

Systematic Review

Global Trends in Port Sustainability: A Bibliometric Analysis and Systematic Review with Insights from the Port of Manzanillo, Mexico

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Abstract

Purpose: This study analyzes the evolution of global research on port sustainability and examines how these trends relate to the governance and development challenges of the Port of Manzanillo, Mexico, with implications for sustainable port transitions in emerging economies. **Method:** A combined Bibliometric and Systematic Review (BSR), following PRISMA 2020 guidelines, analyzed 307 Scopus-indexed documents (1999–2025) using Bibliometrix and VOSviewer, complemented by a documentary review of Manzanillo's main planning instruments. **Results:** Scientific production accelerated after 2020 and remains concentrated mainly in China and Europe, with limited Latin American representation and 29.97% international co-authorship. Thematic evolution shows a shift from environmental management and sustainable development toward Smart Ports, digitalization, and decarbonization. In Manzanillo, sustainability follows a context-specific pathway characterized by infrastructure expansion, operational modernization, environmental management, and progressive technological adoption, while advanced Smart Port technologies remain emerging. **Conclusion:** The findings suggest that sustainable port transitions in emerging economies depend not only on technological innovation but also on governance arrangements, infrastructure priorities, and long-term planning. Manzanillo illustrates how global sustainability agendas can be progressively adapted to regional and local port contexts.



Academic Editors: Guanghui Zhou and Dengyuhui Li

Received: 17 June 2026

Revised: 28 July 2026

Accepted: 29 July 2026

Published: 4 August 2026

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Keywords: sustainable port; smart port; bibliometric analysis; sustainability transition; port governance; emerging economies; digital transformation

1. Introduction

Maritime ports handle over 80% of global cargo, making them key nodes in the trade network. However, their intense loading and unloading, along with vessel traffic, make them significant sources of environmental impact. The main issues include greenhouse gas emissions, air pollution, and alterations to coastal ecosystems [1,2]. Driven by the urgent need to mitigate climate change and align with the United Nations Sustainable

Development Goals (SDGs)—notably SDGs 9, 13, and 14 [3]—port sustainability has shifted from an operational choice to a strategic and regulatory imperative.

Sustainability now goes beyond just managing the environment. The “Twin Transition” is a major idea for how modern ports should be managed. It means combining digital tools (such as IoT, Blockchain, and AI) with green initiatives (such as reducing carbon emissions and reusing materials). Instead of seeing these as different goals, the Twin Transition shows that digital technology supports environmental efforts. Ports are busy logistics hubs and play a big role in this change. Faced with climate and efficiency challenges, the industry must adopt new technologies that transform it. This shift has made Smart Ports and carbon reduction important focuses for ports. Recent studies point to Digital Twins and the combined use of BIM/GIS as key tools for port updates [4,5]. These let ports test different operating modes before making changes.

The academic debate regarding port sustainability has bifurcated into two distinct streams. The first one focuses on operational and engineering aspects, with recent studies examining the efficacy of energy management systems and electrification in reducing dockside emissions [6,7], as well as the implementation of circular economy principles within port industrial zones [8,9]. Innovative approaches, such as biomass gasification, are also being explored as strategic tools to reduce fossil fuel dependency and promote circular maritime logistics [10]. On the other hand, the second stream of literature emphasizes governance and port–city relations, arguing that technological solutions are insufficient without robust stakeholder engagement [11,12]. Bridging these perspectives, the integration of the Internet of Things (IoT) has linked the two streams by driving the emergence of the ‘Smart Port’ paradigm—described by authors such as Yau et al. [13] and Munim et al. [14] as a critical enabler for overcoming efficiency challenges in developing regions.

Latin American ports drive economic growth and global trade for countries such as Mexico, Brazil, and Peru. As gateways connecting emerging economies with global supply chains, these ports operate under institutional, economic, and governance conditions that differ from those of highly industrialized maritime regions. Consequently, sustainability transitions in Latin American ports are shaped by context-specific development priorities, including infrastructure expansion, logistics efficiency, environmental management, and progressive technological modernization [15]. While interest in Green Port and Smart Port initiatives continues to grow, their implementation is influenced by fragmented environmental policies, limited investment capacity, and complex governance practices, stakeholder coordination, and the degree of digital integration within port logistics communities [16]. Recent Review studies have further highlighted the growing role of digital technologies in supporting the transition toward Green and Smart Ports and more sustainable maritime management [17]. Understanding these context-specific transition pathways is therefore essential for interpreting how global sustainability agendas can be adapted within the region.

Although the topic is central, a clear gap remains in the literature. Specifically, while research often centers on technology (Smart and Green), it provides limited understanding of how sustainability transition pathways are shaped by governance and institutional and long-term planning in emerging port systems, particularly in the context of port regionalization, hinterland integration, and institutional coordination across logistics systems [18]. To address this gap, this study undertakes a bibliometric analysis with two main objectives. First, it aims to identify the field’s conceptual structure, scientific evolution, and emerging research trends. Second, based on these findings, it interprets the governance and sustainability transition challenges of the Port of Manzanillo, Mexico—a key logistics actor in the region.

Thus, the present article addresses the gap through a Bibliometric and Systematic Review (BSR). This approach combines a rigorous quantitative analysis (Bibliometrix) to identify publication and collaboration patterns with a qualitative synthesis of the main research trends. It also provides an overview of global scientific knowledge on port sustainability, while examining how the local dynamics of the Port of Manzanillo relate to broader international trends. The Port of Manzanillo was selected as a representative case because it is Mexico's leading container port and one of the principal logistics gateways in Latin America, making it an appropriate setting for examining how global sustainability agendas are interpreted and progressively adapted within the institutional, operational, and governance context of an emerging economy. By contrasting global research developments with a representative case from an emerging economy, the study identifies practical implications for sustainable port transitions and addresses the following research questions:

- RQ1 and RQ2: How has the field of port sustainability evolved in terms of scientific production, collaboration patterns, intellectual structure, and which key actors and seminal contributions have shaped its development?
- RQ3: Which thematic clusters and trends shape the global research agenda on sustainable ports?
- RQ4: How can mapped knowledge guide strategic actions and future research for the sustainability of the Port of Manzanillo?

This study contributes to the literature in three ways. First, it identifies the evolution of global research trends in port sustainability through a combined bibliometric and systematic review approach. Second, it reveals the limited representation of research on sustainable ports in Latin America within the analyzed scientific literature, highlighting a significant regional knowledge gap. Third, it connects global sustainability trends with the governance, planning, and operational context of the Port of Manzanillo, illustrating how sustainability transitions can be interpreted through context-specific development pathways rather than a single universal Smart Port model.

