Maritime Business Review

Smart port performance indicators: future research themes

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Received 22 January 2026
Revised 12 May 2026
Accepted 9 July 2026

Abstract

Purpose – The rapid diffusion of digitalization, automation and sustainability practices has accelerated the transition from conventional ports to smart ports. Despite the expanding literature on smart port technologies, research on performance assessment and performance indicators remains fragmented and largely lacks a holistic perspective. This study aims to systematically review the literature on smart port performance indicators in maritime logistics, identify key research themes and methodological trends and highlight gaps that warrant future research.

Design/methodology/approach – This study employs a systematic literature review combined with bibliometric analysis to investigate academic publications on smart port performance indicators. Relevant studies were collected from a selected academic database using predefined keywords related to smart ports, performance measurement, digitalization and sustainability. The collected data were analyzed using Biblioshiny to conduct scientific mapping analyses, including thematic evolution, keyword co-occurrence and methodological trend assessment.

Findings – The findings reveal that although performance, sustainability and digitalization are frequently addressed together in the smart port literature, they are generally examined in a fragmented and non-integrated manner, with performance measurement largely limited to single operational or environmental dimensions.

Originality/value – The literature lacks a cumulative and holistic development, indicating the need for integrated research frameworks that link digital technologies, sustainability goals and performance indicators. This study offers a concise synthesis of smart port performance indicator research and highlights future research directions. It provides valuable insights for researchers and practitioners seeking to align performance measurement systems with digitalization, sustainability and strategic management in smart ports.

Keywords Logistics management, Digitalization, Performance indicators, Maritime logistics

Paper type Research article

1. Introduction

One of the most enduring sectors throughout history is maritime logistics, and it is a fundamental component of the global economy of trade. Also, seaways carry out 80% of international trade volume (Kilpi *et al.*, 2021; Zhou *et al.*, 2018). By providing transportation, warehousing, distribution and integrated logistics services, the company has been able to play an active role in international trade (Janmethakulwat and Thanasopon, 2025). Moreover, the widespread adoption of digital technologies has facilitated the exchange of information, leading to an increased awareness of sustainability. This phenomenon, in turn, has resulted in the emergence of new demands and the need for the sector to address challenging issues. In the last few years, maritime logistics has experienced a substantial evolution due to the growing penetration of cutting-edge technologies, automation and sustainability practices (Lopes *et al.*, 2025).

More recently, the integration of cutting-edge technologies into business operations has resulted in a range of investment decisions aimed at leveraging the latest applications to ensure

Maritime Business Review
Emerald Publishing Limited
e-ISSN: 2397-3765
p-ISSN: 2397-3757
DOI 10.1108/MABR-01-2026-0012

continued competitiveness within the industry. Furthermore, the use of digital platforms (e.g. the Internet of Things (IoT), sensors, big data and cloud computing) develops port operations and facilitates the productivity of sea-land logistics across all port networks (Castellano *et al.*, 2019). Put differently, as the port process becomes more complex, there is ongoing pressure at ports due to factors such as delays, infrastructure problems, environmental issues, security concerns and labor on a daily basis. Hence, to embrace reliable, optimized and cost-effective port operations, it is critical for ports to acknowledge and utilize the potential of automation and digitalization. As a result, these challenges have led to the emergence of smart ports as a solution (Boadu *et al.*, 2025).

Smart ports, also known as 5th generation ports, have become evident with Industry 4.0 and underscore performance, transparency and connectivity via the latest technologies. In this regard, smart ports combine interconnected systems, automation and data-driven infrastructure to improve operational efficiency, resilience, sustainability and security (Aslam *et al.*, 2020; Li *et al.*, 2023; Molavi *et al.*, 2020).

In parallel, the efficiency of port performance is a building block of success and is highly interconnected with the layout of port infrastructure (e.g. cranes, yard tractors and the working environment). Moreover, environmental and safety drivers are becoming progressively crucial in port operations. Additionally, it has been determined that technological advancements within the port environment contribute to an enhancement in service quality, which, in turn, has a positive effect on customer satisfaction. In summary, how and to what extent overall port performance can be enhanced has become a critical focus in making ports "smarter" (Yen *et al.*, 2023). Alongside operational efficiency, technologies in smart ports are playing an increasingly critical role in the advancement of sustainability objectives. Such progress is achieved through the facilitation of data-driven decision-making processes that are integrated with digitalization, energy efficiency, emissions monitoring, environmental compliance and global decarbonization targets.

Simultaneously, in recent years, there has been an increased focus in the academic literature on digitalization, automation and sustainability applications in smart ports and maritime transport. However, a review of existing studies reveals that research in the context of performance evaluation and performance indicators is fragmented, focusing on specific technologies or individual performance dimensions and it generally lacks a holistic framework. The majority of extant studies in this field evaluate performance dimensions such as operational efficiency, environmental sustainability or service quality separately. Consequently, systematic and comparative analyses encompassing the multidimensional nature of smart port performance remain limited. Moreover, there is a lack of comprehensive syntheses in the existing studies regarding the prominent thematic areas, frequently used performance indicators and the evolution of methodological approaches.

Unlike previous review studies that provide a broad overview of smart port development, this study specifically focuses on the identification, classification and synthesis of performance indicators as the core unit of analysis. While existing reviews (e.g. Li *et al.*, 2023; Bakhsh *et al.*, 2024; Boadu *et al.*, 2025) primarily adopt descriptive or thematic mapping approaches, they tend to treat performance indicators as secondary elements embedded within broader discussions on digitalization and sustainability. As a result, these studies fall short of providing a structured and comparable understanding of how performance is actually measured in smart port contexts. In contrast, this study advances the literature by systematically structuring performance indicators within a key performance indicator (KPI)-oriented analytical framework and examining their interrelationships through bibliometric mapping techniques. This study systematically reviews the literature on smart port performance indicators in maritime logistics by identifying key research themes, methodological trends and research gaps, with a particular focus on how performance indicators are conceptualized, classified and operationalized across studies. In doing so, it provides a structured synthesis of fragmented performance indicator research and highlights areas for future integration and development.

Thus, the study intends to address this gap by making three main contributions to the existing literature. To this end, a detailed review of the literature on smart port performance indicators in the context of maritime logistics was conducted using the systematic literature review (SLR) method. Firstly, it provides a thematic classification of extant studies and addresses the major research topics and themes covered in the context of smart port performance assessment within a holistic framework. Second, it identifies methodological trends and dominant research practices in the literature by analyzing the methodological approaches, data types and empirical research settings used in the studies. This analysis assists in selecting appropriate methods for future studies. Finally, by identifying existing gaps and limitations in the literature, it offers guiding recommendations for future research on smart port performance indicators in terms of thematic focal points, methodological orientations and empirical contexts. Accordingly, this study fulfills a strategic reference function for both academics and port authorities, as well as for policymakers.

In accordance with the objective of the study, the following research questions were addressed:

RQ1. What research topics and themes are being investigated related to performance assessment and performance indicators of smart ports in the context of maritime transport?

RQ2. What trends should future research on smart port performance indicators follow in terms of thematic focus, methodological approaches and empirical settings?

To give answers to these research questions, firstly, Section 2 provides a detailed description of smart ports in the context of maritime transport and outlines some studies conducted on this topic. In the following section, the research methodology is defined and the database used for the bibliometric analysis is explained. Concurrently, the keywords identified in the search string and the approach followed for the bibliometric search and analysis process are also clarified. In Section 4, the visual outputs obtained through the Biblioshiny program for scientific mapping analyses of the collected and filtered data are presented, along with their interpretation. Subsequently, Section 5 proposes research topics for future studies on smart port performance indicators considering the analysis and Section 6 provides the conclusion.

2. Smart port performance in the context of maritime logistics

Maritime transport is a key part of global trade, and ports serve as important nodes in this process. Port performance affects supply chain utilization and is assessed by factors such as ship docking time, cargo handling speed, container efficiency and logistics costs (Wijaya and Nakamura, 2025). Traditional port performance evaluations mainly emphasize operational and financial indicators (Hajar, 2025). Within this context, ship docking and departure times, dock and crane efficiency, container volume, loading and unloading times and cost-effectiveness are notable criteria in defining port efficiency (Molavi *et al.*, 2020). These indicators enhance comparisons between ports and the identification of areas for improvement.

To support trade-driven economic development, port authorities are pressured to improve port efficiency so that ports can compete globally. Ports occupy a pivotal role in the global trade network, and port efficiency is recognized as a key factor in enabling countries to sustain their competitive advantage in the international market (Tongzon, 2001). Along with this, in a highly competitive environment, the measurement of port performance serves as a very effective management strategy for port operators while also forming a fundamental input for the guidance of regional and national port planning and operations. Port performance has traditionally been the focal point of numerous assessments, including the calculation of cargo handling efficiency per berth, the measurement of single-factor efficiency and the comparison of the volume of cargo handled over a specified time with the optimal cargo volume

(Cullinane *et al.*, 2004). Accordingly, traditional performance indicators cover indicators such as ship docking time, crane efficiency, container handling time, total throughput and cost-effectiveness (Issa *et al.*, 2025). However, De Langen (2004) emphasized that firms within port clusters may be reluctant to invest sufficiently in areas that provide collective benefits, particularly in fields such as training and education, innovation, marketing and hinterland accessibility. In addition, the study emphasized that the quality of life in the port region and the existence of a strong knowledge infrastructure have become increasingly important factors for port clusters. On the other hand, the smart port approach integrates these indicators across both technology and sustainability dimensions (Issa *et al.*, 2025).

