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Systematic Review of Smart Ports: Trends and Future Research Directions

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ABSTRACT: The concept of smart ports has gained increasing attention in recent decades. The academic literature on smart ports has expanded considerably, yet remains fragmented. This study conducts a systematic literature review to address three key research questions. Additionally, VOSviewer software is employed for bibliometric mapping and visualization of keyword co-occurrence and thematic clusters. The findings identify fours dominant themes, such as smart port concept and technological foundations, port development and intelligent systems, performance-focused through digitalization and strategic governance and sustainability. In conclusion, the literature reveals that smart ports are not defined solely by their technological capabilities but by their ability to integrate innovation across infrastructure, operations, strategy, and environmental goals. Despite the lack of a concrete definition, there is a growing understanding on the key components and objectives of smart port development. Finally, the review outlines emerging gaps and proposes a forward-looking research agenda focused on areas such as how to address the challenges in smart port concept.

1 INTRODUCTION

Ports play a crucial role in global supply chain performance (Frazzon et al., 2019) and they also play an important role in global shipping. They function in the context of complex infrastructure, business transactions, and regulations. With the global economy demanding maritime transportation, ports have faced increasing pressure to optimize their performance in terms of economic, environmental, energy, and functional challenges that impact their sustainability (Molavi et al., 2020). Improving the efficiency of operating activities while minimizing the impact on the environment are increasingly prioritized of seaports over stiff competition in global supply chains. Incorporating advanced technologies connected with the fourth industrial revolution, smart port has become a strategic direction towards sustainable development of modern seaports (Pham, 2023).

The term smart port is receiving rapidly growing attention in the literature. There are several studies that review the essence of smart ports. The term "smart port" was first introduced in 1994, when the concept of the intelligent transport system was introduced in the ports of maritime transportation hubs, where the most advanced information, communication, electronic control, and computer processing technologies were integrated into the traffic and transportation management system (Lin et al., 2022).

According to Li et al. (2018) smart seaport can be defined with following phrase "all parts of the port terminal operations, warehousing, logistics, yard and port transportation are closely connected through the wireless network or special network, providing all kinds of information for daily production supervision, related government departments and port shipping enterprises" (Li et al., 2018). Othman et al. (2022)

describes the concept of smart ports to be in the presence of a port in which the environmental impacts are addressed, the efficiency of operations is supported, and energy consumption is reduced. This concept helps transform seaports into Smart Sustainable ports in global supply chains. There are five main groups that govern the smart port which are the environmental group, the operations group, safety and security, human factor and the energy group (Othman, El-Gazzar, et al., 2022). Belmourikari et al. (2023) conducted a systematic literature review on smart port concept based on the literature and described as following: ''The smart port is a connected, sustainable, safe and automated port, which relies on smart infrastructure and equipment, skilled personnel and smart managerial practices, to ensure customer satisfaction, environmental protection and a better quality of life for the citizen.(Belmoukari et al., 2023)''

According to the studies, four major domains emerged as central to smart port development: technological foundations, operational performance, governance and strategy, and sustainability integration. In the technological domain, studies highlighted the pivotal role of Industry 4.0 enablers, such as IoT, big data analytics, AI, blockchain and digital twins, in transforming port operations (Basulo-Ribeiro & Teixeira, 2024)(Paraskevas et al., 2024) (Li et al., 2023). In the operational performance domain, findings emphasized that automation and intelligent systems significantly improve efficiency, throughput, and service reliability, but real-world adoption remains uneven due to infrastructure, investment, and interoperability challenges (Bakhsh et al., 2024) (Boullauazan et al., 2023)(Alzate et al., 2024). Within the governance and strategy domain, research underlined the importance of stakeholder collaboration, regulatory alignment, and strategic planning for successful digital transformation, although governance frameworks remain underdeveloped (Li et al., 2023) (Paraskevas et al., 2024). Finally, in the sustainability integration domain, studies revealed growing convergence between digitalization and environmental objectives, with green technologies and standardized sustainability KPIs increasingly seen as essential to smart port competitiveness (Gerrero-Molina et al., 2024)(Alzate et al., 2024). Together, these findings show that while technological innovation has been the dominant driver, the next phase of smart port development will depend on integrating operational efficiency, sustainability, and governance into a unified strategic framework.