This paper is organized as follows: Section 2 details the methodological approach, combining PRISMA guidelines with bibliometric techniques. Section 3 presents the results of the performance and network analysis. Section 4 discusses the findings, contrasting global trends with the local reality of the Port of Manzanillo and the new legislative framework. Finally, Section 5 offers conclusions and future research directions.

2. Scope and Methodology

This study adopts a hybrid methodological approach, integrating a Systematic Bibliometric Review (SBR) with a Qualitative Case Study. This dual strategy allows for mapping global scientific trends while grounding the findings in the specific operational reality of the Port of Manzanillo. The review process strictly adhered to the PRISMA 2020 statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [18]. The PRISMA 2020 flow diagram was generated using the PRISMA2020 R package (version 1.1.4) and its Shiny application [19]. The PRISMA Checklist is provided as Supplementary Material Table S1.

2.1. Bibliometric Search Strategy

2.1.1. Data Source and Search Protocol Scopus

Data Source and Search Protocol Scopus were selected as the primary data source due to its extensive coverage of high-impact journals in transport geography and sustainability. The search strategy was executed in two sequential phases to validate the research gap.

Phase 1: Regional Scoping (The Latin American Gap). Initially, the objective was to analyze sustainable port development specifically within the Latin American context. The following Boolean search string was executed:

TITLE-ABS (“smart port” OR “sustainable port” OR “green port” OR “eco port” OR “resilient port”)

AND TITLE-ABS-KEY (“Latin America” OR “Mexico” OR “Brazil” OR “Chile” OR “Colombia” OR “Argentina” OR “Peru”)

This limited retrieval ($n = 9$) was considered a preliminary indication of the low representation of Latin American port sustainability research within the Scopus-indexed literature, consistent with previous studies addressing port regionalization and logistics development in emerging economies [20].

Phase 2: Global Benchmarking Strategy. Given the insufficient regional volume for a robust bibliometric analysis, the thematic scope was expanded. The goal shifted to identifying global best practices and technological standards that could be transferred to the Latin American context. The revised and final search string was

TITLE-ABS-KEY (“smart port” OR “sustainable port” OR “green port” OR “eco port” OR “resilient port”)

AND TITLE-ABS-KEY (“port governance” OR “environmental management” OR “carbon emissions” OR “energy efficiency” OR “digitalization” OR “circular economy”)

This broader query yielded the final corpus used for this review, providing a representative sample of the global state of the art in port sustainability research. The expanded scope also enabled the identification of international trends, governance approaches, and technological pathways that could serve as a comparative framework for interpreting the challenges and opportunities of the Port of Manzanillo.

2.1.2. Final Corpus Selection the Global Search Yielded 363 Documents

The screening process involved a sequential review of the retrieved records. First, errata, retracted publications, and non-peer-reviewed trade magazines were excluded. Subsequently, documents published before 1999 were removed to focus on the contemporary evolution of port sustainability research. Finally, a manual review of titles and abstracts was conducted to identify duplicate records and studies that were not directly related to sustainable port development. This screening process resulted in the exclusion of 56 records, leading to a final corpus of 307 documents for bibliometric analysis.

The final dataset consists of 307 documents spanning from 1999 to early 2025, including 193 research articles, 70 conference papers, 22 review articles, 17 book chapters, 3 conference reviews, 1 book, and 1 note. The full bibliographic list of included documents is provided as Supplementary Material S2. The selection process is detailed in the PRISMA Flow Diagram (Figure 1).

2.2. Quantitative Data Analysis

The quantitative analysis was performed using the Bibliometrix package (R version 5.1.1) via the Biblioshiny interface, and VOSviewer (1.6.19) for network visualization.

Bibliometrix was used to calculate bibliometric performance indicators and thematic structures through the Biblioshiny graphical interface, while VOSviewer was employed to construct and visualize bibliometric networks. For network analyses, full counting was adopted to ensure equal weighting of each co-authorship and keyword occurrence. Network visualization parameters were adjusted using the software’s default normalization (association strength) and clustering settings to facilitate the interpretation of collaboration and keyword co-occurrence patterns.

The analysis was structured along three main axes addressing the Research Questions (RQs).

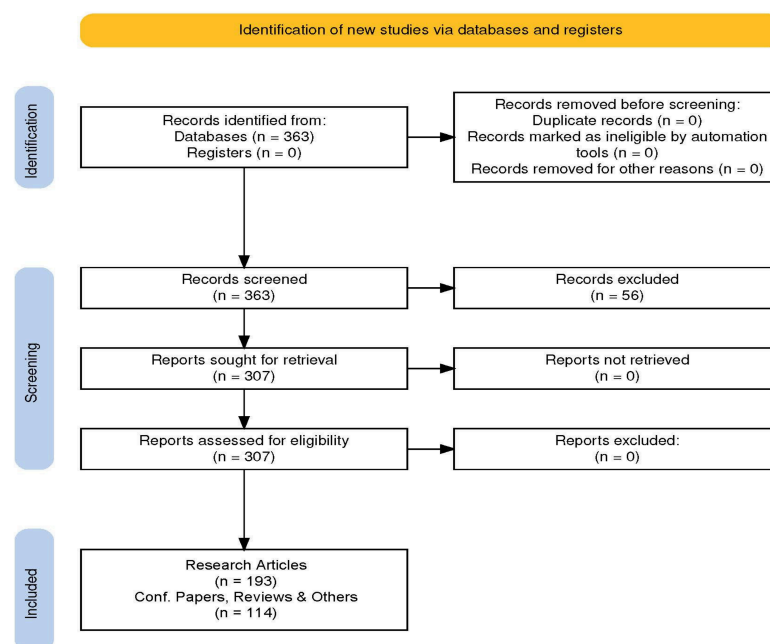


Figure 1. PRISMA 2020 Flow Diagram. ($n = 307$ documents included for quantitative bibliometric analysis; subset of key documents selected for qualitative case study analysis).

2.2.1. Performance Analysis (RQ1)

This analysis focused on research productivity and visibility. Annual Scientific Production was evaluated to observe the temporal evolution of the field. Most relevant sources were identified using Bradford's Law to determine the core journals of the literature. The impact of publications was measured using Total Citations (TCs) and Total Citations per Year (TCpY).

2.2.2. Structural Analysis (RQ2)

This analysis examines how researchers collaborate (collaboration networks) as well as the field's main ideas and theories (theoretical foundations). We studied how researchers from different countries and institutions work as teams by tracking co-authorship—when two or more researchers write a paper together. This allowed us to see working relationships in science. This analysis examined collaboration networks through co-authorship patterns among countries and institutions, allowing the identification of international scientific collaboration structures within the field.

