such as IMO's MARPOL Annex VI. Based on research by j. Rodrigo (2016), It enhances market competitiveness by attracting cargo and ship owners seeking environmentally sustainable logistics chains [75].

Moreover, precise navigation and AI-optimized routing effectively reduce congestion hazards, minimizing berth occupancy durations and increasing port throughput capacity, thereby associating environmental conservation with concrete financial benefits. By integrating sustainability into pilotage operations, seaports shift from a compliance-oriented approach to a value-creation framework, where environmental protections are immediately monetized, and operational excellence serves as a fundamental competitive advantage. This synergy demonstrates that innovative pilotage is crucial for concurrently promoting ecological integrity and economic growth.

Economic ↔ Social: Maritime pilots enhance operational efficiency and promote strategic sustainability by influencing port adaptations to changing international standards. Their accuracy lowers vessel congestion and environmental impact, matching port operations with global sustainability objectives. This operational enhancement bolsters the port's market standing, establishing it as a favored hub for environmentally concerned shipping companies. Ports that attract sustainable enterprise foster permanent job possibilities, hence promoting socioeconomic mobility in adjacent areas. Moreover, pilots' knowledge-sharing techniques cultivate a culture of safety and innovation among port stakeholders, connecting operational excellence to the development of social capital. The interaction of operational excellence, environmental stewardship, and social progress establishes a holistic framework for seaport sustainability, wherein one aspect enhances and perpetuates the others throughout time.

Social ↔ Environmental: Pilots are essential in aligning operational efficiency with environmental conservation, serving as a link between maritime risk management and environmental consciousness. In addition to reducing marine pollution via safer navigation, pilotage interventions enhance predictive environmental modeling, allowing port authorities and stakeholders to foresee environmental vulnerabilities and proactively modify operations. This strategic alignment enhances community trust by mitigating latent ecological threats and incorporates environmental intelligence into port governance frameworks.

Furthermore, pilotage services represent a practical application of corporate social responsibility (CSR), transforming CSR from theoretical commitments into quantifiable and actionable results, including habitat conservation metrics and emission reduction objectives. Pilotage establishes a feedback loop in which improved environmental performance leads to increased community support, subsequently motivating ports to invest more in sustainable innovation. These evolving dynamic shifts pilotage from a conventional safety role to a strategic component of comprehensive port sustainability, integrating ecological health, social legitimacy, and operational excellence.

4.2. Analyzing Indicators

Recent research by the authors of this study in 2023 indicates that maritime emissions account for over 56% of total emissions at the studied port, highlighting their significance within port boundaries [18]. Furthermore, many ports have begun implementing CI and OPS to reduce fuel consumption for vessels at the jetties and during hoteling [76]. As a result, a significant portion of the primary emissions is solely linked to maneuvering operations during the pilot's time onboard and pilotage activities. Given that a pilot's primary responsibility is precise navigation, it is also essential to emphasize the role of sustainable practices within pilotage.

In summary, identifying and analyzing indicators to assess the sustainability impact of maritime pilotage is a significant concern. This research's findings categorize the indicators

into three dimensions, namely, environmental, economic, and social. These dimensions can be further divided into additional categories.

4.3. Framework

Figure 7 illustrates a sustainability framework for maritime pilotage and seaport sustainability, integrating environmental, economic, and social indicators. Additionally, the arrows within each domain, such as environmental sustainability, economic sustainability, and social sustainability, represent various components' mutual influence and interdependence. For instance, elements like emissions reduction and climate change mitigation contribution in the environmental sustainability section are connected through bidirectional arrows, reflecting their interconnected roles in reducing environmental impacts. Similarly, the economic sustainability block shows how long-term strategic benefits are linked to competitiveness and revenue generation, highlighting the financial importance of sustainable practices.