The motivation of this paper arise from the growing attention to smart ports and previous systematic literature reviews that have explored the smart port literature advancement. For instance, Pham (2023) has conducted a systematic and bibliometric literature analysis based on Web of Science that pointed out three main thematic areas in smart port literature and suggested repeating the search. While previous studies have made important contributions to understanding smart port development, they have generally focused on specific facets or periods, leaving a need for a more comprehensive and up-to-date synthesis. Gerrero-Molina et al. (2024) explored the convergence of green and smart technologies, Boullauazan et al. (2023) validated a practical maturity model and Basulo-Ribeiro and Teixeira (2024) focused on Industry 4.0 technologies and adoption barriers. Paraskevas et al. (2024) integrated conceptual, technological, and performance perspectives in the Industry 4.0 context, while Li et al. (2023) provided the first large-scale bibliometric mapping of the field. Bakhsh et al. (2024) offered a consolidated classification of performance indicators linked to technological evolution and Alzate et al. (2024) conducted a comprehensive review of operational efficiency and sustainability in smart ports. Each of these works advanced the field but was limited in either temporal coverage, thematic breadth, or methodological integration. Existing literature covers different aspects of smart ports, describing the concept of smart port and technology in use, but where smart port literature is expanding and which aspects of smart port could be explored, is not clear. This study aims to bridge this gap by systematically consolidating existing knowledge by categorizing the clusters in the literature.

To investigate the current advancement of smart ports in the literature and future domains, the following research questions have been formulated.

- R.Q.1 What is the current advancement in smart port literature?
- R.Q.2 To what direction does the smart port literature evolute?
- R.Q.3. What are the possible future research areas in the smart port domain?

This study adopts a hybrid review approach, combining a PRISMA-guided systematic literature review with bibliometric co-occurrence analysis using VOSviewer. Unlike purely bibliometric works such as Li et al. (2023), which focus on mapping research networks, or purely qualitative literature reviews such as Bakhsh et al. (2024), this approach integrates quantitative trend and network analysis with in-depth thematic synthesis. This dual method allows to capture both the structural evolution of smart port research and the substantive thematic developments, producing a more comprehensive and actionable understanding of the field.

The research utilizes the PRISMA framework to conduct a systematic literature review, aiming to investigate the current state of art of smart port literature in Web of Science database. This systematic literature review is conducted to assist both researchers and maritime industry practitioners to understand the research gaps of previous studies. Considering the broadness of the topic regards to smart ports, systematic literature review (SLR) is necessary to explain the breakthroughs of past contributions regarding current state of art, how the smart port term has evolved over the years and to which direction the smart port domain discussions could evolve in the future research.

The structure of the paper is as follows: Section 2 describes methodology of completed systematic literature review method using PRISMA approach. Results and discussion section describing the results of literature review are visualized with VOSviewer in Section 3. Finally, Section 4 draws conclusions of the research work, and it outlines the main results as well as provides directions for future studies and research areas.

2 METHODOLOGY

A systematic review methodology was adopted to analyze and synthesize the existing state of art in specific database. Systematic literature review (SLR) is used for giving an overview of current state of art. This method is particularly suited for consolidating current knowledge, offering a structured approach to listing each stage of the research process and ensuring the reproducibility of the findings.

Furthermore, for this study the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was chosen as it provides standardized and transparent process for reporting systematic reviews. It has been also gained widespread acceptance and proven effectiveness in conducting systematic literature reviews across diverse disciplines. The subsequent sections provide a detailed explanation of the methodology and outline the proposed frame.

PRISMA offers the advantage of incorporating specific procedures that promote consistency, transparency, and adherence to high standards in generating qualitative research reports. This method is known as a systematic process because it follows a clear protocol for production and has a broad scope that includes all pertinent and reusable materials (replicate) that previous researchers who have taken a similar approach to the topic have used to discuss it. Researchers can benefit from accessing works from reputable and well-known databases by adopting a systematic approach using the PRISMA method in the social sciences. This approach allows for the use of keywords to clearly define the scope and limitations of the study. These rules also prevent writers from wasting time and second-guessing if the highlights of their work are sufficient. Through the four procedures of identification, screening, eligibility, and inclusion, PRISMA assists the author in finding the appropriate literature in accordance with the study's objectives (Jamaludin et al., 2020).