After examining social connections among researchers, the analysis next examined the field's intellectual structure. Intellectual structure refers to the ideas and research that underpin a topic. We identified the most frequently cited research articles, meaning other researchers reference them in their own work. Frequently cited articles are referred to as 'seminal works'—research that is especially important because it strongly influences the development and direction of the field.

The inclusion criteria comprised peer-reviewed publications indexed in Scopus that addressed port sustainability, green ports, Smart Ports, environmental management, decarbonization, digitalization, or related governance issues. Eligible document types included research articles, review articles, conference papers, conference reviews, book chapters, books, and notes. The exclusion criteria comprised duplicate records, errata, retracted publications, trade magazines, documents published before 1999, and studies whose titles and abstracts indicated no direct relevance to sustainable port development.

2.2.3. Conceptual Analysis (RQ3)

A co-occurrence analysis of keywords was used to examine patterns among frequently co-mentioned terms. This helped visualize the field's thematic structure. The approach revealed distinct keyword clusters and highlighted major thematic areas. A Thematic Mapping organized clusters based on their relationships. This was conducted using the Walktrap algorithm, which identifies densely connected groups in networks through random-walk-based community detection procedures [21]. The algorithm was chosen for its superior efficiency in handling dense subgraphs in bibliometric networks. It is more efficient than modularity-based methods. This mapping categorized clusters into quadrants: Motor Themes (central and well-developed topics), Basic Themes (important but less developed topics), Niche Themes (specialized topics), and Emerging Themes (new or underdeveloped topics) [22,23]. This categorization offers insights into the field's structure and focus.

In order to identify emerging thematic shifts, the study divided the analysis into two periods. The first period (1999–2023) captures the historical development and consolidation of port sustainability research, while the second period (2024–2025) represents the most recent stage of scientific production. This division was selected to distinguish long-term thematic foundations from newly emerging research priorities, particularly those associated with Smart Ports, digitalization, and decarbonization. The second period was intentionally chosen to capture the most recent surge in scientific production and the rapid emergence of technology-oriented themes, including Smart Ports, Digital Twins, and decarbonization strategies.

Subsequently, a Thematic Evolution Analysis tracked changes in research topics over time. This analysis compared the early period (1999–2023) with the recent period (2024–2025). It helped identify emerging research trends in sustainable ports.

2.3. Qualitative Case Study Methodology

To bridge the gap between global theory and local practice, a qualitative documentary analysis was conducted focusing on the Port of Manzanillo, Mexico. This phase involved the systematic review of official planning instruments:

- The Master Program for Port Development (PMDP) 2026–2031 [24].
- The Integrated Management System (SGI) Manuals [25], developed in accordance with ISO 14001:2015 [26].
- The New State Law for Economic Development (2025) [27].

This triangulation strengthens the connection between global bibliometric trends and the local planning and governance context of the Port of Manzanillo, supporting the interpretation developed in Sections 4 and 5.

The documentary analysis followed an interpretative approach aimed at identifying governance priorities, sustainability strategies, and institutional mechanisms described in the selected planning instruments. These findings were subsequently contrasted with the bibliometric evidence to identify convergences and divergences between the global research agenda and the local governance context.

3. Results

This section presents the bibliometric analysis findings, organized around three key dimensions aligned with the research questions. First, Section 3.1 (Performance Analysis) examines how scientific production has evolved over time and identifies the most influential journals and authors (RQ1). Next, Section 3.2 (Social and Intellectual Structure) maps the field's geographic distribution and theoretical foundations through seminal works (RQ2).

Finally, Section 3.3 (Conceptual Structure) visualizes the evolution of themes and keyword clusters shaping the global research agenda (RQ3).

3.1. Performance and Growth Analysis (RQ1)

This section addresses the research question regarding the temporal evolution of studies in the field and identifies the most influential sources and authors.

We begin by analyzing the annual publication trend to assess the maturity of the research domain.

Execution Step: The dataset was processed and examined through a Bibliometric and Systematic Review (BSR) methodology using VOSviewer for bibliometric mapping [28] and following the PRISMA 2020 Statement for the systematic review process [29], to obtain the Annual Scientific Production, followed by the generation of the graph presented below (Figure 2).

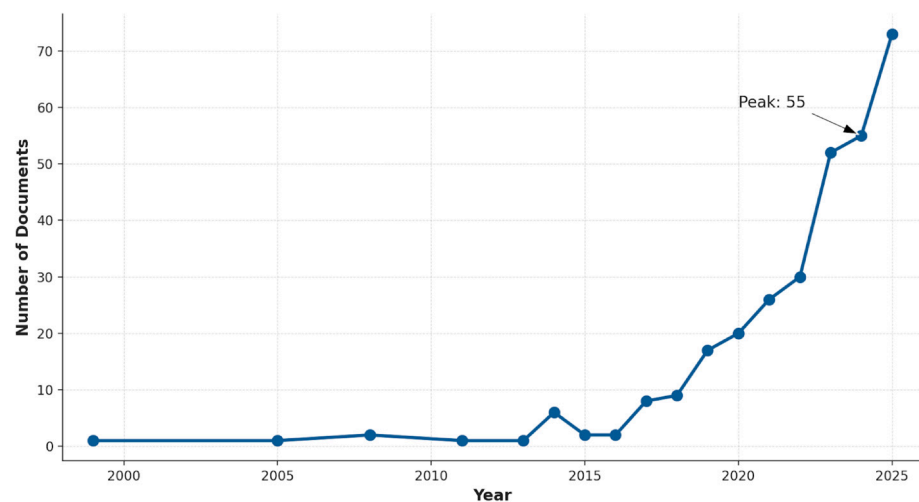


Figure 2. Evolution of Annual Scientific Production (1999–2025) (Source: Bibliometric Analysis).

3.1.1. Evolution of Annual Scientific Production

The analysis of scientific production from 1999 to early 2025 (Figure 2) reveals a research trajectory that has evolved from an initial stage to exponential and sustained growth in recent years.

1. Incipient Phase (1999–2016): Research output was minimal, with a single article published in both 1999 and 2005, accompanied by a few isolated surges.
2. Turning Point (2017): A significant shift occurred with the publication of eight articles, suggesting the beginning of the topic's recognition within the global research agenda.
3. Exponential Growth phase (2020–2025): When research activity increased sharply, rising from 20 articles in 2020 to 73 in 2025. This trend indicates that port sustainability has become a highly emergent and academically demanded topic.

This pattern confirms the relevance and timeliness of the present study within a field currently experiencing its highest historical level of activity.

3.1.2. Most Relevant Sources and Authors

The analysis of the most productive sources (journals) and authors addresses the need to identify the key channels and contributors driving knowledge generation in the field.

