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OPEN SUSTAINABLE INNOVATION IN PORT ECOSYSTEMS: A LITERATURE REVIEW

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ABSTRACT

Maritime ports are under growing pressure to reconcile operational efficiency with environmental and social sustainability. This paper investigates how open innovation can accelerate sustainable transformation across port ecosystems by proposing the integrative paradigm of Open Sustainable Innovation (OSI). The study adopts a semi-systematic literature review of peer-reviewed articles indexed in Scopus and Web of Science (2014–2024). Bibliometric mapping techniques were combined with qualitative synthesis to identify recurrent practices and trends. Comparative evidence from leading European ports complements the analysis. The findings reveal that OSI practices—such as open data initiatives, incubators, start-up challenge programs, and multi-stakeholder governance intermediaries—support improvements in process efficiency, environmental performance, and digital capability building. At the same time, significant barriers persist, including institutional inertia, fragmented funding, regulatory misalignment, uneven digital maturity, and limited impact assessment. Evidence from Rotterdam, Valencia, Barcelona, and Motril demonstrates that the orchestration capacity of port authorities and intermediaries, supported by robust digital infrastructures and inclusive innovation cultures, determines the scalability of OSI initiatives. Conceptually, OSI is positioned as the coupling of cross-boundary knowledge flows with triple-bottom-line objectives. The article concludes by outlining a future research agenda focused on ecosystem governance, value distribution, and long-term impact evaluation. By consolidating fragmented knowledge, this study contributes to both academic discourse and managerial practice, providing guidance for ports seeking to move beyond isolated pilot projects towards systemic, sustainability-aligned innovation.

Keywords: *Open Sustainable Innovation, Port Ecosystem, Digitalisation, Maritime Ports, Innovation Strategies, Stakeholders*

1. INTRODUCTION

Maritime ports are pivotal nodes in global logistics, serving as gateways where goods, services, information, and capital converge. Increasingly, they face mounting pressures to reconcile operational efficiency with environmental and social sustainability. Climate risks, regulatory demands, digital transformation, and intensified competition have heightened the need for ports to adapt not only economically but also environmentally and socially.

In this context, the concept of open innovation (OI) has emerged as a strategic framework to accelerate transformation in complex ecosystems. Initially defined by Chesbrough (2003) as the purposive inflow and outflow of knowledge to foster innovation, OI has since evolved into collaborative, ecosystem-oriented approaches involving diverse stakeholders, such as firms, universities, technology providers, regulators, and local communities. When linked to sustainability goals, OI enables co-creation, knowledge sharing, and participatory governance, offering ports mechanisms to address digital, environmental, and social challenges simultaneously.

However, the integration of OI with sustainability in the maritime port context remains fragmented. While some studies highlight isolated practices such as incubators, collaborative platforms, or digital governance initiatives, there is still no consolidated framework that synthesises how OI contributes to systemic sustainability transitions in ports. This lack of integration hinders both theoretical progress and the design of effective policy and managerial strategies, especially in view of the European Green Deal and global decarbonisation agendas.

Building on recent debates on sustainability-oriented innovation (Adams et al., 2016) and ecosystem-based models such as the quadruple and quintuple helix (Carayannis et al., 2021), this article proposes Open Sustainable Innovation (OSI) as an integrative paradigm that explicitly couples cross-boundary knowledge flows with triple-bottom-line objectives in port ecosystems. Rather than treating openness and sustainability as separate domains, OSI conceptualises them as mutually reinforcing principles that shape how innovation is organised, governed, and evaluated.

The objective of this article is therefore to explore the interplay between OI and sustainability in maritime port ecosystems and to conceptualise OSI as a lens for understanding and guiding sustainable transformation. To this end, the study adopts a semi-systematic literature review combining bibliometric mapping and qualitative synthesis of peer-reviewed articles indexed in Scopus and Web of Science (2014–2024), complemented by illustrative case evidence from selected European ports.

The article makes three main contributions. First, it consolidates fragmented knowledge at the intersection of OI, sustainability, and port governance, providing a structured overview of key themes and trends. Second, it develops OSI as a conceptual paradigm, clarifying its underpinning components and how it extends existing notions of OI and eco-innovation in complex infrastructures. Third, it distils strategic lessons and a future research agenda focused on ecosystem governance, value distribution, and long-term impact assessment in port innovation ecosystems.

The remainder of the paper is organised as follows. Section 2 describes the review methodology. Section 3 presents the main results, including bibliometric patterns, conceptual insights, and illustrative case evidence. Section 4 discusses the implications of these findings for reframing port innovation through the OSI framework, highlighting institutional conditions and research gaps. Section 5 concludes by summarising the article's contributions, managerial implications, and avenues for future research.

2. METHODS

This study adopts a semi-systematic literature review to explore the intersection of OI, sustainability, and maritime port ecosystems. The methodological design combines a structured database search, PRISMA-guided screening, and qualitative thematic synthesis supported by bibliometric mapping. This mixed approach allows for both conceptual consolidation and analytical breadth in a research domain that remains fragmented across innovation, sustainability, and transport studies.