The proposed framework for review is presented in Fig 1. A systematic approach based on PRISMA has been applied to cover the published articles over the last decades. The PRISMA procedure streamlines objectivity and permits the researcher to evaluate the review's quality and it also provides a guideline that consists of items in the form of a checklist to improve transparency and clarity in reviews (Page and Moher, 2017).

For identification phase we have established a comprehensive set of criteria to be employed to Web of Science database to retrieve the articles that align with the research objective, exploring the smart port term in the literature. Only one data base Web of Science was used to ensure about the quality of articles. Web of Science is the leading and prestigious academic database. To retrieve high-quality content and increase reliability of studies, only one databased was chosen for this research, as Web of Science includes peer-reviewed and high-impact journals. For instance, a search with keywords''smart port'' was conducted in order to understand the situation in the literature considering all the topics on smart ports. The time frame was not set to review all the articles related to the topic. To ensure the quality of the data, we limited our search to peer-reviewed journal articles published in English.

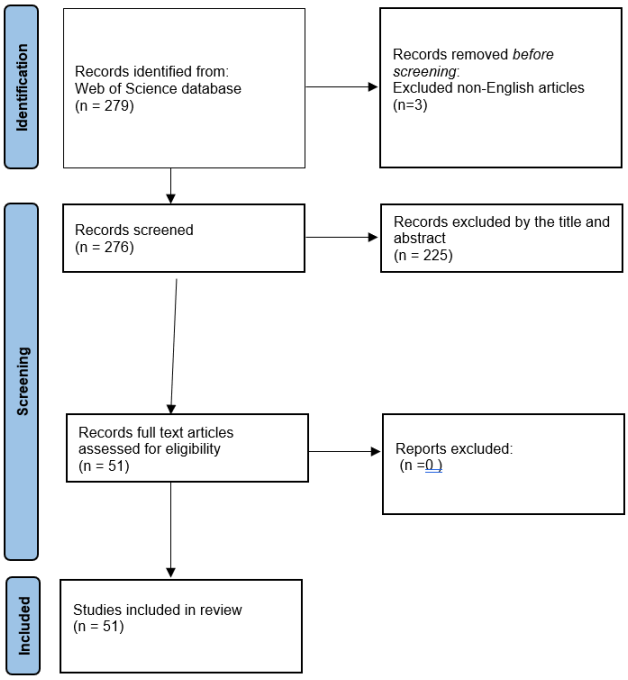

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses flowchart for systematic review.

In the screening phase, the initial search yielded 279 articles taken as of 02.05.2025. The next step involved a detailed assessment of the titles and abstracts where the articles were reviewed to determine their relevance to the research focus. This screening resulted in the exclusion of 225 articles that did not relate to smart port term itself, its advancements or foresight for the future of the smart ports. Additionally, we excluded conference papers and book chapters to maintain the high quality of the final dataset.

In the eligibility phase, the remaining 51 articles underwent an abstract review. Each article was carefully assessed for its eligibility, focusing on its relevance to smart port terminology.

In the last phase of inclusion, 51 articles were identified as fully relevant to the study, and included by conducting in-depth analysis. These articles form the basis for addressing the research questions related Fig. 1 above presents the PRISMA flowchart, which visually outlines the entire review process, from identification through to the final inclusion of studies.VOSviewer leveraged the analysis of the articles to identify the latent structure of the smart port literature, VOSviewer is a useful visualization tool for analyzing vast number of keywords and their connections, while showing different clusters in different colours.

3 FINDINGS AND DISCUSSION

This study reviewed 51 articles, which were directly related to the keywords inserted to the database. There was no time limit set, the selected articles were written between 2018 and 2025. The evolution of extracted articles is shown in Fig 1. There is a significant increase in published articles after 2019. The highest number of

articles (14) were published in 2022. There was a slight decrease in 2023, which followed an increase in 2024. As the data was collected in May 2025, the number of publications for 2025 is not accurate.