Journals. According to Bradford's Law (core of the literature), the research output is concentrated within a small set of specialized publications (Table 1):

Table 1. Top 5 Bradford’s Law Core Journals.

Source (Journal)	Articles (N)	Implication
Sustainability (Switzerland)	30	The most important publication channel, confirming the topic’s relevance for this journal.
Journal of Marine Science and Engineering	17	Focused on maritime engineering solutions.
Maritime Policy and Management	12	Focused on management, policy, and economic aspects.
Journal of Cleaner Production	8	Focused on ecological efficiency and clean production.
Transportation Research Part D: Transport and Environment	8	Focused on the environmental dimension of transportation.

Source: Author’s own elaboration based on data obtained from the Bibliometric Analysis (BA).

The journal Sustainability (Switzerland) is the primary source, with 30 documents, demonstrating its leadership in publishing on this topic. This core group of journals suggests that the subject is being approached from a multidisciplinary perspective, combining engineering, maritime policy, and environmental sustainability.

Most Influential Authors: The author analysis highlights the leading figures based on their academic impact within the field. Table 2 presents the top authors ranked by Total Citations (TCs) within the analyzed corpus. Acciaro, M., emerges as the most influential author with 402 citations across 3 documents, followed by Ghiara and Cusano (308 citations), indicating that impact is driven by highly cited seminal papers rather than high production volume.

Table 2. Top 10 Most Influential Authors based on Total Citations (TCs).

#	Author	Total Citations (TCs)	Articles (N)
1	Michele Acciaro	402	3
2	Hilda Ghiara	308	1
3	Maria Inés Cusano	308	1
4	Lan Wang	295	6
5	Leonard Heilig	271	3
6	Stefan Voß	271	3
7	Eduardo Aníbal Lalla-Ruiz	227	2
8	Herodotos Herodotou	218	1
9	Sheraz Aslam	218	1
10	Michalis P. Michaelides	218	1

Source: Author’s own elaboration based on data obtained from the Bibliometric Analysis (BA).

In addition, it shows that, the most influential authors, by Total Citations (TCs), are Acciaro, M., followed by Ghiara, H., and Cusano, M.I. (Table 2). Acciaro’s work is pivotal in defining energy efficiency strategies [1]. Ghiara and Cusano’s high impact comes from their collaborative research on the evolving role of Port Authorities in energy management [30]. This confirms that the field’s leadership focuses on strategic management policies and energy standards, not just technical implementation.

3.2. Social and Intellectual Structure (RQ2)

The following section presents the analysis of the Social and Intellectual Structure (RQ2), focusing on international collaboration patterns, the temporal evolution of scientific production across countries (Figure 3), and the intellectual foundations of the field through the identification of seminal publications.

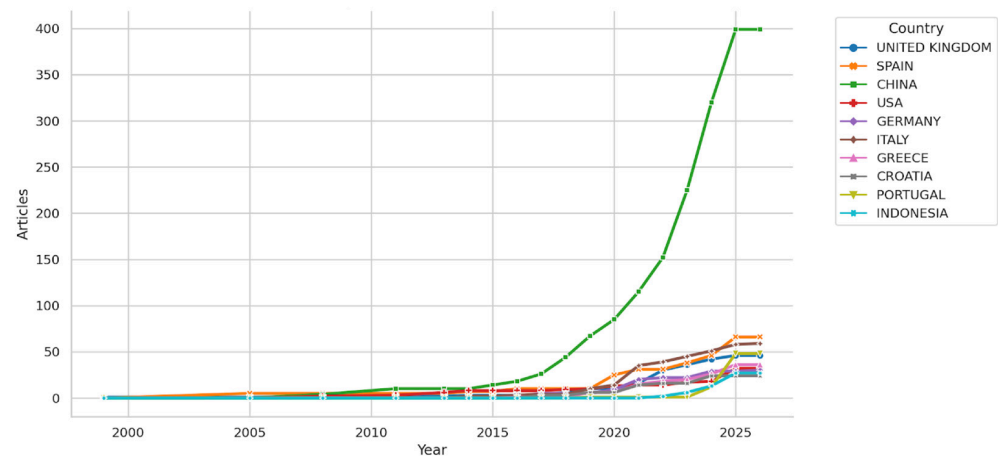


Figure 3. Scientific Production Trends by Country over Time (Source: Bibliometric Analysis).

3.2.1. Collaboration and Geographical Imbalance

The analysis of scientific production by country over time reveals a highly uneven distribution of research activity within the field of port sustainability. As shown in Figure 3, scientific output has increased substantially since 2017, although this growth has been concentrated in a limited number of countries. The most notable trend is the rapid expansion of research activity in China, particularly after 2019, which contrasts with the more gradual growth observed in European countries and the limited participation of Latin American nations.

Figure 4 shows that China has the highest level of scientific participation in the field, with 399 country-affiliated contributions. Spain (66), Italy (59), Portugal (48), and the United Kingdom (46) also demonstrate strong participation. These findings reflect country contributions based on author affiliations and international collaborations rather than unique documents. Because a single publication may involve authors from multiple countries, the number of country-affiliated contributions can exceed the total number of documents included in the corpus. Overall, these findings suggest that countries with advanced maritime sectors play a dominant role in shaping the global discourse on port sustainability.

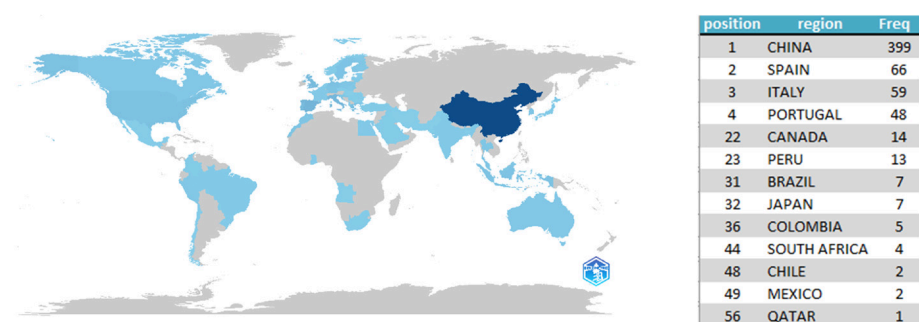


Figure 4. Country Scientific Production, Highlighting the Context of Asia, Europe, and Latin America. Darker shades of blue indicate higher scientific production, while lighter shades represent lower scientific production. Gray indicates countries with no publications in the analyzed dataset. Source: Bibliometric Analysis.

Within Latin America, Peru records the highest level of participation, with 13 country-affiliated contributions, followed by Brazil (7) and Colombia (5). Mexico and Chile each register two contributions, highlighting the limited visibility of the region within the global scientific production on port sustainability.