2. 1. LITERATURE SEARCH STRATEGY

The literature search was conducted using two major bibliographic databases: Scopus and Web of Science (WoS). The following Boolean string was applied in both databases, restricted to title, abstract, and keywords:

"open innovation" OR "collaborative innovation" OR "innovation ecosystem" OR "co-creation" OR "co-innovation" AND ("sustainability" OR "sustainable development" OR "green port" OR "circular economy" OR "SDG*") AND ("maritime port" OR "seaport" OR "port ecosystem" OR "port authority").

The time window was limited to 2014–2024 to capture the most recent decade of research, coinciding with the growing emphasis on sustainability and digitalisation in ports. Only peer-reviewed journal articles written in English were included. Exclusion criteria comprised conference proceedings, books and book chapters, grey literature, and studies not primarily focused on maritime ports.

The final search was performed on 19 March 2024, capturing all publications indexed up to that date.

2. 2. ELIGIBILITY CRITERIA AND PRISMA-GUIDED SCREENING

The review followed the PRISMA 2020 guidelines (Page et al., 2021) for transparent reporting of identification, screening, and eligibility procedures. A total of 280 records were retrieved from Scopus and WoS. After removing 43 duplicates, 237 unique records proceeded to title and abstract screening.

Screening was conducted using the Rayyan (Ouzzani et al., 2016) platform, following a two-reviewer procedure in accordance with PRISMA 2020. Both reviewers independently assessed all titles and abstracts, working in Rayyan's blinded mode. Discrepancies were discussed until consensus was achieved. No automation tools, machine-learning classifiers, or AI-assisted systems were used at any stage of screening or coding.

During the first-stage screening, 152 records were excluded for the following reasons: wrong population or sector (n = 65), irrelevance to OI or sustainability in port contexts (n = 47), ineligible publication type (n = 21), and inadequate methodological detail (n = 19).

A total of 85 articles were selected for full-text assessment. Using the predefined eligibility criteria, 48 additional articles were excluded because they failed to address all three core dimensions simultaneously:

(i) engagement with OI or collaborative innovation;

(ii) environmental and/or social sustainability; and

(iii) maritime ports or port ecosystems as the central analytical setting.

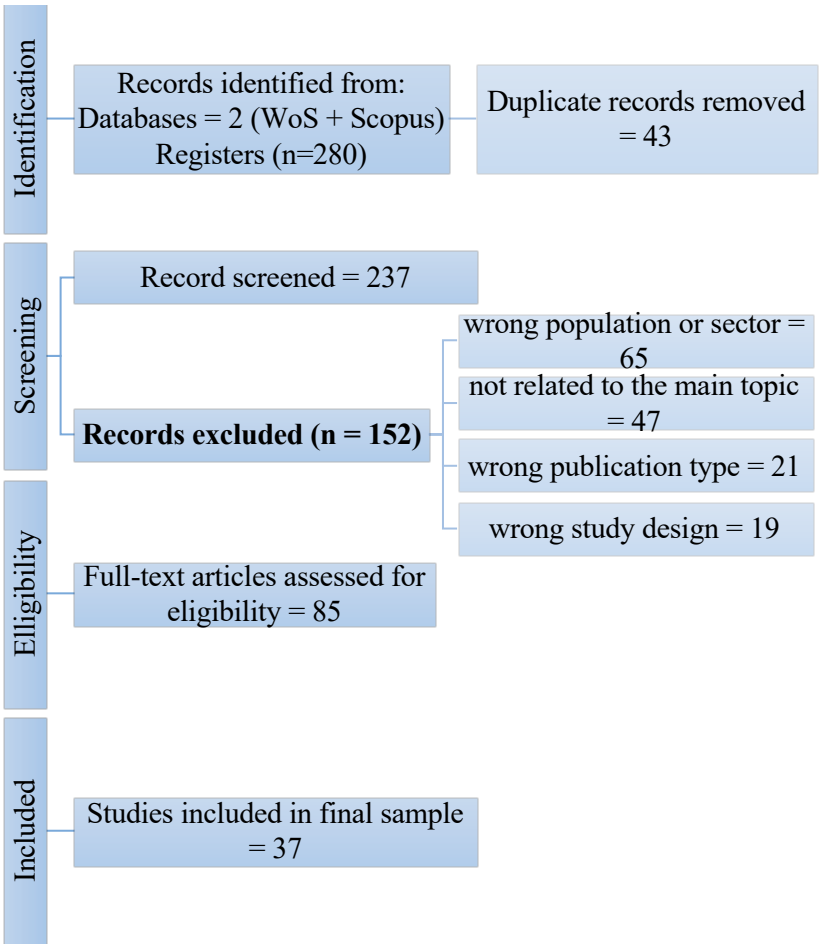
The final analytical sample comprised 37 peer-reviewed studies, which constitute the corpus for bibliometric mapping and qualitative synthesis. The complete PRISMA 2020 flow diagram is shown in Figure 1, and Table 1 presents the detailed breakdown of identification and

Figure 1. PRISMA 2020 diagram

It presents the identification, screening, eligibility, and inclusion stages of the semi-systematic review:

(a) The upper part displays the records identified through database searching, the removal of duplicates, and the initial screening of titles and abstracts;

(b) The lower part presents the full-text eligibility assessment, reasons for exclusion, and the final number of studies included in the analytical sample.