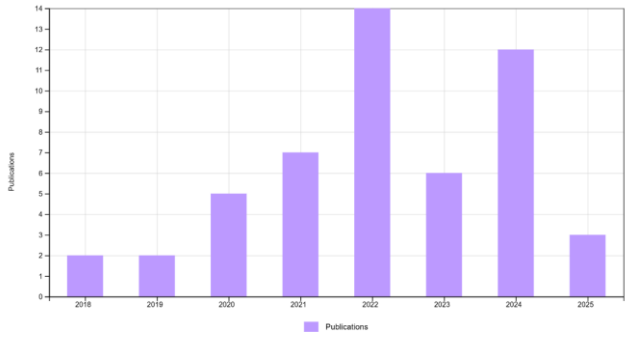

Figure 1. Number of publications over the years. (Source: Web of Science).

In Fig 2 it was revealed that smart port literature citations have been increased drastically in recent years. That explains the growing attention and studies in smart port field.

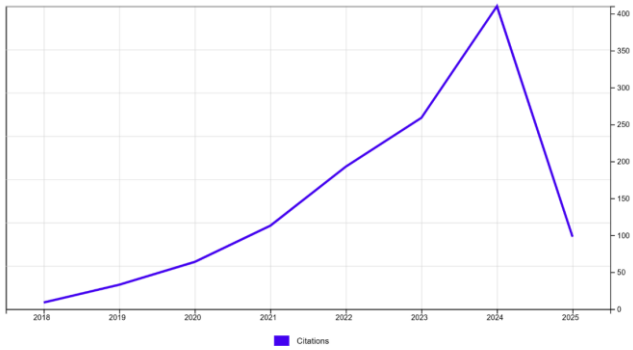

Figure 2. Citation report. (Source: Web of Science).

In this section, VOSviewer was used to visualize the clusters within the research area. The visualization results obtained from VOSviewer experiments is shown in Fig 3. The analysis revealed the existence of four research clusters focused on the following main thematic areas: smart port concept and technological foundations, port development and intelligent systems, performance- focused through digitalization and strategic governance and sustainability. The coloured lines between clusters reflect the cluster-relatedness, with a line width indicating the number of citations between clusters.

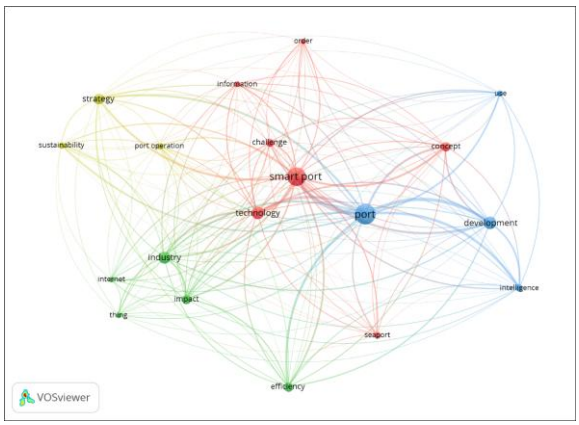

Figure 3. Network visualization (Source: created with VOSviewer)

At the center of this network lies the term ‘smart port’’, which connects those four dominant clusters to each other. These clusters directly inform the first two research questions.

The first cluster (red) can be named as smart port concept and technological foundations, which forms a distinct cluster in the network. The visualization relates smart ports with technology, challenges, concept, information and order, which indicated to articles that focused on establishing the digital and conceptual infrastructure for smart ports and also that a substantial portion of the literature is devoted to exploring and refining the core technologies underlying smart port system.