Today, with the widespread adoption of digitalization, the concept of a "smart port" has emerged as a pivotal concept in the literature. Smart ports are outlined as ports where advanced information and communication technologies, IoT, sensor systems, automation and data analytics platforms are employed seamlessly to optimize port operations (Khalifeh and Caliskan, 2025). The primary objective of these ports encompasses boosting operational efficiency, optimizing energy and resource use, ensuring safety and sustainability and accelerating decision-making processes (Erdogan *et al.*, 2025). For instance, IoT sensors monitor ship and container movements in real time, while automated cranes and guidance systems optimize cargo handling processes. Additionally, data integration platforms enable planning and performance evaluation by managing all operational information within the port from a central location (Liu *et al.*, 2025).

In evaluating the performance of smart ports, it is important to conduct more extensive and dynamic analyses that incorporate data analytics and IoT-based real-time measurements, in addition to standard operational indicators (Paraskevas *et al.*, 2025). Various studies and methodologies examining smart port performance have been published in the literature, with these studies making considerable contributions to strategic decision-making processes in port management. Table 1 summarizes these studies.

Traditional port performance indicators primarily focus on operational efficiency. On the other hand, smart port performance necessitates a multifaceted evaluation. In the existing literature, the assessment is conducted by integrating factors such as digital maturity, data integration, automation level, sustainability and operational efficiency. The domain of port management and maritime transport literature increasingly recognizes the smart port concept and offers innovative metrics to evaluate performance. Accordingly, the measurement of smart port performance is perceived as a critical domain for both academic research and port management regarding efficiency, sustainability and technology integration. In this context, a substantial and methodical review of studies on evaluating smart port performance in the literature is essential. The present study deploys an SLR methodology to extensively evaluate the literature on smart port performance. This method facilitates an objective and reproducible analysis of the methods, scope and findings of extant studies in the research area and assists in the identification of gaps, trends and future research opportunities in the literature. The following section addresses the research methodology.

3. Research methodology

Literature reviews are an important research output because they allow research to build on the findings of previously published studies. Traditional literature reviews typically rely on the knowledge of the authors, while the SLR process is considered a more scientific approach. It involves using empirical research methodologies to increase transparency and reproducibility, thereby reducing the potential for biased results (Lame, 2019). Nevertheless, in comparison with alternative techniques, bibliometric analysis provides both objective and reliable outputs. The recent information obtained, conceptual developments and volume of data provide an environment in which bibliometrics are useful for evaluating trends and topics researched over time, identifying changes at the boundaries of disciplines, identifying the most productive academics and institutions and presenting the broader perspective of current research by

Table 1. Studies about smart port performance

Author(s)	Research aim	Research method
Philipp (2020)	Identify which tools can be used to measure digital performance in ports and make recommendations accordingly	Digital readiness index (DRIP)
Othman *et al.* (2022)	By evaluating the potential use of smart methodologies, assess the extent to which technology can be utilized to improve sustainable port performance	Qualitative research method
Akyıldız *et al.* (2025)	Addressing the obstacles to the development of smart ports based on strategic management and sustainability and offering suggestions on how these challenges can be minimized	Qualitative research method
Molavi *et al.* (2020)	The development of a Smart Port Index that will assist ports in enhancing their resilience and sustainability	Quantitative metric /Smart port index
Boadu *et al.* (2025)	To analyze the development and benefits of smart ports based on operational development and sustainability to establish the Smart Port Concept Implementation	Systematic literature review
Yen *et al.* (2023)	To investigate the extent to which the smart port design can affect efficiency in maritime transport	Three-step DEA-Tobit modeling
Min (2022)	To evaluate the smart port concept and its developmental process and provide guidance for addressing the challenges and opportunities presented by smart ports	Qualitative research method
Bakhsh *et al.* (2024)	To review the Smart Port concept, the technologies utilized and the KPIs, as well as to analyze development trends within the scholars	Systematic literature review and bibliometric analysis
Makkawan and Muangpan (2021)	Establishing smart port indices to conceptualize a smart performance model in the case study of Thailand's Eastern Economic Corridor	Qualitative research method
Yang and Hsieh (2024)	To identify the development potential of smart ports in the post-COVID-19 era and the obstacles encountered during the digitalization of ports	Fuzzy Delphi and the fuzzy analytic hierarchy process
Rodrigo González *et al.* (2020)	To develop a method for assessing the alignment of ports within the Spanish Port System with the Smart Port concept and to rank these ports according to their performance	Index-based performance evaluation and benchmarking
de la Peña Zarzuelo *et al.* (2020)	The aim is to determine how ports and terminals are implementing projects in line with the concepts of smart ports and Ports 4.0, while taking advanced technologies into account	Literature review
Nguyen *et al.* (2025)	The purpose is to assess the competitive strength of the ten container terminals at Haiphong Port based on traditional and modern performance indicators	Entropy–TOPSIS and fuzzy C-means
Li *et al.* (2023)	To establish a coherent academic basis for the smart ports' framework and to pinpoint areas of research that will generate more attention in this field	Systematic bibliometric review
Boullauazan *et al.* (2023)	The development of a strategic maturity model that ports can utilize in their digitalization and sustainability transformation	Systematic literature review, novel maturity model development and case study

(*continued*)

Table 1. Continued

Author(s)	Research aim	Research method
Heikkilä *et al.* (2022)	It determines how smart ports and the Port 4.0 concept will take shape in the future and in which directions they will evolve	Scenario building theory
Paraskevas *et al.* (2025)	To develop a systematic and scientific evaluation framework that takes uncertainties into account in order to measure the smartness of ports	Neutrosophic cognitive maps (Ncms)
Chen *et al.* (2019)	The development of a systematic, scientific and quantitative assessment method to accurately measure the intelligence level of ports	Single-valued neutrosophic exponential similarity measure
Hsu *et al.* (2023)	The aim is to develop a standard model for assessing the service quality of smart ports in the post-COVID-19 era and to identify the key success factors	SERVQUAL, Analytical Hierarchy Process (AHP) and DEMATEL
Lin *et al.* (2022)	Examining the impact of different port governance structures on smart port development strategies	Borda count and fuzzy AHP

offering a structured analysis of a large body of information (Aria and Cuccurullo, 2017). In light of these findings, scholars employ bibliometric analysis for various purposes, including the identification of emergent trends, the exploration of collaborative models and the identification of research components within related domains. Furthermore, this approach facilitates understanding and enables comprehension of the main structure in a specific field. The existing literature (Donthu *et al.*, 2021) has demonstrated this methodology.

Along these lines, Bibliometrix was chosen as the tool for this SLR. It was developed in 2017 by Dr Massimo Aria and Dr Corrado Cuccurullo (Arruda *et al.*, 2022). The Bibliometrix R package is a set of tools for quantitative research in bibliometrics and scientific metrics. The software is also written in the R language, which is an open-source environment. Thus, the statistical features provided by this system and its integrated mapping and graphical tools have made it a viable option for scientific calculations (Aria and Cuccurullo, 2017; Mühl and De Oliveira, 2022).

The objective of this study is to present a comprehensive bibliometric literature review of research related to Smart Ports. The Web of Science (WoS) database was selected for the relevant data in this study. WoS is a database extensively utilized by scholars and has been designated as the search engine with the highest quality standards internationally (Yan and Zhiping, 2023). The WoS database is the most widely used database for bibliometric studies in the fields of management and organization. Moreover, scholars can readily access the WoS database because it contains sufficient data for most bibliometric analyses and is included in the subscription packages of most universities (Zupic and Čater, 2015). Although the inclusion of multiple databases (e.g. Scopus) could potentially increase coverage, WoS was selected as a single data source to ensure data consistency, high-quality indexing and compatibility with bibliometric analysis tools. Nevertheless, this is acknowledged as a limitation of the study and future research may benefit from incorporating multiple databases to enhance the comprehensiveness of the dataset. Besides, the scope of the review was defined using Boolean searches with a series of keywords provided in Table 2, covering studies published between 2016 and 2026. The review exclusively included articles, conference papers, editorial materials and book chapters published in English. Concurrently, categories not related to the subject (e.g. physics, chemistry and health) were excluded from the research. The scanning and data download process was completed on 22 December 2025. As a result of the search strings, a total of 692 studies were identified and obtained. The bibliographic data were converted to BibTeX format and loaded into the Biblioshiny program for further analysis.