This pattern highlights the underrepresentation of Latin America within the global scientific production on port sustainability. The findings suggest that the region continues

to play a comparatively limited role in shaping the international research agenda, with much of the current conceptual and thematic development being driven by institutions and research networks located in Asia and Europe (Figure 4).

3.2.2. Intellectual Foundation of the Field

The identification of the most cited documents establishes the theoretical foundation of global research—that is, the seminal papers that any new study in the field should consider. The analysis of global citations indicates that the field is supported by seminal publications summarized in Table 3, which constitute the principal theoretical foundations of port sustainability research.

Table 3. Top 5 Most Globally Cited Papers.

#	Seminal Document	Global Citations	Main Theme
1	Acciaro, 2014, Energy Policy [30]	308	Energy policy, efficiency, and port competitiveness.
2	Aslam, 2020, IEEE Internet of Things Journal [31]	218	Implementation of IoT and Smart Port technologies.
3	Heilig, 2017, Netnomics: Economic Research Electronic Networks [4]	203	Digital strategies and electronic networks in ports.
4	Peris-Mora, 2005, Marine Pollution Bulletin [2]	200	Pollution assessment and environmental performance management.
5	Molavi, 2020, International Journal of Sustainable Transportation [32]	197	Optimization models and sustainable transport.

Source: Author's own elaboration based on data obtained from the Bibliometric Analysis (BA).

These foundational documents reveal that the intellectual base of the field rests on two main pillars:

1. Environmental impact management and policy (Acciaro, Peris-Mora).
2. The integration of digital technologies (IoT, Smart Ports) to optimize efficiency and reduce emissions (Aslam, Heilig).

The strong emphasis on technology points to future research agendas, a critical aspect for the Manzanillo case study.

3.3. Conceptual Structure and Trends (RQ3)

To show how ideas in the field connect, a network analysis of author keywords—tracking how often keywords co-occur—was conducted. As shown in Figure 5, this network illustrates the evolution of the field from foundational environmental management approaches toward more advanced technology-driven sustainability strategies. The analysis identifies three main groups of related topics. The first group, focused on ‘Energy Management’, is based on Acciaro et al. [30], who outlined the main ideas for energy saving in port authorities. Gonzalez-Aregall et al. [20] and Sadiq et al. [33] later expanded this perspective to include hinterland connectivity and environmentally sustainable infrastructure planning.

Although terms such as Smart Port, Digitalization, and Digital Twin Smart Ports do not rank among the most frequent keywords in the dataset, their central position within the co-occurrence network indicates a growing strategic relevance. This pattern suggests that recent research is increasingly structured around technological innovation and digital transformation, despite the relatively recent emergence of these concepts within the literature. Their connectivity with themes such as energy efficiency, sustainability, and port governance further demonstrates how digitalization is becoming integrated into broader sustainability agendas.

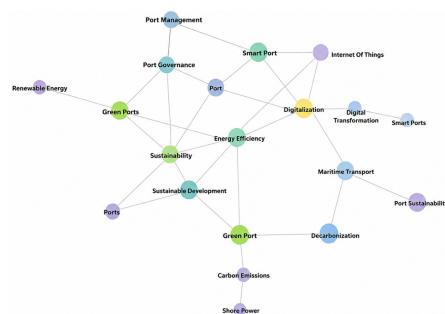


Figure 5. Co-occurrence Network of High-Frequency Keywords.

Building on this evolution, a second cluster emerges. In parallel, the “Pollution Mitigation” research front features simulation studies such as those by Yun et al. [34] and Wan et al. [35], which quantify carbon emission reduction strategies in container terminals. Shifting the focus to governance models, Cao [36] and Alamoush et al. [37] provide critical frameworks for understanding institutional barriers associated with port spatial structures—that is, how port land, infrastructure, and facilities are organized and managed. Additionally, recent studies by Tijan et al. [38] and Bjerkan and Seter [39] emphasize the role of digital tools and digital transformation processes in advancing sustainability objectives and supporting the Sustainable Development Goals (SDGs) within maritime and port systems, while also highlighting adaptation challenges related to climate resilience, as explored by Becker et al. [40] and Ng et al. [41]. Finally, comparative studies by Davarzani et al. [42] and Hossain et al. [43] confirm that while developed nations tend to prioritize automation and advanced technological solutions, developing regions often remain focused on achieving basic environmental compliance [44].

Complementing the network analysis, Table 4 lists the most frequent keywords after consolidating synonyms (e.g., merging “Green port” and “Green ports”). The dominance of “Sustainable Development” ($n = 118$) and “Green Ports” ($n = 109$) underscores the field’s dual focus on theoretical frameworks and operational branding.

Table 4. Top Most Frequent Keywords (Consolidated).

#	Keyword	Frequency (N)	Thematic Implication
1	Sustainable development *	118	Central axis of the research field.
2	Green ports **	109	Main operational concept of port sustainability.
3	Energy efficiency	52	Key technological focus for cost/emission reduction.
4	Ports and harbors	50	Generic terms defining infrastructure scope.
5	Port operation	50	Practical focus on process optimization.
6	Emission Control	38	Primary environmental objective.
7	Environmental management and sustainability practices	36	Emerging paradigm of digital integration.

Source: Data derived from Scopus and processed using the Bibliometrix R-package (version 5.3.0). * Includes counts for “Sustainability”. ** Includes counts for “Green Port”.

As shown in Table 4, the field is dominated by broad terms such as ‘sustainable development’ and ‘green ports.’ These keywords form the macro-structure of the research landscape. While these terms are foundational, they may be too generic to offer granular insight on their own. However, shifting focus to the co-occurrence network (Figure 5) clarifies the thematic depth. Through this cluster analysis, general concepts are systematically broken into specific operational niches. Notably, it demonstrates that ‘sustainable development’ is implemented through sub-themes like ‘energy efficiency,’ ‘emissions control,’ and ‘alternative fuels.’ These sub-themes are grouped within the ‘Decarbonization’ and ‘Environmental Management’ clusters in Figure 5.

Thematic Evolution (1999–2025). The evolution analysis reveals a clear shift in research focus over time. During the Initial Period, from 1999 to 2023, the focus was on problem definition and generic Environmental Management concepts alongside pollution-control measures. In contrast, the Recent Period, covering 2024 to 2025, marks a phase of field maturity, with themes turning to practical technological solutions. This transition is defined by three dynamic axes that now drive the agenda: (1) smart port, linked to IoT and digitalization; (2) decarbonization, defined by energy transition and shore power; and (3) maritime transportation, focused on supply chain optimization. Consequently, the field has shifted from asking, “What is port sustainability?” to “How can digitalization implement it?”, positioning technological innovation as the next central driver.