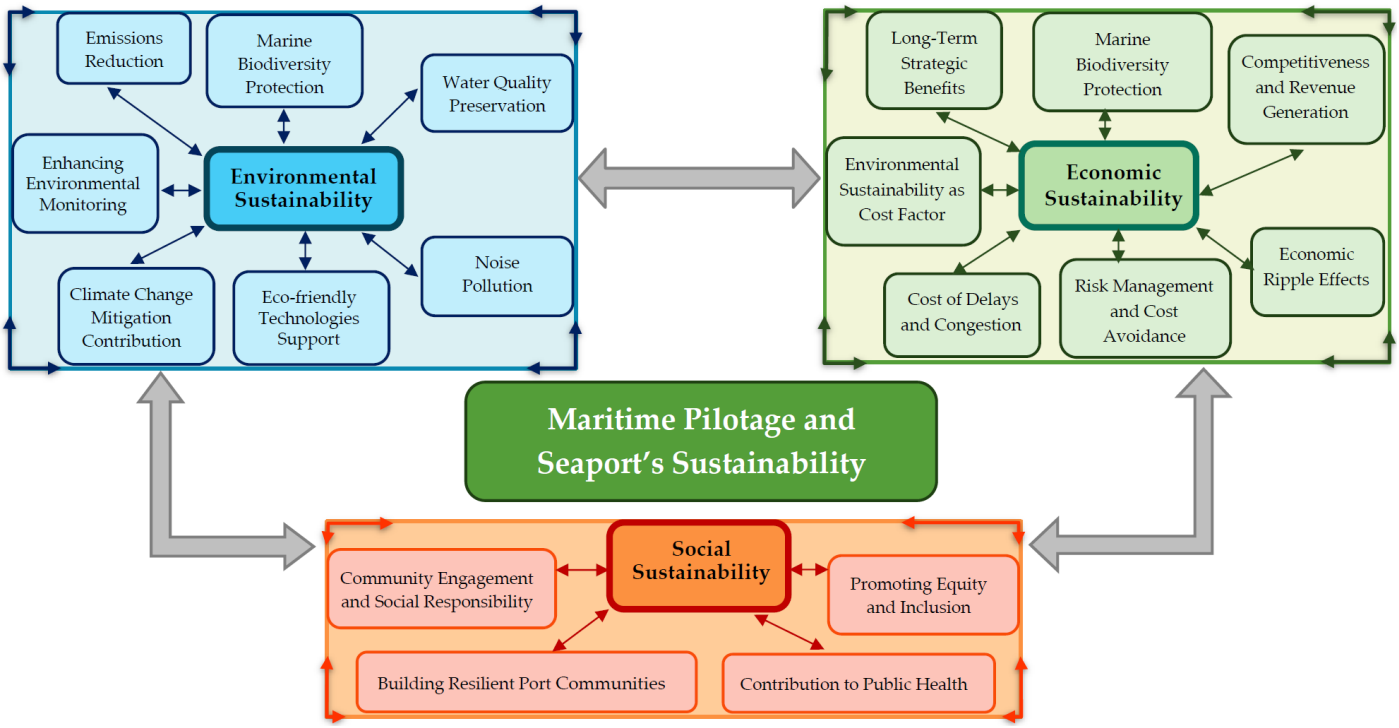


Figure 7. Maritime pilotage and port sustainability interaction framework (author's ownership).

The gray arrows connecting the three main domains symbolize the cross-dimensional interactions essential for achieving overall maritime sustainability (inside a port boundary). For example, environmental sustainability supports economic sustainability by reducing costs associated with delays and congestion, while social sustainability links to environmental through community engagement and economic through public health contributions. At the center, the maritime pilotage and seaport's sustainability box acts as a core integrator, emphasizing that successful maritime operations rely on a balanced approach across all three pillars. This continuous loop of influence underscores the feedback nature of sustainability in maritime contexts, where improvements in one domain can positively or negatively impact the others, creating a complex but essential balance for long-term sustainability.

As Figure 7 shows, the sustainability impact of pilotage on seaports is evaluated through environmental indicators that measure reductions in fuel consumption, emissions, and pollution incidents. Water quality around ports is monitored, indicating the

environmental advantages of safe and efficient ship maneuvering. On the other hand, economic indicators assess the operational and financial benefits derived from pilotage, encompassing time and cost savings per vessel movement, enhanced port revenue or shipping traffic attributable to reliability, and reductions in fuel costs for port clients. Lastly, social indicators emphasize the effects on individuals and communities, including incident frequency, employment prospects for local pilotage personnel, and community satisfaction with port operations. These indicators highlight the role of pilotage in promoting trust and social welfare.

The interconnection among these indicators illustrates a comprehensive approach to seaport sustainability and indicates that environmental protections, including emission reductions, stimulate economic advantages and social benefits, establishing a virtuous cycle. Ports using sustainable pilotage practices enhance air and water quality, save operational expenses, attract investments, and cultivate resilient port communities. These observations corroborate the conceptual framework posited in this study, highlighting the dynamic interaction between pilotage procedures and sustainability outcomes and indicators.

Any deviation in contributions within an impact section can influence contributions from others. This relationship indicates the strategic importance of integrating sustainable practices in pilotage, resulting in long-term benefits for port resilience and global sustainability goals. Pilotage improves operational efficiency and fosters environmental and social harmony by reducing risks and incorporating eco-friendly technologies. Conversely, it endorses overarching objectives such as protecting marine biodiversity and mitigating climate change, highlighting the maritime industry's responsibility in conserving natural resources and minimizing its ecological impact.

Additionally, it highlights the significance of community engagement and social responsibility, framing maritime pilotage to promote equity and inclusion while contributing to public health. The economic ripple effects of sustainable practices are highlighted, potentially resulting in broader economic benefits and long-term strategic advantages. Economic factors, such as the avoidance of delay costs, directly impact environmental sustainability by mitigating emissions associated with congestion.