Table 2. The search string used in WoS

Step	Search string	Results
1	*"smart port"* OR *"port smartness"* OR *"seaport"* OR *"port"* OR *"maritime"* (All Fields)	449,228
2	*"smart port"* OR *"port smartness"* OR *"seaport"* OR *"port"* OR *"maritime"* AND *"performance"* OR *"performance indicators"* OR *"key performance"* OR *"KPI"*(All Fields)	71,250
3	*"smart port"* OR *"port smartness"* OR *"seaport"* OR *"port"* OR *"maritime"* AND *"performance"* OR *"performance indicators"* OR *"key performance"* OR *"KPI"*AND *"sustainability"* OR *"green"* (All Fields)	4,566
4	*"smart port"* OR *"port smartness"* OR *"seaport"* OR *"port"* OR *"maritime"* AND *"performance"* OR *"performance indicators"* OR *"key performance"* OR *"KPI"*AND *"sustainability"* OR *"green"* AND *"digital"* OR *"technology"* OR *"smart"* OR *"digitalization"* (All Fields)	1,850
5	*"smart port"* OR *"port smartness"* OR *"seaport"* OR *"port"* OR *"maritime"* AND *"performance"* OR *"performance indicators"* OR *"key performance"* OR *"KPI"*AND *"sustainability"* OR *"green"* AND *"digital"* OR *"technology"* OR *"smart"* OR *"digitalization" Refined by: Language* (English), *Years of Publication* (2016–2026), *Excluded by:* Irrelevant Subjects	692

While bibliometric studies in this field mainly focus on publication trends, keyword networks and thematic mapping, they often remain descriptive in nature and do not explicitly structure performance indicators as analytical units. In contrast to previous descriptive review studies, this research introduces a structured KPI-oriented analytical framework that integrates co-word analysis, thematic mapping and performance indicator clustering to provide a more systematic synthesis of smart port performance literature. This allows not only the identification of research trends but also the classification of performance indicators into meaningful conceptual groups, thereby improving interpretability and comparability across studies.

Accordingly, to address the first research question and to enhance the transparency and reproducibility of the review process, this study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. PRISMA provides a structured and standardized approach for identifying, screening and selecting relevant studies, thereby ensuring methodological rigor in SLRs. In line with this framework, the study adopts the four-phase PRISMA process: identification, screening, eligibility and inclusion, as illustrated in Figure 1.

In the initial phase, the WoS database was selected for the research for the reasons previously outlined. In the secondary stage of the research, keywords associated with the subject were determined, and 1,850 publications were identified. Following this step, a set of eligibility criteria was established. The study was predicated on four criteria. Initially, studies conducted between 2016 and 2026 were considered. However, it should be noted that only studies written in English were taken into account. Concurrently, all document types were incorporated into the study, while irrelevant categories such as physics, chemistry and health were excluded. Accordingly, the study incorporated a total of 692 publications. In the fourth step of the research process, the 692 publications were interpreted for bibliometric analysis using the Bibliometrix and Biblioshiny packages in R programming and RStudio. This analysis identified trends, detected gaps in the subject and led to the identification of potential research areas while showing the annual scientific production rate, the contributions of sources and authors to the subject, the number of citations received by studies on the subject and the relationships between keywords. The final stage of the process involves evaluating the studies identified as research outputs. In summary, this analysis shows the topic's importance in the social sciences and how much scholars have studied it. The following section explains these in detail.

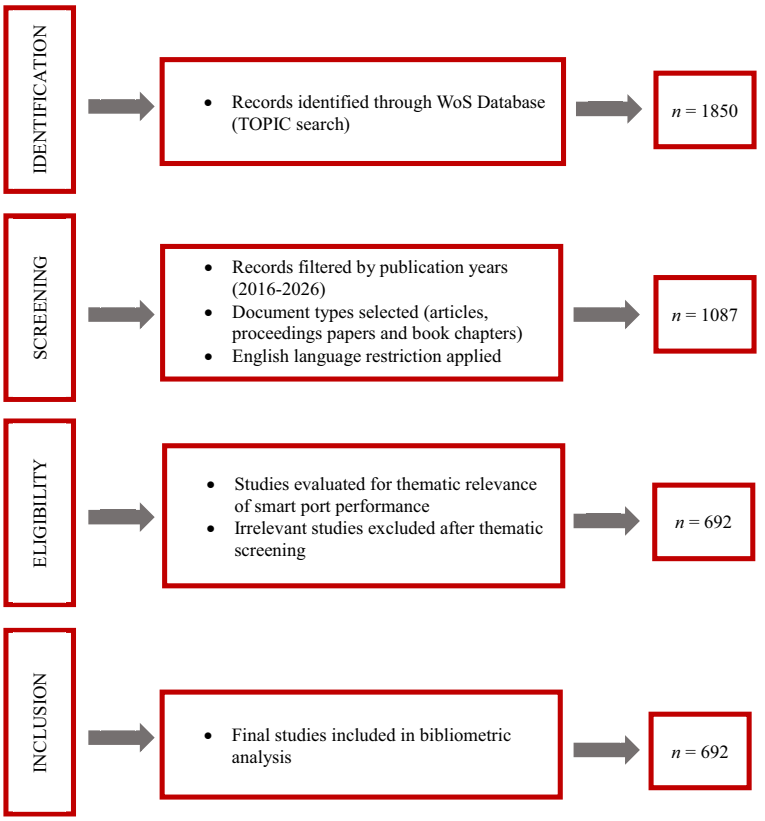

Figure 1. PRISMA four-phase flow diagram

4. Implementation and results of the current research on smart port performance indicators

The study was conducted by searching the WoS database using the search string provided in the previous section. The metadata of 692 articles were downloaded and analyzed. The dataset included one article with partially missing references, 20 articles lacking digital object identifier information, six articles with inaccessible abstracts, 36 articles with missing keywords and 81 articles without "keywords plus" information. However, these issues were not considered critical for the overall analysis. Biblioshiny classified the completeness level of the dataset as "good" and "acceptable," indicating that the proportion of missing or incomplete data remains within tolerable limits for bibliometric analysis. Since the missing elements are distributed randomly rather than systematically, their impact on the overall results is expected to be minimal. Therefore, the inclusion of this dataset does not introduce a significant bias or deviation that would meaningfully affect the reliability or validity of the findings.

Accordingly, Table 3 presents the statistical overview of the studies included in the analysis. The data were generated using R programming and RStudio with the support of the Bibliometrix and Biblioshiny tools. According to the findings, between 2016 and 2026, a total of 692 studies related to smart ports were published by 12,103 authors across 243 different sources in the WoS database. Among these publications, 657 were categorized as articles. More specifically, these articles consisted of 579 standard research articles, 15 early access articles, 59 review articles, 2 early access reviews, 2 letters and 1 retracted publication. In

Table 3. Main information data

Description	Results
Main information data	
Timespan	2016:2026
Sources (journals, books, etc.)	243
Documents	692
Average citations per doc	18,22
Document contents	
Keywords plus (ID)	1,737
Author's keywords (DE)	3,053
Authors	
Authors	12,103
Single-authored docs	25
Co-authors per doc	22,3
International co-authorships %	36,56
Document types	
Article	657
Article; book chapter	2
Proceedings paper	33

addition, the remaining publications consisted of two article-book chapter combinations and 33 proceedings papers.

Furthermore, the average number of citations per document was calculated to be 18.22. The analysis also revealed that the total number of Keywords Plus terms was 1,737, while the total number of authors' keywords reached 3,053. In terms of authorship characteristics, the number of single-authored publications was found to be relatively limited, with only 25 documents written by a single author. On the other hand, the average number of co-authors per document was 22.3, and the international co-authorship rate was calculated as 36.56%.

These findings suggest that the smart port concept has attracted increasing academic attention over the years, particularly with the growing importance of digital transformation and sustainability in maritime transportation. The high number of co-authors per document also reflects the interdisciplinary nature of the field, as smart port studies often bring together researchers from logistics, maritime transportation, environmental management and information technologies. In addition, the relatively high rate of international collaboration indicates that smart port development has become a global research topic shaped by common operational, environmental and technological challenges faced by ports worldwide.

Figure 2 presents a graphical representation of the annual scientific production. The graph indicates that research-related publications have been published since 2016 ($n = 21$), albeit at a low rate and have increased since 2020, reaching a peak of 172 publications in 2025. It is evident that the concept of smart ports has emerged as a prominent subject of interest within the social sciences community in 2025. Nevertheless, a notable decline was seen in 2026 ($n = 5$). This decline is due to the extraction of data from the WoS database on 22 December 2025. It is estimated that changes to the graph will become apparent once the year is over.