4. Discussion

The transition to a sustainable port model requires holistic integration of technology and strategy. For instance, Fruth and Teuteberg [45] argue that digitization is essential for modern maritime logistics, enabling operational efficiency. Building on this digital foundation, Fei et al. [46] highlight that contemporary green port development relies on comprehensive evaluation frameworks that integrate environmental performance, energy efficiency, resource management, and sustainability indicators. Furthermore, building on these theoretical frameworks, real-life applications of environmental performance indicators proposed by Puig et al. [47], demonstrate that robust monitoring indicators are vital for validating green policies. Taken together, these perspectives illustrate a progression from technological innovation to environmental performance assessment and practical policy validation.

The results revealed a sustained increase in scientific production, accompanied by a pronounced geographical concentration of research in Asia and Europe. Based on these findings, the following discussion situates the evidence within the broader context of sustainability transitions in Latin American (LA) ports, using the Port of Manzanillo as a representative case study. To address the research questions (RQs), the discussion examines the theoretical and practical implications of the global research landscape, acknowledging that sustainability transitions do not follow a universal trajectory but instead are shaped by institutional, governance, infrastructure, and socioeconomic conditions. From this perspective, the Port of Manzanillo is analyzed as an example of an emerging economy pursuing a context-specific pathway toward port sustainability, rather than being evaluated against the standards of highly digitalized and resource-intensive ports.

4.1. Reflection on the Intellectual Base and the Global Agenda

The sustained growth in scientific production observed after 2020 reflects a broader transformation in the maritime sector, where sustainability has evolved from an environmental concern into a strategic competitiveness factor. This trend coincides with the growing international pressure to decarbonize maritime transport, improve energy efficiency, and accelerate the digital transformation of logistics systems. Consequently, research has progressively shifted from isolated environmental management practices toward integrated frameworks that combine operational efficiency, governance, and technological innovation.

The largest scientific output is located in China and several European countries, which suggests that the contemporary global sustainability agenda is shaped mainly by regions that have demonstrated a greater capacity for technological innovation in the maritime sector. This finding is consistent with the evolution of the thematic clusters identified in this study, where concepts such as Smart Ports, Digital Twins, Artificial Intelligence, and energy transition have become central research priorities. Rather than representing independent technological trends, these themes reflect a broader transition toward data-driven port governance and low-carbon logistics systems.

In the Latin American context, the bibliometric results reveal a contrasting pattern. The comparatively limited scientific output should not be interpreted solely as an academic gap; it may also be considered in relation to the institutional, economic, and governance conditions that influence sustainability transitions in developing port systems. Previous research on Latin American ports has highlighted challenges related to governance practices, stakeholder coordination, institutional capacity, and digital integration [16]. As a result, ports in the region may follow transition pathways in which operational growth, infrastructure development, and institutional strengthening coexist with the progressive incorporation of digitalization and decarbonization strategies.

This evolution signals a broader transformation underway. Specifically, the twin transition—digital and green—is changing industrial ecosystems. Komninos [48] confirms that this shift drives systemic innovation and relies on prioritization, an ecosystem view, and platform-based solutions.

Based on this shift, the findings suggest that technological adoption alone may be insufficient to achieve sustainable port transitions in emerging economies. The successful implementation of Smart Port and decarbonization strategies also depends on institutional readiness, including governance capacity, stakeholder coordination and the ability to align long-term planning instruments with evolving international sustainability agendas [11,12,37]. Within this context, the Port of Manzanillo exemplifies a context-specific sustainability transition pathway, where infrastructure expansion, institutional coordination among port authorities, and environmental compliance remain the primary strategic priorities, while digital transformation is gradually incorporated into long-term planning in line with local governance priorities and institutional capacities.

4.2. The Gap Between Global Trends and Local Planning (RQ4)

To interpret the global findings within the specific institutional and operational context of the Port of Manzanillo, a qualitative documentary analysis was conducted. Unlike the broad bibliometric scope, this phase focused on a selected set of structural instruments—ranging from local planning manuals to the new legislative framework—that directly govern the port’s development. Table 5 summarizes the core documents selected for this in-depth case study analysis.

Table 5. Summary of Key Planning Instruments and Documents analyzed for the Case Study (Qualitative Synthesis).

ID	Document/Study Type	Title/Focus	Year	Source/Reference	Relevance to Study
Doc 1	Strategic Planning Instrument	Master Program for Port Development (PMDP) 2026–2031	2026	ASIPONA Manzanillo [24]	Defines current infrastructure priorities (roads/expansion) vs. sustainability goals.
Doc 2	Operational Manual	Manual of the Integrated Management System (SGI)	2023	ASIPONA Manzanillo [25]	Evidences the compliance-based management model (ISO 14001/9001).
Doc 3	Legislative Framework	Law for Economic Development of the State of Colima	2025	H. Congreso del Estado [27]	Identifies legislative instruments that may support future sustainability and technological modernization initiatives.
Doc 4	Regional Report	Decarbonization in Maritime Transport in Latin America	2023	CEPAL [49]	Provides the regional benchmarking context for decarbonization gaps.
Doc 5	Scientific Study (Case)	Optimization of Port Asset Management (Digital Twin)	2025	González-Cancelas et al. [5]	Validates the feasibility of Digital Twin technologies in Spanish contexts for comparison.

Source: Author’s own elaboration based on the selected corpus for the qualitative analysis. Note: While the bibliometric analysis processed a total of $n = 307$ documents quantitatively, this table details the core documents selected for the qualitative documentary analysis of the Case Study.

A distinct transition pathway emerges when contrasting the global Smart Port discourse with the current institutional and operational context of the Port of Manzanillo [24]. While the bibliometric analysis highlights the growing importance of IoT, Blockchain, Artificial Intelligence, and Digital Twins as key enablers of port sustainability, the documentary analysis reveals a governance and management model primarily structured around procedural compliance and environmental risk prevention. Evidence from the Integrated Management System Manual (SGI) indicates that the port's environmental strategy is strongly aligned with internationally recognized standards, particularly ISO 14001:2015 for environmental management and ISO 9001:2015 for quality assurance [25].

The SGI establishes clear procedures for pollution prevention, environmental monitoring, and risk management; however, the mechanisms described remain predominantly administrative and operational rather than digitally integrated [25]. This finding should not be interpreted as an absence of sustainability efforts. Instead, it suggests that the Port of Manzanillo currently reflects a context-specific governance model focused on regulatory compliance and operational control, while the contemporary global agenda increasingly emphasizes digital integration, data-driven decision-making, and digital twin-enabled smart maritime logistics [50]. Consequently, the findings suggest that this transition pathway is better understood in terms of institutional readiness rather than as a purely technological gap, considering the governance, investment and institutional challenges commonly faced by emerging port systems during sustainability transitions [51,52]. Accordingly, the principal challenge lies not only in the adoption of new technologies but also in strengthening governance capacities that can support the Twin Transition through coherent, context-sensitive, and long-term strategies, in line with emerging Smart Governance frameworks proposed in the literature [53].