In summary, the framework offers a thorough view of marine pilotage's significance in promoting seaport sustainability, including environmental, social, and economic aspects. It underscores the significance of reconciling operational efficiency with sustainability goals. The interrelated elements emphasize the necessity for coordinated initiatives to enhance the resilience of port communities. Moreover, contingent upon each port's distinct conditions, location, and features, additional essential aspects may influence the attainment of sustainable port growth.

4.4. Recommendations for Actions

Port authorities should incorporate marine pilotage into their sustainability plans since it helps achieve environmental, economic, and social goals. To reduce emissions during vessel maneuvering, pilotage operations must actively engage in and promote green technology, including shore power supply systems, cold ironing, and automated mooring systems. In addition, port authorities should also create and use quantitative indicators to measure the impact of pilotage methods on sustainability outcomes for data-driven decision-making and progress assessment. They should also encourage pilots to learn new technology, sustainable navigation, and environmental stewardship through ongoing training.

Pilots should optimize ship maneuvering, minimize engine idle, and use efficient routing tactics to reduce fuel consumption and emissions. Environmental stewardship includes following waste management rules, avoiding unlawful discharges, and safeguard-

ing marine ecosystems during navigation. Moreover, pilots must use green technology like smart glass and remote piloting systems to improve efficiency and reduce environmental impact. Pilots are also urged to provide environmental and operational risk data to help port authorities build sustainable facilities and procedures.

The regulatory bodies must prioritize the formulation and execution of explicit rules and standards that include sustainability concepts in pilotage activities, therefore fostering the adoption of best practices that enhance environmental protection, economic efficiency, and social responsibility. Adhering to international environmental norms and regulations, including the IMO's MARPOL and GHG initiatives, is essential for alleviating climate change and safeguarding maritime ecosystems. To attain these objectives, regulatory agencies must promote coordination among port authorities, pilots, shipping companies, and environmental organizations, therefore promoting a unified effort to improve sustainability in marine pilotage.

5. Conclusions

The findings of this study emphasize the pivotal role maritime pilotage plays in advancing the sustainability of seaports across different dimensions. By framing pilotage as a critical determinant of port sustainability, the research bridges existing gaps in the literature, particularly regarding measurable indicators and their interconnections.

From an environmental standpoint, pilotage is crucial in diminishing emissions, safeguarding marine biodiversity, and improving water quality. Pilots' strategic navigation tactics help reduce fuel usage and pollution. Pilotage activities that promote sustainable port technology, including OPS systems and CI, enhance these initiatives. Furthermore, pilots are essential in reducing dangers linked to invasive species and oil spills, assuring adherence to international standards while protecting maritime ecosystems.

Economically, pilotage improves port efficiency and competitiveness by minimizing delays, streamlining logistics, and decreasing operating costs, all of which coincide with the objectives of the circular economy. Practical pilotage minimizes transit duration, enhances throughput, and decreases vessel fuel costs. Moreover, the competitive edge obtained by dependable pilotage services draws increased shipping and fortifies regional trade networks. The correlation between environmental and economic advantages is apparent in the decreased fines and increased income stemming from adherence to sustainability standards.

On the other hand, this study emphasizes social sustainability, which is often disregarded in maritime studies. Pilotage substantially contributes to community wellbeing and economic stability by assuring safe navigation and creating local job opportunities. It fosters community trust via open operations and engagement activities, including training programs and emergency preparedness drills. Furthermore, the function of pilotage in improving public health through emissions reduction and accident avoidance enhances the quality of life for populations next to seaports.

Although this study provides a thorough analysis, classifies it, and then provides a conceptual framework about the effects of pilotage, it encounters specific limitations. The lack of empirical confirmation via case studies or longitudinal data diminishes the framework's practical significance. A primary limitation was the lack of suitable and pertinent literature; among the restricted amount of available research, especially that with quantitative and quantifiable markers. Moreover, the available reports were frequently overly short, unauthorized, or deficient in the methodological rigor necessary for scholarly research, thus constraining this study's depth. Furthermore, the generalizability of the findings is limited, as variations in operating environments, governance, and regulatory frameworks among seaports may affect the application of the conclusions. Localized

studies and standardized data would be essential in validating and augmenting the insights provided by this research.

Future studies can investigate the differences discovered in greater depth to ascertain the most effective approaches for various maritime contexts. Adapting the suggested framework to suit the distinct features of different maritime habitats will improve its applicability and resilience in varied operational scenarios. Likewise, future research may concentrate on each sustainability indicator separately, doing a comprehensive analysis to provide more profound insights and consequences. Researchers are advised to implement and assess the suggested framework via empirical case studies, enhancing its practical significance and facilitating its refinement through real-world application.

Author Contributions: Conceptualization; methodology; validation; formal analysis; investigation; resources; data curation; writing—original draft preparation; writing—reviewing and editing; visualization; and supervision by S.B.I.-Z. and C.L.G.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

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