As Figure 3 shows, studies on smart ports received a clear number of citations. Although the average number of citations was just 2.2 in 2016, it increased annually until reaching a peak of 9.2 in 2021. This can be attributed to the recognition of the importance of digitalization brought about by COVID-19 and the intensification of innovative studies aimed at improving maritime processes. However, after 2021, researchers noted a substantial decrease in the number of citations, and by 2025, the average number of citations had declined to 2.1. This

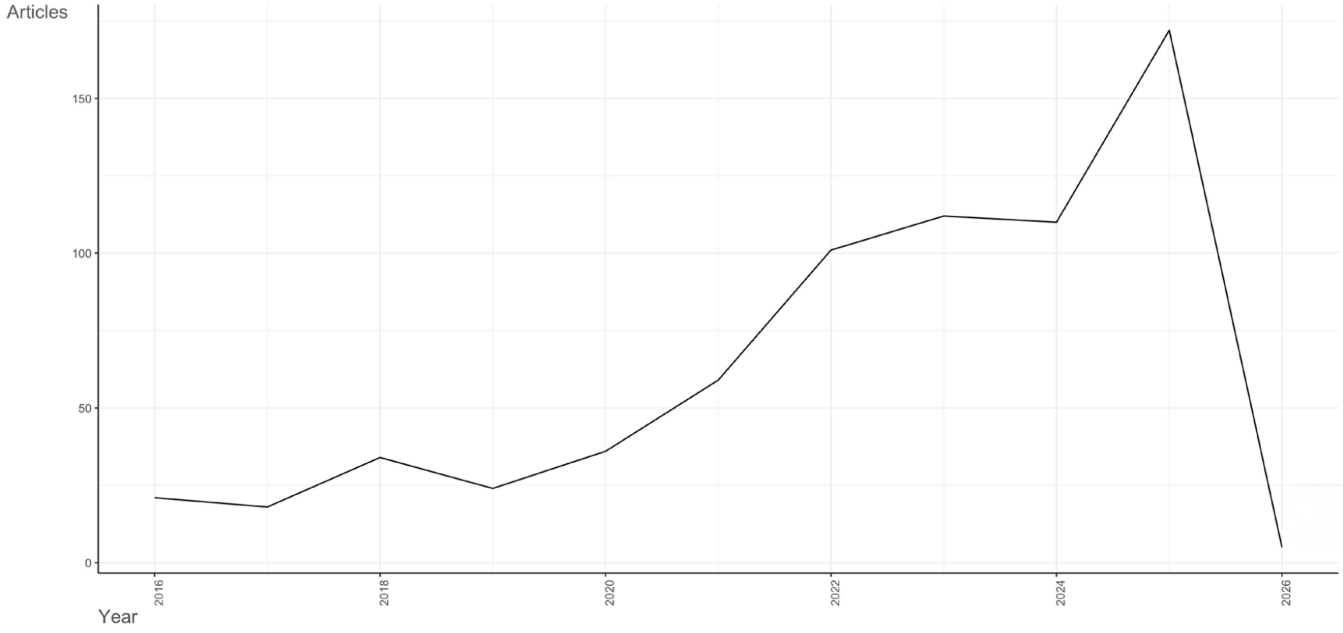

Figure 2. The frequency of scientific production by authors

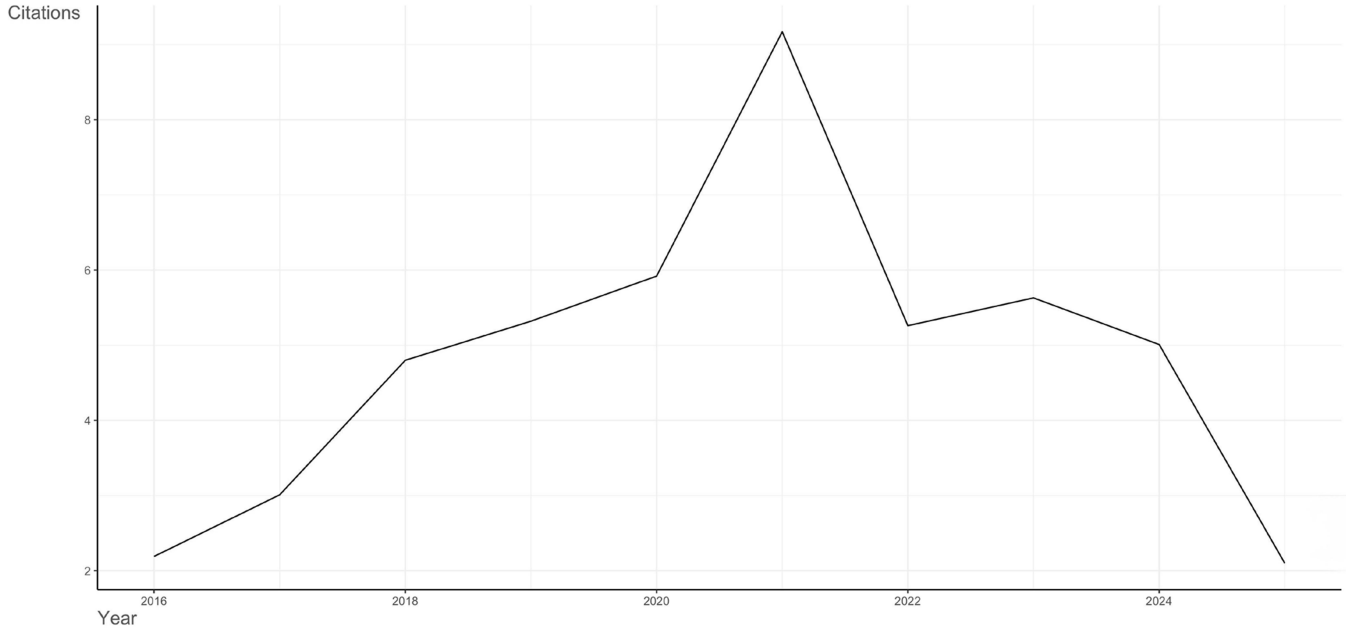

Figure 3. Average number of citations per year

trend can be attributed to the increase in publications in 2025, which led to a dispersion of the impact of citations and caused the average number of citations to decline.

Furthermore, Figure 4 presents the citation network based on publications. In this network, the most significant and influential articles are located at the largest nodes (Shaikh and Khan, 2025). The red, blue and purple clusters, which are concentrated on the left side of the network, generally indicate that the fundamental studies on smart ports are located there and that there is a strong citation relationship between the studies. The extant studies that emerged before these are Lam and Zhang (2014), Molavi *et al.* (2020) and Shipper *et al.* (2017). In the context of research conducted within the domain of smart ports, it is important to consider the studies that form the large nodes in this network. Conversely, although a citation link has been established between the green cluster on the right and the three clusters on the left, the strength of this relationship is considered to be weak.

Moreover, a Sankey diagram (three-field plot) has been devised in Figure 5 to facilitate a more profound examination of the relationship between journals, authors' keywords and universities. Journals are positioned on the left side of the diagram, authors' keywords are in the middle and universities are positioned on the right. Thus, universities that incorporate the terms "sustainability," "supply chain", "performance", "model" and "innovation" in their academic programs are predominantly located in China, Hong Kong and the United Kingdom. These institutions' target journals include "*Sustainability*", "*Journal of Cleaner Production*" and "*Journal of Marine Science and Engineering*".

Figure 6 demonstrates the co-occurrence network of keywords. The most frequently co-occurring words in this network are performance (212), sustainability (116), management (89), model (69), impact (54), system (49), efficiency (44), emissions (44), energy (43) and optimization (43). Consequently, these terms are frequently used in association with the context of smart port studies.

Figure 7 shows the thematic map created using keywords. This map is divided into four quadrants: motor, niche, basic and emerging/declining. The upper right (motor) quadrant represents the most intense and prominent themes in a given field. The upper left (niche) quadrant represents themes that are relatively intense but limited in scope. The bottom right (basic) quadrant contains the fundamental concepts that are generally encountered in the relevant subject. Finally, the bottom left (emerging/declining) quadrant represents concepts that are either unused or, conversely, slowly gaining traction but are underutilized in current research. In short, the left side can be interpreted as a potential theme for future studies, while

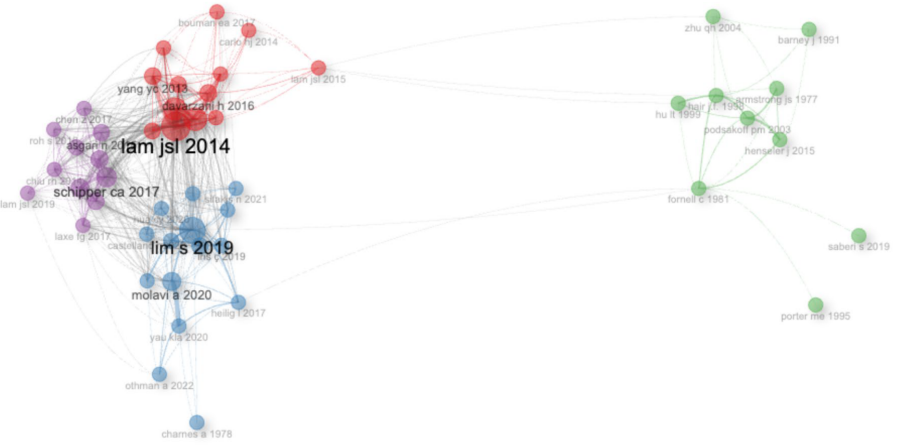

Figure 4. Citation network by publications

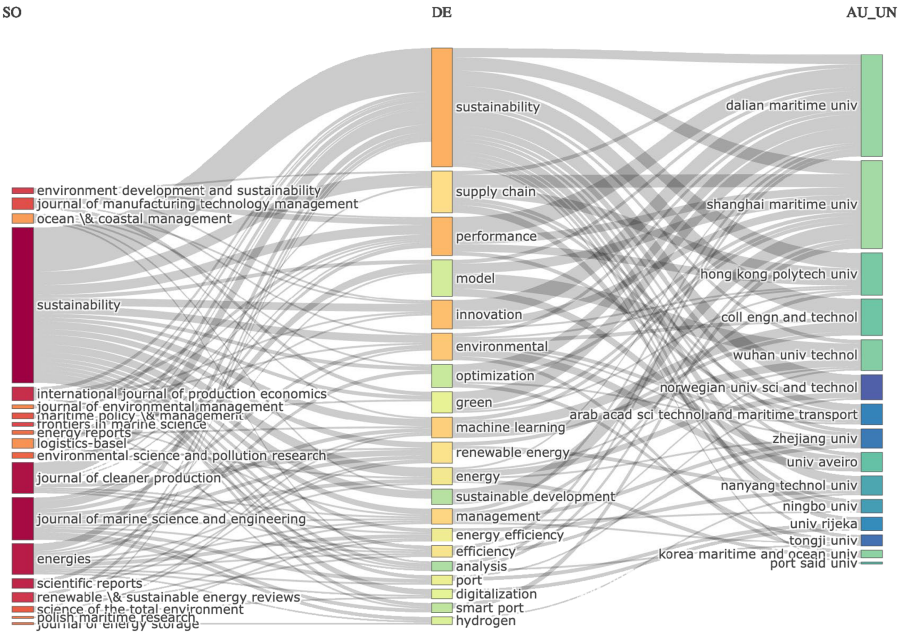

Figure 5. Sankey diagram of journals (left), author's keywords (middle) and institutions (right)