There are several studies that define the concept of smart port. According to Karas (2020) smart port is an idea without a very specific definition. Therefore, this is a one of modern development perspectives in ports and shipping where the concept is still undergoing transformation. The idea of smart ports is not only management of technological processes, but also digitalization, increasing the efficiency of operations in ports, integration of ports with cities and acquiring energy from alternative sources. Smart port - the new model of management is a series of innovative tools used on technological and organizational level (Karaś, 2020). Yen et al. (2023) integrated previous studies to define general smart port concept as the concept characterized by environment, automation and intelligence (Yen et al., 2023). Smart port is not only associated with the technological processess. For instance, Chen et al. (2019) and Molavi et al. (2020) proposed five key aspects for a smart port that should have: smart infrastructure, well-educated personnel, automation, skilled workers and environmental awareness (Chen et al., 2019)(Molavi et al., 2020). Smart infrastructure and automation are directly related to the technology and indicating to the smart port concept. As mentioned before, smart ports are mostly associated with using technology in order to improve the smart port operations. Yet, there are challenges when trying to automate processes. Triska et al (2024) proposed conceptual framework that contributes to defining the relations between smart ports and intelligent systems. Molavi, Lim, and Race (2020) concluded that they have all the infra-structure and info-structure of IT and new technologies in telecommunications, electronics, and mechanical equipment, gather better-educated individuals, skilled workforces, and automation to promote knowledge development and sharing, optimize port operations, increase port resiliency, lead to sustainable development, and ensure safe and secure activities (Molavi et al., 2020). Karas (2020) describes that technological innovations give the opportunity to create so-called Smart Ports. However, determining which technologies to choose, how to implement them remains a challenge (Karaś, 2020). Othman et al (2022) highlights the essence of using technology to facilitate process imprvements across port logistics. In addition, By going smart, connectivity and automation will help decrease environmental foot-prints of the port industry, as will smart transport systems that reduce CO2 emissions (Othman et al., 2022). Smart port applications have other dimensions that affect their characteristics, related to scope of decision-making and

level of information sharing among stakeholders (Triska et al., 2024).

The second cluster (blue) can be named " port development and intelligent systems. The keywords, i.e. port, development, intelligence and use may be conceptually linked to the strategic management of ports. This cluster highlights research that explores how legacy ports are being upgraded to accommodate new digital technologies. Furthermore, this cluster emphasizes the transformation of existing port infrastructure through the integration of smart technologies. According to Gonzales et al. (2020), digitalization is a fundamental factor for a port to become more intelligent (Rodrigo González et al., 2020). In addition, as mentioned in the previous cluster, according to Molavi et al. (2020), an intelligent port has all the infrastructure and info-structure of information technology and the most recent technologies in telecommunications, electronic, and mechanics (Molavi et al., 2020). (Xiao et al., 2022) introduced a framework of smart ports including production operation, production management, intelligent services, risk management and control, and intelligent scheduling. There are plenty of systems that can be applied to smart ports, which makes them more intelligent. However, a smart port is a certain level of development in port. There is still a long way to go to reach the mature concept of port and probably is not the final step in port development (Karaś, 2020). Gao et al. (2022) conducted a literature review on data governance issues in applying the advanced IoT technologies in the smart port operation and highlights that the Internet of Things is considered to be the foundation of the innovation and high-level automation of the smart ports, IoT data governance is essential for ensuring the stable and efficient operation of the smart ports. However, there may still be required in-depth study as the IoT implementation become complicated for high-level automation and is deeply integrated with the current port infrastructure(Gao et al., 2024). (Zhou and Suh, 2024)explained the smart port development to be connected with using cutting-edge technology, which has become the most common approach to increase port efficiency. Sadri et al. (2021) concluded that as stated in previous research, green and smart ports are the primary strategy for the development of industrial infrastructure and maritime transit industries. Therefore, evaluating the efficiency of ports is very important in terms of compliance with the indicators of greenness and intelligence (Sadri et al., 2022).

The third cluster (green) can be named performance- focused through digitalization. The following keywords appear: Industry, impact, internet, efficiency and thing. This cluster suggested a strong focus on performance outcomes and technological convergence. Industry 4.0 is closely related to smart ports. However, the four industrial revolutions did not affect port operations in the same way that they affected manufacturing (Triska et al., 2024). To be labeled smart, a port does not have to handle the information of all machines, environmental aspects, and stakeholders in real-time. Instead, the port is smart to a certain degree if it has one or more smart applications, in a similar way that smart objects may have different levels of intelligence (Triska et al., 2024). It is expected that future fully automated smart ports will be data-driven, harvesting power from advanced analytics and artificial intelligence. Under the hood, Internet of Things (IoT) technologies are considered as an enabling foundation of new data sources for innovations and high-level automation. Although the IoT adoption in smart ports receives significant interest from the port authority, the effectiveness of the IoT adoption lacks proper evaluation and support of comprehensive data management policy and guidelines (Gao et al., 2024). Therefore, the authors highlighted the complicity of IoT implementation for high-level automation. For instance, when it comes to efficiency, Zhou et al. (2020) explored the key challenges and critical success factors of blockchain implementation. According to the authors, blockchain has the potential to improve the efficiency and transparency of maritime businesses and operations (Zhou et al., 2020). Sadiq et al. (2024) investigated in their study the development of next-generation smart ports, wherein the integration of Internet of Things (IoT) and sensors transforms ports into intelligent hubs. The research highlights the potential of smart ports to significantly reduce greenhouse gas emissions, optimize energy consumption, and enhance operational accuracy. Similarly to previously mentioned study, (Yau et al., 2020) conducted a review of the research literature on smart ports, including Internet of Things platform, greenhouse gases emission reduction, energy efficiency enhancement.