To illustrate this context-specific transition, Table 6 summarizes the main differences between the dominant themes identified in the global research agenda and the current governance and management approach observed in the Port of Manzanillo.

Table 6. Comparison between the Contemporary Smart Port Research Agenda and the Context-Specific Governance Model of the Port of Manzanillo.

Strategic Dimension	Global Research Paradigm (2024–2025)	Current Governance and Development Approach of the Port of Manzanillo
Primary Focus	Smart Port & Decarbonization: Emphasis on AI, IoT, and real-time automation.	Physical Infrastructure: Expansion of Northern Zone and road connectivity.
Management Model	Ecosystem-based: Integration of stakeholders via digital platforms (“Twin Transition”).	Standardized Management: Procedural compliance based on ISO 14001 and ISO 9001.
Sustainability Goal	Net Zero & Energy Transition: Focus on Cold Ironing and renewable energy grids.	Risk Prevention: Focus on pollution mitigation and environmental impact control.
Key Enabler	Digital and Technological Innovation: Digital Twins, Blockchain and AI.	Institutional and Regulatory Framework: New State Law for Economic Development (2025).

Source: Author's own elaboration based on bibliometric results and documentary analysis of ASIPONA's planning instruments.

The comparison presented in Table 6 illustrates not only differences in technological adoption but also distinct strategic approaches used to evaluate port performance. Recent research highlights that contemporary port assessment frameworks increasingly combine operational efficiency indicators with environmental, social, and institutional sustainability dimensions, allowing a more comprehensive evaluation of port performance [51].

This divergence is further reflected in investment priorities. The Master Program for Port Development 2026–2031 (PMDP) establishes a strategic vision centered on strength-

ening the operational capacity and competitiveness of the Port of Manzanillo through the expansion of port infrastructure, the development of the Laguna de Cuyutlán area, improvements in road and rail connectivity, and the modernization of logistics facilities [24]. These priorities respond to the sustained growth in cargo volumes and the increasing demand for multimodal transport services associated with one of the most important port systems in the Pacific region.

The PMDP also incorporates elements of technological modernization. Among them are maritime traffic control systems, digital communication platforms, monitoring technologies, and operational coordination mechanisms that contribute to improving the efficiency and safety of port activities [24]. These initiatives indicate that technological transformation is already present within the port system. Nevertheless, compared with the contemporary Smart Port research agenda identified in the bibliometric analysis, the technological components described in the PMDP are primarily oriented toward operational management and infrastructure support rather than advanced digital ecosystems based on Artificial Intelligence, Digital Twins, Blockchain, or integrated data-driven governance [54]. This dissimilarity becomes particularly relevant when contrasted with Smart Port frameworks that emphasize the systematic integration of digital technologies, sustainability objectives, and performance measurement systems as core elements of port transformation [32].

From a sustainability perspective, the program maintains a strong emphasis on environmental management, operational efficiency, and the mitigation of impacts associated with port development [25]. Recent decarbonization assessments for the Port of Manzanillo have identified the adoption of alternative fuels, including Liquefied Natural Gas (LNG), together with the progressive electrification of cargo-handling equipment, as potential pathways for reducing greenhouse gas emissions associated with port operations [55]. The presence of LNG infrastructure within the broader port system further supports future opportunities for implementing low-carbon initiatives [24,55]. These strategies contribute to the modernization of port assets while supporting broader sustainability objectives related to SDG 9 (Industry, Innovation and Infrastructure) and SDG 13 (Climate Action).

Rather than reflecting lower levels of commitment to sustainability or innovation, the evidence suggests that the Port of Manzanillo is following a context-specific transition pathway in which infrastructure expansion, logistics efficiency, and operational modernization remain immediate priorities, while advanced digitalization and decarbonization strategies are being progressively incorporated in accordance with local governance priorities and long-term planning processes. This interpretation is reinforced by recent changes in the local legislative framework. The New Law for Economic Development introduces incentives aimed at technological modernization and sustainable industrial practices [27]. Although the legislation does not explicitly adopt the Smart Port or Smart Governance concepts identified in the international literature, it establishes instruments that may facilitate technological upgrading, inter-institutional coordination, and long-term sustainability planning. Consequently, the law represents a complementary mechanism that could strengthen the conditions necessary to support future digital and green transitions within the Port of Manzanillo.

Overall, the comparison between the global sustainability agenda and the Port of Manzanillo highlights complementary approaches to sustainability transition. Although the international literature increasingly emphasizes advanced digitalization, integrated governance models, decarbonization strategies and the adoption of green port initiatives [37], evidence from local planning instruments indicates that Manzanillo currently prioritizes infrastructure expansion, operational modernization, and regulatory compliance as the foundational pillars of its development strategy. Rather than indicating divergent levels

of sustainability performance, these priorities reflect a context-specific transition pathway shaped by local economic, logistical, and institutional conditions.

In this context, the challenge for emerging economy port systems is not only to incorporate technologies that improve operational efficiency and competitiveness, but also to progressively strengthen the governance, institutional coordination, and long-term planning conditions required to support digital and green transitions. Ultimately, these transformations should contribute not only to environmental performance but also to broader social and economic benefits for port communities, consistent with broader sustainable development frameworks for smart and resilient territories [56].

4.3. Managerial Implications

This study provides practical implications for port authorities, policymakers, and logistics stakeholders seeking to advance sustainability transitions in emerging port systems. Rather than proposing a universal Smart Port model, the bibliometric evidence suggests that sustainability strategies should be adapted to each port's institutional, economic, and governance context.

For the Port of Manzanillo, the identified research trends highlight the importance of progressively integrating digital technologies, environmental management practices, and collaborative governance mechanisms. While technological innovation—including digitalization, artificial intelligence, and Smart Port applications—constitutes an important component of sustainable port development, the findings suggest that these initiatives should be accompanied by coordinated planning, regulatory support, and stakeholder participation.

More broadly, the study provides a strategic reference for other Latin American ports facing similar institutional, operational, and governance challenges. By aligning local sustainability initiatives with internationally recognized research trends, port authorities and decision-makers can prioritize actions that enhance environmental performance while maintaining logistics competitiveness. Consequently, the bibliometric framework presented in this study may serve as a decision-support tool for identifying emerging priorities, guiding long-term planning, and supporting context-specific sustainability transition pathways in emerging port systems.