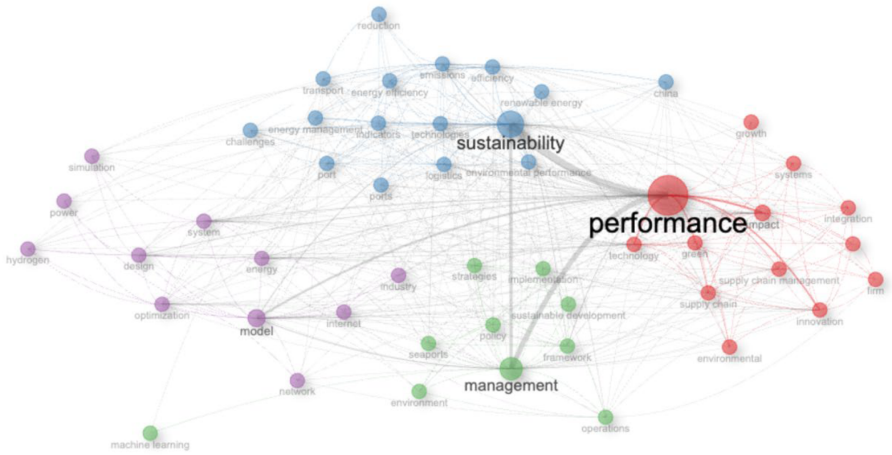

Figure 6. The co-occurrence of the keyword network on smart ports

the right side can be interpreted as themes that should be discussed in future studies (Thangavel and Chandra, 2023). Accordingly, it is observed that the themes of performance, impact and innovation stand out as driving forces in smart ports, while the concepts of sustainability, management and logistics should be mentioned in future studies due to their presence in both the motor and basic themes. On the other hand, although the concepts of emissions, energy

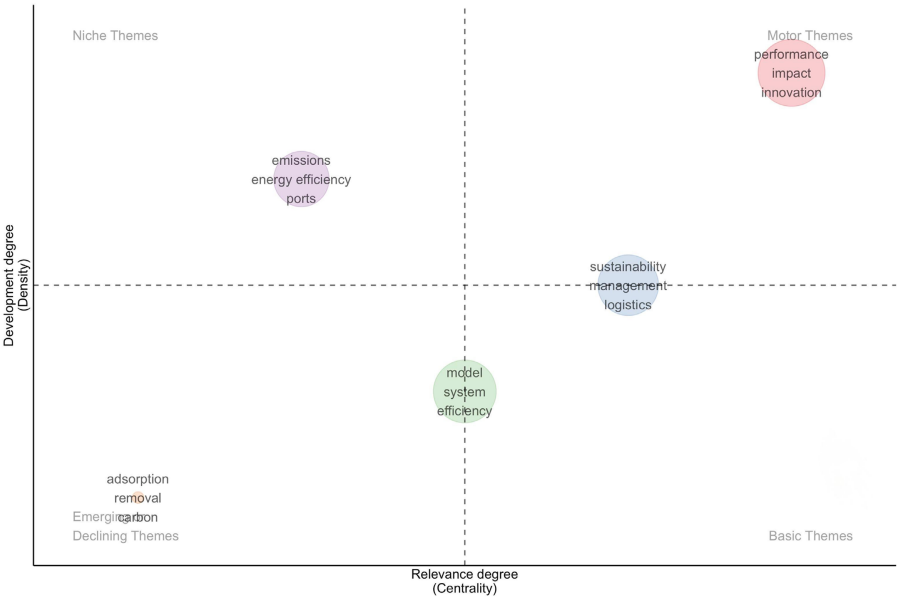

Figure 7. Keyword thematic map showing smart port by themes

efficiency and ports are developed concepts in themselves, they remain limited in the context of smart ports. Furthermore, the themes of model, system and efficiency can be interpreted as being caught between the basic quadrant and the emerging/declining quadrant, meaning they are beginning to establish a connection with smart ports but have not yet been sufficiently explored. Finally, the themes of adsorption, removal and carbon can be described as either outdated or emerging themes. To understand whether these themes are declining or emerging, they must be interpreted by considering their frequency of use over time.

Furthermore, Figure 8 demonstrates the thematic evolution of keywords used in Smart Port research over three time periods: 2016–2026. Visual examination of the "Smart Port" concept shows a stable progression in the concepts of "sustainability" and "performance" from 2016 to 2026. These keywords are fundamental to the research framework. While the terms "system", "efficiency" and "design" were used in the 2016–2022 period, the term "energy" joined the list of keywords in 2023, providing a more comprehensive term.

In addition, the word cloud in Figure 9 and the tree map in Figure 10 illustrate essential keywords associated with Smart Ports. Analysis of the word cloud reveals a focus on terms such as "performance," "sustainability," "management," "model," "impact" and "system". In other words, the size of a word in the word cloud indicates how frequently it is used in the Smart Ports research framework. Similarly, the Tree Map was created using the same logic as the word cloud to enable a clearer understanding and analysis of the themes in the word cloud. Similar observations can be made when examining the tree map, which also highlights the themes of "sustainability," "management," "model," "impact" and "system."

Figure 11 shows that the factor analysis graph indicates the largest blue cluster, thereby emphasizing the close connection between technology, performance and sustainability. Therefore, these areas can be seen as forming the basis of the research and as requiring focus. Meanwhile, the red cluster identifies topics such as finance, supply chain management and innovation. Lastly, the green cluster exclusively depicts performance indicators as a standalone theme, revealing their absence in technology-, sustainability- and operations-

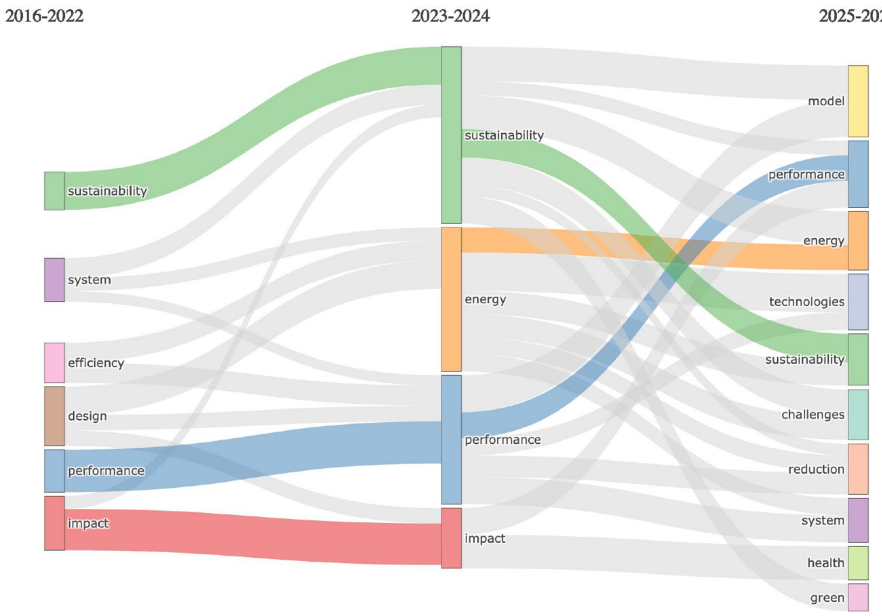

Figure 8. The thematic map demonstrate the evolution of keywords of smart port over three-time slices (2016–2026)

Figure 9. Word cloud

focused studies. In summary, this graph highlights the need for a more holistic approach in future studies. Furthermore, the Single Country Publications (SCP) and Multiple Country Publications (MCP) analysis reveals countries' national and international collaboration patterns. China, Korea, Egypt and Italy have the highest research output. Although China participates in international collaborations, domestic collaborations remain dominant. Overall, international collaboration appears to positively influence publication performance.