The fourth cluster (yellow) can be named as strategic governance and sustainability . The following keywords appear: strategy, port operations and sustainability, which are deeply connected as the port strategy defines port operations, which is, in turn, associated with the sustainability of port. This indicates a growing recognition of the need for long-term planning, environmental stewardship, and policy frameworks to guide smart port development. As Karas 2020 connects smart port concept to port strategy, he defines: 'To make the Smart Port concept an element of port strategies, it takes a lot of courage and creativity from the ports. And modern ports without intelligent solutions cannot survive the intensity of competition. (Karaś, 2020)'' Due to the fact that the port is a diverse area, all activities must take place at the terminal level and at the port level. Implementation based on the concept of a Smart Port should bring benefits to stakeholders and the port authorities (Karaś, 2020). When it comes to sustainability, there are many studies connecting smart ports with sustainability. Port development and management can also use road mapping to explore how digital technologies can advance the smart and sustainable development of ports, port cities, and global value chains (Liao et al., 2023). According to Othman et al. (2022) there is no integrated vision provided before to capture different comprehensive elements of smart port and show its impact on sustainably. Therefore, this research aimed at developing an integrated smart port index SPI, capturing different elements of SP and linking them to port sustainability performance. The same authors did another study, which investigated to what extent the Egyptian ports could apply the smart practices and employ technology to achieve and improve sustainability performance through identifying the current situation of the Egyptian ports' performance and investigating the level of readiness and

adaptability to smart port practices and technology employment in the Egyptian ports across five factors–operations, energy, environment, safety, and human resources–and their influence on achieving and improving sustainability performance (Othman et al., 2022). As already mentioned, there is no certain definition for smart port, (Lin et al., 2022) stated there is no standard definition of a smart port, resulting in each country having its own smart port development strategy. Therefore, they explore how varied port governance of port authorities may impact the smart port development strategy (Lin et al., 2022) The study also relieved that different countries on different continents have different focus, when it comes to smart port management.

Based on Fig 4. there is visible how literature has evolved over the time starting with port, technology, development, information and industry, which opened a discussion about how intelligence affect smart port and its concept, relating the impact of Internet to the industry, also connecting the use of technology to sustainability. Finally, starting a discussion on port operations that are affecting efficiency, which are determined by the strategy of the port.

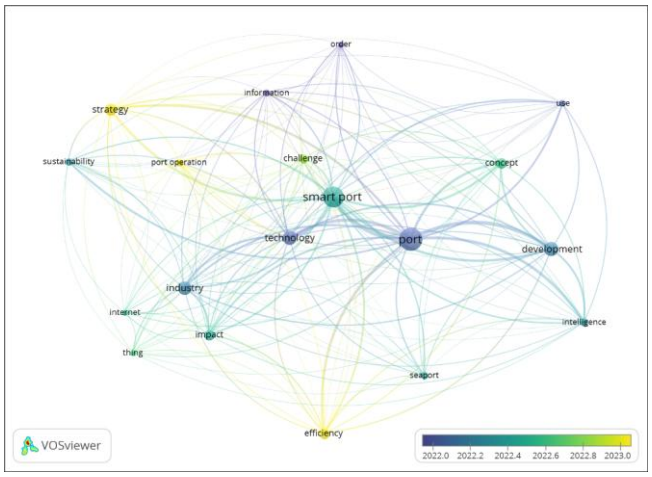

Figure 4. Overlay visualization. (Source: created with VOSviewer).