5. Conclusions and Future Research Lines

The present study aimed to analyze the evolution and thematic trends of global research on port sustainability through a bibliometric analysis, using these findings to contextualize the governance challenges faced by the Port of Manzanillo. The findings highlight the potential value of bibliometric methods as strategic tools for interpreting sustainability transitions within complex port systems.

5.1. Conclusions

The results allow for concise responses to the proposed research questions (RQs):

RQ1 and RQ2: How has the field of port sustainability evolved in terms of scientific production, collaboration patterns, intellectual structure, and which key actors and seminal contributions have shaped its development?

To address RQ1 and RQ2, the results show sustained growth in scientific production, particularly after 2020, alongside a strong geographical concentration of research in China and several European countries. The relatively low international co-authorship rate (29.97%) indicates that knowledge production remains concentrated within specific regional research networks. Regarding the intellectual structure of the field, the analysis shows an evolution from Sustainable Development and Environmental Management, which dominated the 1999–2023 period, toward two converging research areas during 2024–2025: Smart Ports,

associated with digitalization and logistics optimization, and Decarbonization, associated with energy transition and shore power. The analysis of authors, institutions, countries, and seminal contributions further identifies the main actors and knowledge foundations that have shaped the development of the field.

RQ3: Which thematic clusters and trends shape the global research agenda on sustainable ports?

The thematic analysis reveals that the global research agenda on sustainable ports is increasingly structured around the convergence of digital and environmental transformation. Recent research emphasizes smart ports, digitalization, logistics optimization, artificial intelligence, digital twins, energy transition, and decarbonization. These thematic clusters indicate a shift from predominantly environmental management approaches toward integrated sustainability frameworks in which technological innovation, operational efficiency, and low-carbon strategies increasingly converge.

RQ4: How can mapped knowledge guide strategic actions and future research for the sustainability of the Port of Manzanillo?

The comparison between the global sustainability agenda and the Port of Manzanillo suggests that mapped knowledge can provide a strategic reference for interpreting local sustainability priorities and identifying potential areas for future development. While the international literature increasingly emphasizes advanced digitalization, integrated governance models, and decarbonization strategies [11,12,31], the documentary analysis indicates that Manzanillo is following a context-specific development pathway that prioritizes infrastructure expansion, operational modernization, environmental management, and logistics efficiency. These priorities are reflected in the Port Development Master Program 2026–2031 and in the operational framework established by ASIPONA [43,44].

Rather than indicating a technological deficit, the findings suggest that the Port of Manzanillo is following a sustainability transition pathway shaped by local operational demands, infrastructure requirements, governance conditions, and long-term planning processes. In this context, recent legislative reforms, including the New Law for Economic Development (2025), may strengthen the institutional conditions necessary to support future digital and green transitions [45]. Consequently, the principal challenge identified is not the absence of sustainability initiatives, but the progressive integration of technological innovation, governance mechanisms, stakeholder coordination, and long-term planning within a coherent development strategy.

Overall, the findings suggest that sustainable port transitions may not follow a universal pathway but instead evolve according to governance arrangements, institutional capacities, infrastructure priorities, and regional development contexts. From this perspective, the Port of Manzanillo illustrates how global sustainability agendas can be progressively adapted to local conditions, advancing digital and green transition objectives within an emerging economy.

5.2. Study Limitations

While the bibliometric analysis provides a robust overview of the field's intellectual evolution, several limitations are acknowledged and addressed:

Database Coverage and Language Bias: The primary limitation involves the exclusive use of Scopus as the data source. While chosen for its rigorous quality standards and compatibility with Bibliometrix, this decision may exclude specific regional contributions indexed in local databases like Latindex or SciELO, particularly those published in Spanish or Portuguese. However, recent bibliometric reviews on smart maritime logistics and port digitalization [43] indicate that the trends identified in this study are consistent with broader

international research patterns, particularly regarding sustainability, digital transformation, and technological innovation.

Methodological Integration: To complement the bibliometric analysis and contextualize the limited representation of Latin American port research within the analyzed scientific literature, this study incorporated a Qualitative Case Study (Section 4). This phase draws on grey literature, including local government reports and specific regulatory and planning frameworks, such as the Port Development Master Program and the Integrated Management System of the Port of Manzanillo. Although these documents do not undergo the same peer-review process as academic journal articles, they provide relevant documentary evidence for interpreting the local governance and planning context that international bibliographic databases cannot fully capture.

Scope of Analysis: Finally, the descriptive nature of the bibliometric approach constitutes an inherent limitation of this study. While it provides a robust overview of research trends, thematic priorities, and emerging knowledge domains, it does not evaluate the operational performance, implementation, or effectiveness of the technologies identified. Accordingly, the findings should be interpreted as a bibliometric and documentary framework for informing governance and long-term strategic planning rather than as a direct assessment of technological or operational outcomes.

5.3. Future Research Lines

First, future studies should evaluate whether and to what extent the Economic Development Law of Colima (2025) effectively promotes private-sector investment in sustainable technologies and innovation within port-related activities.

Second, future studies should develop financing mechanisms and cost–benefit assessment models for emerging decarbonization technologies, including Shore Power and equipment electrification, particularly in developing economies where infrastructure expansion and sustainability objectives must be pursued simultaneously.

In addition, future empirical research should assess the implementation and operational outcomes of sustainability and digitalization initiatives in emerging port systems. Field-based studies involving port authorities, terminal operators, logistics stakeholders, and local communities could complement bibliometric and documentary evidence by evaluating how sustainability strategies are implemented in practice and identifying the institutional and operational factors that facilitate or constrain their effectiveness.

Finally, further research should examine governance models capable of integrating Smart Port principles with local institutional, social, and economic conditions. Particular attention should be given to understanding how digitalization, transparency, stakeholder coordination, and sustainability objectives can be aligned to support long-term port development and strengthen port–city relationships.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su18157897/s1>. Table S1: PRISMA 2020 Checklist. Supplementary Material S2: List of 307 included documents.

Author Contributions: Conceptualization, D.J.-A.; methodology, D.J.-A.; software, D.J.-A.; validation, A.O.-O., E.Y.V.L., M.P. and J.H.-L.; data curation, A.O.-O., E.Y.V.L., M.P. and J.H.-L.; writing—original draft preparation, D.J.-A.; writing—review and editing, M.P. and R.A.; supervision, R.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data supporting the findings of this study are available within the article and its Supplementary Materials. The bibliographic dataset was obtained from the

Scopus database under institutional access. Additional supporting documents used in the case study, including publicly available policy and planning documents, are cited in the reference list.

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

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