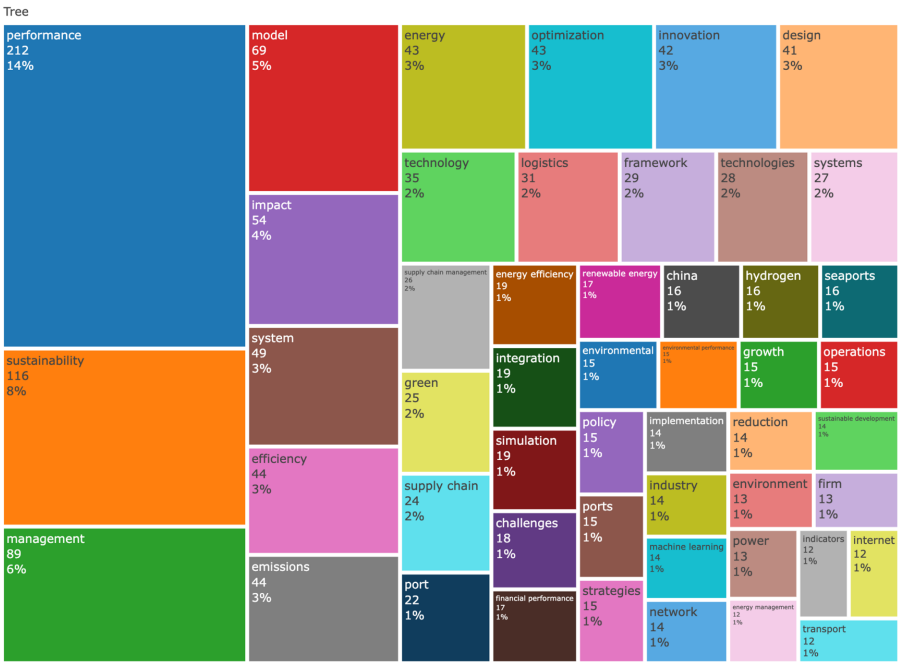

Figure 10. Tree map

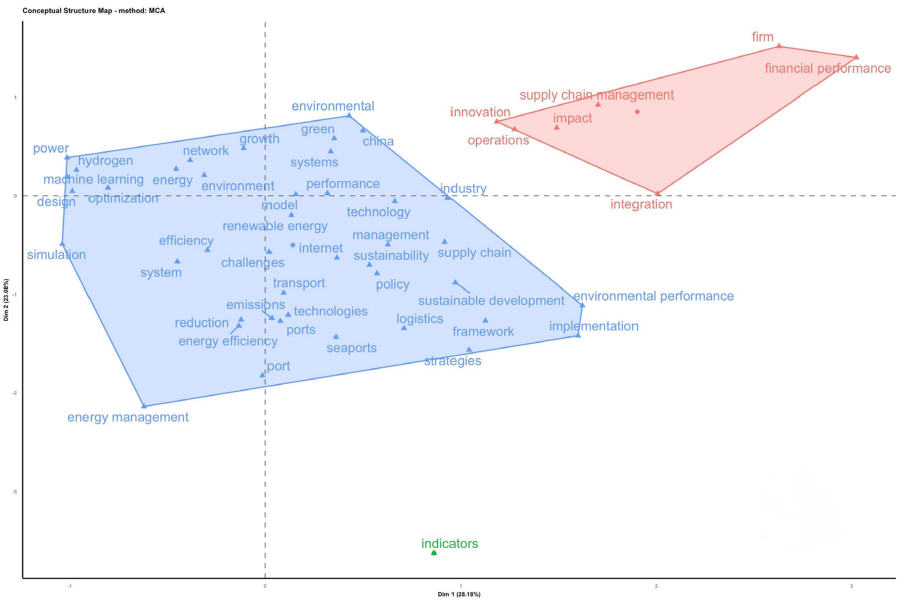

Figure 11. Factor analysis

Furthermore, the countries with the highest number of citations are shown in Figure 12 As indicated by the data, China is evidently the nation with the highest number of citations, with 4,773 citations. China is followed by Italy with 626 citations and Finland with 619 citations. Accordingly, it can be interpreted that the majority of studies that inform academic outputs in the domain of smart ports are China-focused.

Furthermore, Figure 13 illustrates the most frequently cited publications amongst the included studies, obtained from the WoS database. Accordingly, Molavi *et al.* (2020), Sifakis and Tsoutsos (2021) and Mallouppas and Yfantis (2021) are among the most significant studies with the highest number of local citations on the subject. Consequently, future research on this subject should examine these studies.

As illustrated in Figure 14, the initial phase of the trend topic data demonstrates an emphasis on the concept of energy. However, subsequent to 2020, there has been a notable shift toward considerations such as model, application, finance, technology and green. In recent years, the concepts that have come to the fore historically are "storage," "algorithm" and "deep learning"; in terms of magnitude, they are "performance," "management" and "sustainability."

The findings indicate that the concept of performance is assuming an increasingly central role in the literature. While traditional indicators maintain their relevance, recent studies show that smart port performance indicators are evolving through the incorporation of digitalization, sustainability and data-driven metrics. This evolution demonstrates that smart port performance measurement is no longer static but rather a dynamic and multi-dimensional construct.

Despite this growing interest, the literature still lacks a standardized and widely accepted KPI framework for smart port performance. Existing studies typically examine performance indicators in isolation or within single thematic dimensions, which limits cross-study comparability and prevents the development of cumulative knowledge.

To address this limitation, this study restructures existing performance indicators into integrated thematic and methodological clusters by combining bibliometric mapping results with a KPI-oriented analytical perspective. In this way, performance indicators are not only identified but also systematically categorized, enabling a more coherent and comparable understanding of smart port performance research. More specifically, existing studies reveal that operational performance is often measured through indicators such as vessel turnaround time and cargo handling efficiency, while sustainability-oriented studies focus on emissions reduction, energy consumption and environmental compliance. In parallel, technology-driven research highlights the role of IoT-based monitoring systems, automation and data analytics in enhancing real-time decision-making and operational visibility. However, these findings remain largely disconnected, as only a limited number of studies integrate these dimensions into a unified performance measurement framework.

5. Proposed research themes for future studies on smart port performance indicators

The bibliometric, thematic and trend analyses conducted in this study show that the literature on smart port performance indicators is growing rapidly in quantitative terms; however, it is still immature in terms of conceptual integrity and methodological depth. The annual distribution of scientific output (Figure 2) reveals a steady increase in the number of publications since 2016 and a significant acceleration in the literature, especially in the period after 2020. This increase clearly demonstrates the strengthening of academic interest in the smart port concept.

Thematic mapping and keyword co-occurrence analyses show that the concepts of performance, sustainability and digitalization are frequently used together in the literature; however, these concepts are not addressed within a strong and integrated framework. In particular, performance indicators are mostly linked to technology-based transformation, and most studies only address sustainability goals to a limited extent, and performance measurement is predominantly considered through single operational or environmental