4 CONCLUSION

This systematic review makes several novel contributions to the advancing smart port literature. Unlike earlier works that focused on specific aspects—such as technological innovations (Gerrero-Molina et al., 2024), performance metrics (Bakhsh et al., 2024), operational efficiency–sustainability integration (Alzate et al., 2024) or conceptual definitions (Li et al., 2023)(Paraskevas et al., 2024)—this study bridges technology, operations, strategy, and sustainability. Using a PRISMA-guided review of 51 journal articles (2018–2025) from Web of Science and VOSviewer co-occurrence analysis, four thematic clusters are identified: smart port concepts and technological foundations, port development and intelligent systems, performance-focused digitalization, and strategic governance and sustainability. This hybrid bibliometric–thematic approach connects previously fragmented research streams into a holistic framework.

The concept of the smart port lies at the intersection of multiple interconnected research clusters, each contributing to a comprehensive understanding of its evolution. The literature indicated that while the smart port remains an emerging and fluid concept, it is fundamentally rooted in technological innovation, digitalization, and strategic transformation. The first cluster underlines the foundational role of technology and conceptual definitions, highlighting both the opportunities and challenges of adopting smart systems. The second cluster emphasizes the gradual transformation of existing port infrastructure into intelligent systems, driven by digital technologies and strategic development. The third cluster focuses on performance outcomes, with strong links to Industry 4.0, Internet of Things, and automation, reflecting a clear trajectory toward data-driven and efficient port operations. Finally, the fourth cluster connects strategic governance with sustainability, underlining the critical role of long-term planning and policy in shaping future-ready, environmentally conscious ports.

In conclusion, the literature reveals that smart ports are not defined solely by their technological capabilities, but by their ability to integrate innovation across infrastructure, operations, strategy, and environmental goals. Despite the lack of a concrete definition, there is a growing understanding on the key components and objectives of smart port development. The research points to a dynamic transition in global port systems, where intelligence, efficiency, and sustainability are becoming central pillars of competitive advantage and future growth. The transition to an intelligent port requires port authorities to prioritize innovative technologies and management practices to be adopted according to their specific challenges and limited resources to face current and future challenges (Belmoukari et al., 2023).

The findings reinforce and extend earlier insights: Industry 4.0 technologies and automation remain central (Basulo-Ribeiro and Teixeira, 2024)(Paraskevas et al., 2024), sustainability–digitalization convergence is a core trajectory (Gerrero-Molina et al., 2024), standardized sustainability KPIs are needed(Alzate et al., 2024), and technology–performance integration is essential (Bakhsh et al., 2024). The review confirms (Li et al., 2023) observation that the "smart port" definition remains fluid but anchored by pillars such as automation, connectivity, sustainability, and stakeholder integration.

Nevertheless, this study differs from prior works in three ways: 1) it combines bibliometric mapping with qualitative synthesis, unlike purely bibliometric (Li et al., 2023) or purely narrative reviews (Bakhsh et al., 2024); 2) it uses only peer-reviewed journal articles for a curated, high-quality dataset; and 3) it captures developments through 2025, including digital twins, AI-driven optimization, and resilience strategies. By addressing gaps in governance, socio-economic dimensions, interoperability, and sustainability metrics, this study provides an up-to-date, evidence-based roadmap for advancing smart port research and practice.

Those four clusters analyzed, there arise questions on what are the areas and domains that are still missing from the literature. Most studies focus heavily on technology and systems, but limited attention is given to human factors. Furthermore, there is a lack of research on cross-port digital interoperability and

global standards that enable smart ports to operate as part of a coordinated global logistics chain. The literature underrepresents economic modeling and policy evaluation for smart port investments. Therefore, future studies could explore how human operators interact with AI-systems in hybrid decision-making processes.

Another idea could be investigating collaborative smart port ecosystems, including shared services, cybersecurity resilience, and cross-border IoT integration. There is also the possibility to perform cost-benefit analyses and economic impact studies of smart port technologies over time.

The primary limitation of this study lies in the exclusive reliance on a single data source, namely the Web of Science database. To enhance the comprehensiveness of the findings, future research could incorporate additional reputable academic databases, such as Scopus and Google Scholar.

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