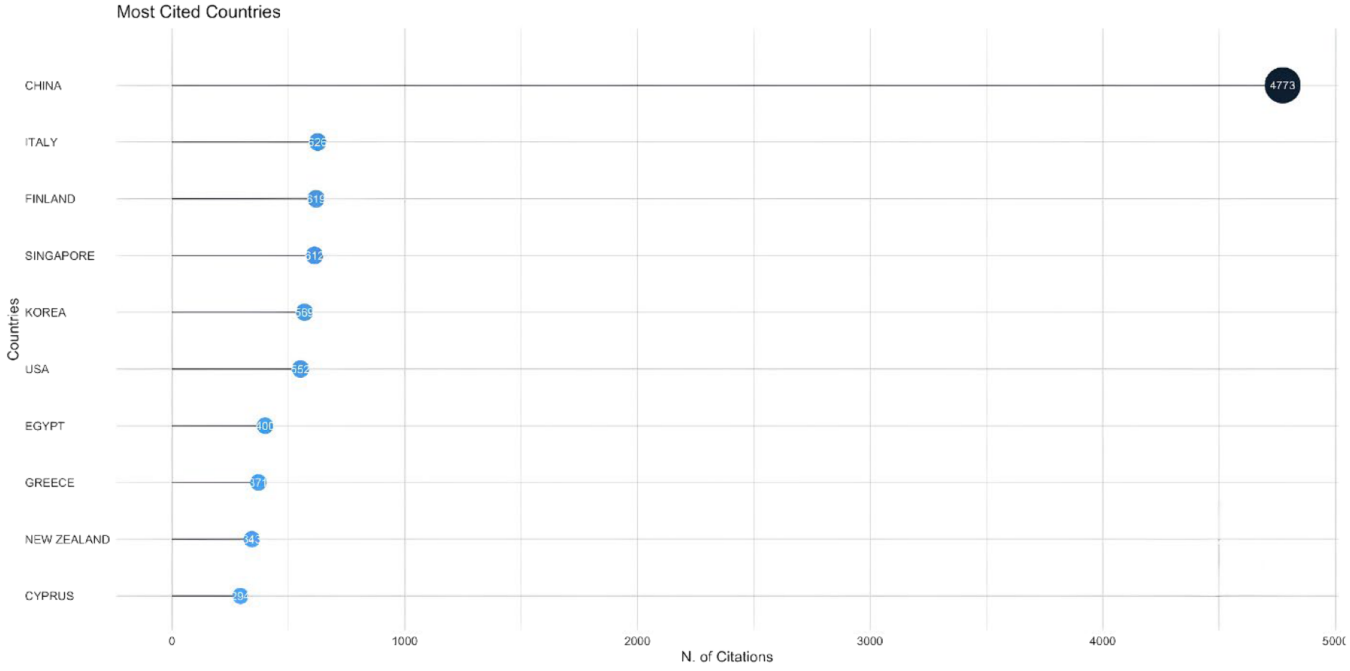

Figure 12. Most cited countries

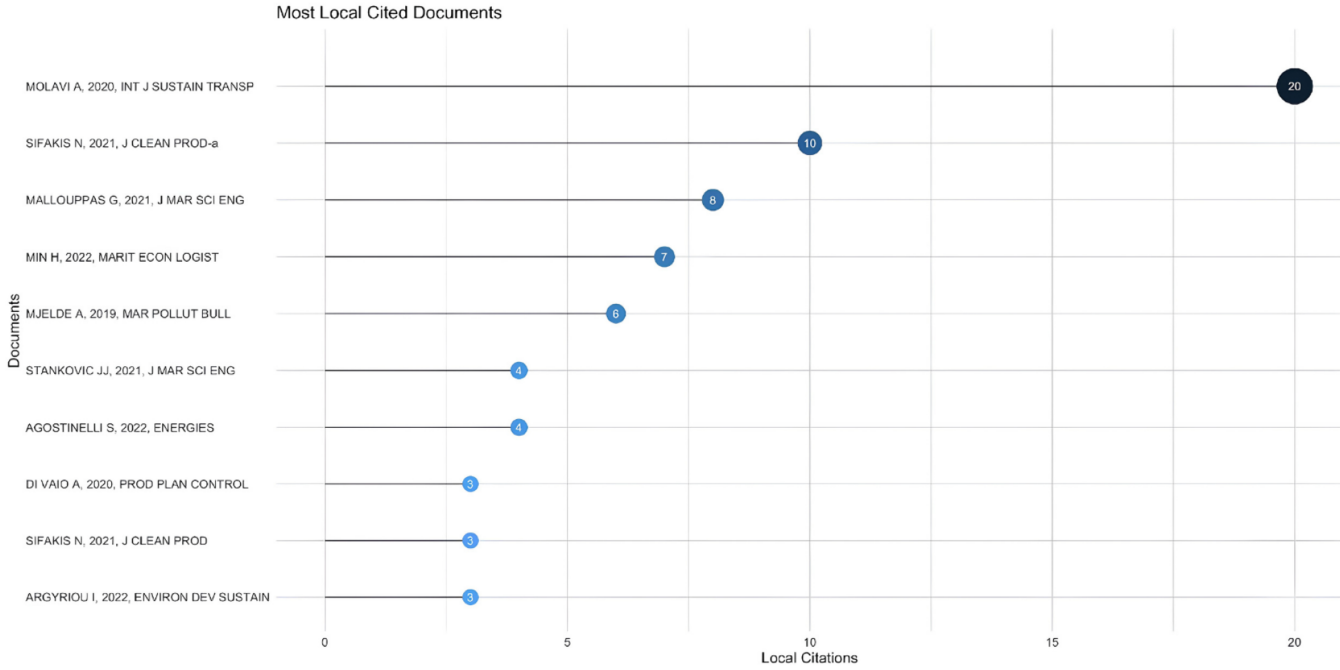

Figure 13. Most local cited documents

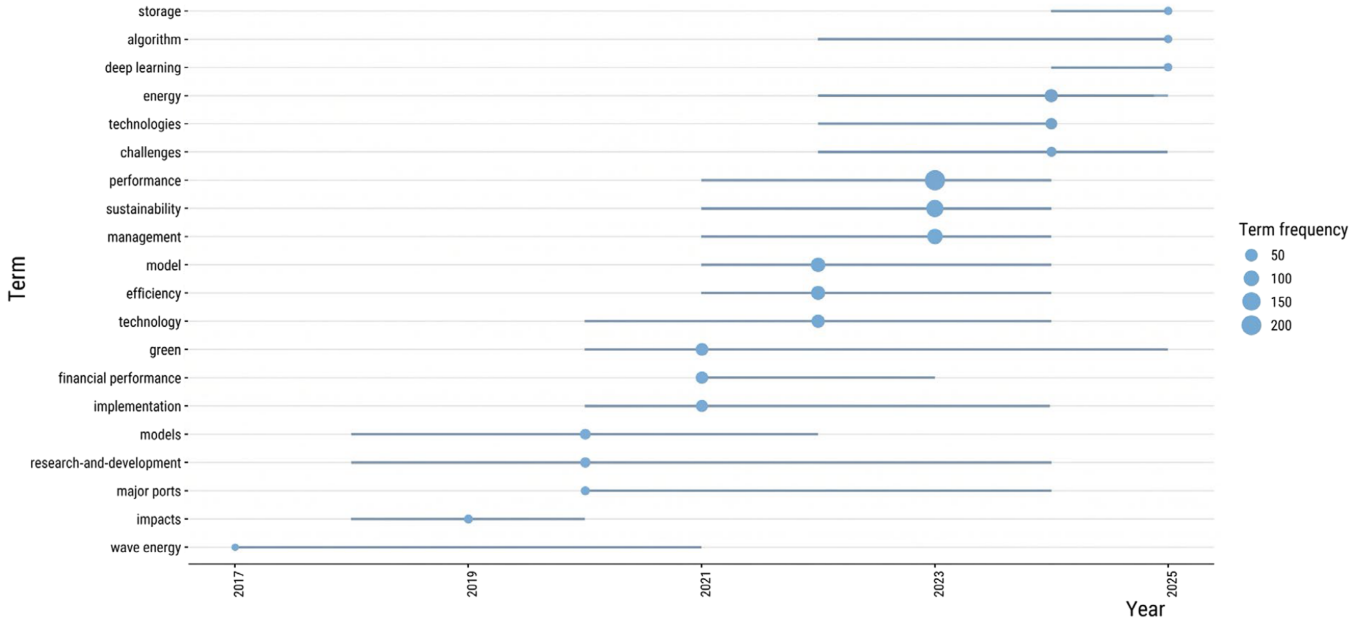

Figure 14. Trend topics

dimensions. Temporal analyses reveal that research focuses on the literature change periodically, but this change does not exhibit a cumulative and integrative development. These findings indicate that smart port performance indicators are still addressed within a fragmented structure and that more holistic research approaches are needed.

In this context, future research should primarily focus on explaining the multifaceted relationships between digital technologies, sustainability goals and performance indicators. In other words, future research should focus on proposing new performance indicators and explaining the context, technological infrastructure and strategic objectives for their use. Although bibliometric findings show that technology, performance and sustainability are strongly mentioned together in the literature, they reveal that the integration of these concepts mostly remains at the theoretical or descriptive level. Therefore, there is a need for integrated performance frameworks that consider indicators such as digital maturity level, data integration capacity and automation level together with operational, environmental and economic performance measures. Therefore, the proposed research themes for future studies on smart port performance indicators are given below.

In this context, Figure 15 highlights key themes in the smart port performance indicators literature within a holistic framework that can guide future research. The proposed research themes are directly derived from the bibliometric and empirical findings of this study. The themes in the above figure were established on the basis of the bibliometric and thematic findings acquired in this study and directly correspond to the conceptual and methodological gaps identified in the existing literature.

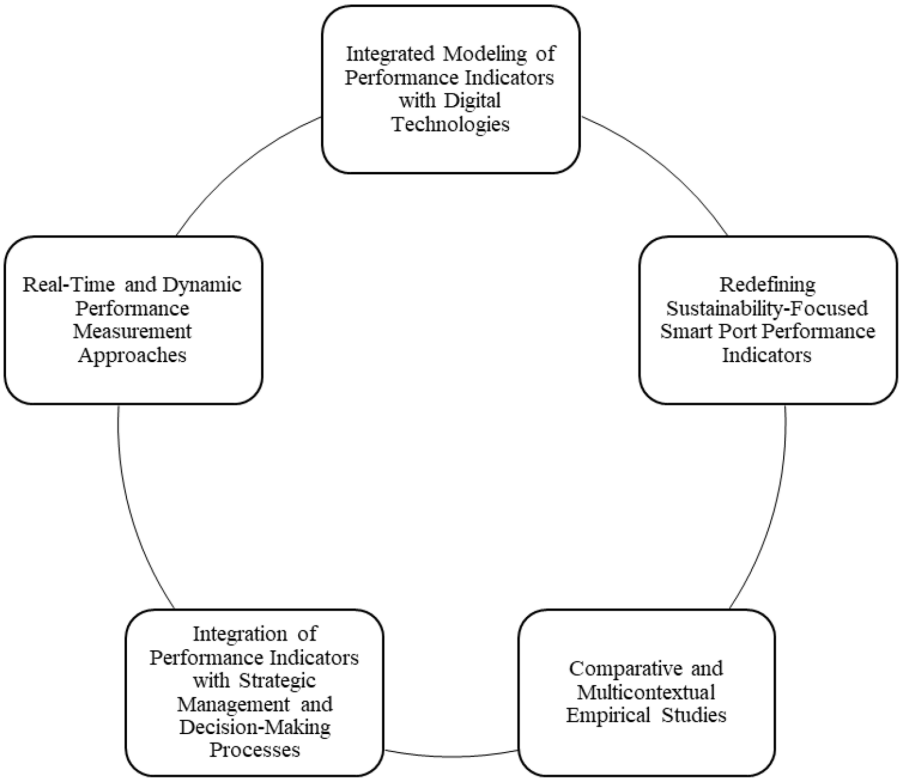

Figure 15. Proposed research themes for future studies on smart port performance indicators

Based on the bibliometric findings, particularly the co-occurrence analysis and thematic map, which show a strong but fragmented relationship between digitalization and performance, the theme of "Modeling performance indicators integrated with digital technologies" reflects a significant gap in the existing literature. This is because, while researchers frequently discuss technology and performance concepts together, they remain superficial and descriptive in the majority of studies. A significant proportion of current research considers digital technologies to be mere tools that support operational processes; it does not systematically integrate indicators such as digital maturity, data integration and automation level into performance measurement frameworks (Boadu *et al.*, 2025). In this context, future research should concentrate on the development of integrated models that consider digital competency indicators within the same analytical framework as operational, environmental and economic performance outcomes.

Additionally, based on thematic evolution and keyword trends highlighting sustainability and energy-related concepts, the theme "Redefining sustainability-oriented smart port performance indicators" is predicated on the concepts of energy efficiency, emissions and environmental impact, which are prominent in thematic evolution and trend analyses. Despite the growing prevalence of sustainability indicators in the literature, researchers frequently examine them in isolation from the context of digitalization processes (Sankla and Muangpan, 2022). This complicates the process of evaluating the full extent to which digital technologies contribute to environmental performance. Thus, future studies should concentrate on performance measurement approaches that integrate sustainability indicators with real-time data collection, digital monitoring and smart energy management systems.

Furthermore, based on factor analysis results, which indicate that performance indicators are weakly connected to strategic and operational dimensions, the theme, "Integration of performance indicators with strategic management and decision-making process" is a critical yet underdeveloped area of inquiry in the smart port literature. This theme underscores the imperative to integrate sustainability indicators with digitalization processes and to develop performance measurement systems with real-time monitoring capabilities. In short, the findings reveal that performance indicators are predominantly utilized as outcome-oriented evaluation tools in the smart port literature, with their relationship to strategic planning, investment decisions and governance processes receiving only minimal examination. However, given the substantial costs and long-term impacts of digitalization investments, it is imperative to establish a direct correlation between performance indicators and strategic goals. In this regard, it is essential to reposition performance measurement systems as dynamic mechanisms that facilitate strategic decision-making processes, rather than merely serving as monitoring and reporting tools. As is evident in the literature, approaches to strategic performance management provide the theoretical basis for this transformation. However, researchers have conducted only a limited number of empirical studies on integrated decision support models in the smart port context (Gonçalves and Teixeira, 2025).

Another important research direction is the development of "real-time and dynamic performance measurement approaches." according to the findings that existing studies predominantly rely on static and historical data for performance evaluation. The vast majority of current smart port studies offer performance measurements based on static and historical data; this does not adequately reflect the potential of smart port infrastructures that continuously generate data (Paraskevas *et al.*, 2025). However, thanks to IoT, sensor-based systems and big data analytics, port operations can be monitored in real time and performance indicators can be dynamically updated. Therefore, the development of predictive and adaptive models that take into account the changes in performance indicators over time stands out as a critical research direction for the future of the literature. Artificial intelligence and machine learning-based approaches make it possible not only to evaluate current performance but also to predict future risks and opportunities.

Finally, it appears that existing empirical studies, which focus on specific countries and port types, limit the generalizability of performance indicators. Therefore, based on country-level

analysis, which shows a concentration of studies in specific regions, "comparative and multi-contextual empirical research" encompassing different geographic regions, governance models and technological maturity levels will make significant contributions to revealing both the universal and context-specific dimensions of smart port performance indicators. Most existing empirical studies on smart port performance indicators focus on specific countries or port types, which limits the generalizability of the findings (Zou *et al.*, 2025). The levels of digitalization, governance structures and sustainability priorities of ports in different geographic regions differ significantly. Moreover, comparative empirical studies covering different contexts are important in revealing performance indicators' universals and particularities. The findings of such studies will contribute to the development of more flexible, adaptable and context-sensitive performance measurement frameworks for policymakers and port managers.

Overall, future research should focus on dynamic and decision-support-oriented approaches that incorporate digitalization, sustainability and performance measurement within a holistic framework. This would substantially enable the theoretical and practical contributions of smart port literature.

6. Discussions and conclusions

The evolution of ports into smart ports has been a pivotal development in maritime logistics. Besides, ports have focused on establishing a competitive advantage through the integration of digitalization, automation and sustainability practices into their operational processes and striving to improve their performance. This transformation has prompted interest from scholars and has emerged as a prominent theme within the existing literature. However, given that extant literature fails to address performance indicators comprehensively, it is not sufficient to capture the multidimensional nature of smart port performance. The main contribution of this study lies in its focus on systematically structuring and prioritizing smart port performance indicators, rather than only reviewing them. This finding is consistent with previous review studies, which also emphasize the fragmented nature of smart port performance research. However, unlike earlier studies that mainly describe existing themes, this study demonstrates that fragmentation is also evident at the level of performance indicator construction, which limits comparability across studies.

To address the aforementioned issues, the present study has examined and responded to two research questions. Regarding the first research question, an SLR was conducted to identify the main research topics and themes related to smart port performance indicators in maritime transport. The WoS database was selected, and relevant keywords such as smart port, key performance indicators, digitalization and sustainability were used. Eligibility criteria based on publication date, language, document type and research category were applied, resulting in 692 studies. The analysis was conducted using the Bibliometrix and Biblioshiny packages in R. The bibliometric results further reveal that performance indicators are predominantly embedded within broader digitalization and sustainability discussions, rather than being treated as a standalone analytical construct.

After that, to answer Research Question 2, which is "What trends should future research on smart port performance indicators follow in terms of thematic focus, methodological approaches and empirical settings?" five research themes have been identified for future studies. These themes do not emerge arbitrarily but are directly grounded in the gaps observed in the co-occurrence network, thematic map and trend analysis, particularly the weak integration between operational, environmental and technological performance dimensions. These are, in order, as follows: modeling performance indicators integrated with digital technologies, redefining sustainability-focused smart port performance indicators, performance indicators integrated with strategic management and decision-making processes, real-time and dynamic performance measurement approaches and comparative and multi-context empirical research. The present study has identified research gaps in the

extant literature on this subject and then addressed these gaps, thus providing a framework for future work in this field. Compared to previous bibliometric studies, the contribution of this research is not only descriptive but also structuring, as it reorganizes fragmented indicators into an interpretable KPI-oriented framework.

In this context, it is important to clarify that maritime transport refers specifically to sea-based transportation activities, port logistics refers to operational processes within ports and maritime logistics represents a broader system integrating both transport and port operations within the supply chain. The study consistently applies this distinction to avoid any conceptual ambiguity.

Overall, the findings of this study suggest a fundamental tension in the smart port literature. On the one hand, there is a strong emphasis on technological advancement and sustainability transitions; on the other hand, the mechanisms through which these transformations translate into measurable performance outcomes remain fragmented. This gap explains why existing studies struggle to provide comparable and generalizable performance evaluation frameworks. By systematically structuring performance indicators within a KPI-oriented perspective, this study attempts to bridge this gap and establish a foundation for cumulative knowledge development.

Moreover, the findings of this study provide several practical implications for port authorities, policymakers and industry practitioners. First, the fragmented structure of performance indicators suggests that port managers should adopt integrated performance measurement systems that simultaneously consider operational efficiency, environmental sustainability and digitalization capabilities. Second, the increasing role of digital technologies highlights the need for investments in IoT-based monitoring systems, data analytics platforms and automation tools to enable real-time performance tracking and decision-making. Third, policymakers should support the development of standardized KPI frameworks to enhance comparability across ports and facilitate benchmarking practices. Finally, the identified lack of cross-regional studies indicates that port authorities can benefit from international collaboration and knowledge transfer to develop more adaptive and context-sensitive performance management systems.

International trade is inherently dynamic and variable. To maintain competitiveness and respond to shifts in demand, ports are continually exploring ways to optimize their processes. This ongoing process of refinement can result in alterations to existing performance indicators or the introduction of new indicators. In this regard, the main limitation of this study is that it encompasses studies analyzing the performance indicators of existing smart ports; therefore, new studies are constantly emerging. Consequently, the study should incorporate new studies at designated intervals. In this regard, the main limitation of this study is that it encompasses studies analyzing the performance indicators of existing smart ports; therefore, new studies are constantly emerging. Although WoS provides high-quality and reliable indexing, the use of a single database may have led to the exclusion of relevant studies indexed in Scopus or other regional databases. This may result in a partial representation of the literature, particularly for emerging economies where smart port research is rapidly developing. Therefore, the observed fragmentation in performance indicators may be influenced not only by conceptual limitations in the literature but also by the scope of the dataset used in this study. In subsequent studies, it is possible that the thematic framework may be subject to variation or that individual themes may merge to form a single theme.

Overall, the study suggests that smart port performance research is transitioning from technology-centered evaluations toward more integrated, multidimensional assessment frameworks. However, this transition remains incomplete, as existing studies still lack a unified conceptualization of performance indicators. Addressing this gap requires moving beyond isolated indicator analysis toward system-level performance measurement architectures that align operational, environmental and digital transformation objectives.

Declaration of generative Artificial Intelligence (AI) and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used GRAMMARLY in order to improve the clarity and language quality of the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Acknowledgments

This article is part of Betül Parlak's master's thesis at Yaşar University Graduate School, supervised by Assistant Professor (Ph.D.) Melisa Özbiltekin Pala.

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