Source: Author's own construction

To complement Figure 1, Table 1 reports the number of records at each step of the process.

Table 1. Overview of article identification and screening.

Stage	Records
Records identified in Scopus and WoS	280
Duplicate records removed	43
Records after duplicates	237
Records excluded at title/abstract screening*	152
Articles selected for full-text assessment	85
Full text excluded	48
Articles included in the core analytical sample	37

Source: Authors' elaboration based on PRISMA screening.

Building on this screening process, the next step was to prepare the final corpus of 37 articles for analysis. Next section describes the dataset processing and the thematic classification of the selected studies to support both the bibliometric mapping and the qualitative synthesis.

2. 3. DATASET PROCESSING AND THEMATIC CLASSIFICATION

The final set of 37 articles was exported in .csv format for processing and bibliometric analysis. Each article was manually coded according to the thematic dimensions identified in the literature on OI and sustainability: openness and knowledge flows; sustainability (environmental, social, economic); ecosystem or cluster perspectives; collaboration and stakeholder engagement; digitalisation and innovative port initiatives; governance and/or policy frameworks.

To enhance coding reliability, a preliminary coding scheme was piloted on a subset of articles and refined iteratively. Both reviewers jointly examined cases of ambiguity until consensus was reached, following best practice in qualitative research methodology (Miles et al., 2014). This coding served as input for both the bibliometric mapping and the qualitative synthesis developed in Section 3.

Bibliometric mapping was conducted using VOSviewer (version 1.6.19), with the following parameters:

- unit of analysis: author keywords
- counting method: complete counting
- minimum occurrences of a keyword: 5
- mapping technique: co-occurrence and bibliographic coupling.

In addition, Litmaps was used to visualise citation linkages and intellectual structures in the broader set of 85 full-text articles prior to final screening. This enhances methodological transparency and provides additional context for thematic consolidation.

2. 4. CASE ILLUSTRATIONS

To contextualise the bibliometric insights and connect them to real-world practices, we reviewed secondary case evidence from four European seaports: Rotterdam, Valencia, Barcelona, and Motril-Granada. These ports were selected using two criteria: (i) recurrent presence in the reviewed literature as examples of collaborative or sustainability-oriented innovation, and (ii) diversity in terms of size, governance arrangements, and technological maturity.

It is important to emphasise that these are illustrative cases based exclusively on secondary data (scientific articles and policy reports). They are not primary empirical case studies, and no interviews or original data collection were conducted. Their role is to exemplify how OSI-related mechanisms are being mobilised in different institutional contexts rather than to provide exhaustive evaluations of each port.

2. 5. LIMITATIONS OF THE REVIEW

As a semi-systematic review, this study has several methodological limitations. First, the search was restricted to two major databases (Scopus and WoS) and to articles published in English between 2014 and 2024. Relevant studies published in other languages, outside this time window, or indexed in alternative databases may therefore have been omitted.

Second, the bibliometric analysis focused on keyword co-occurrence and citation-based relationships. Other potentially informative dimensions, such as co-authorship networks, institutional collaboration patterns, or geographical mappings, were not systematically analysed and could be explored in future research.

Third, the case evidence relies solely on secondary sources. While this allows for a broad and comparative perspective, it also limits the ability to validate findings in situ or to capture the perspectives of specific stakeholder groups. Finally, as with any manual coding process, interpretive bias cannot be entirely eliminated, despite the use of a structured coding scheme and iterative refinement.

These limitations should be considered when interpreting the findings and highlight several avenues for further empirical and methodological research on OSI in port ecosystems.

3. RESULTS

This section presents the findings of the semi-systematic literature review. It is organised into three components that reflect the sequential analytical strategy employed in the study: (i) bibliometric analysis, (ii) evidence from the selected literature, and (iii) illustrative case evidence that contextualises how OSI mechanisms manifest in practice.

3. 1. BIBLIOMETRIC ANALYSIS

To complement the qualitative synthesis, a bibliometric analysis was conducted to map the intellectual structure and thematic evolution of research at the intersection of OI, sustainability, and maritime ports. This analysis enhances the transparency of the review process and supports the identification of conceptual clusters, key contributors, and emerging research trends.

VOSviewer calculates a relevance score for each keyword, which indicates how informative the term is for distinguishing clusters in the network. In simplified terms, keywords that appear frequently but mainly within a single cluster tend to have higher relevance scores than generic terms that are widely distributed across the network. In this study, relevance scores were used to identify keywords that structure thematic clusters around OI, sustainability, digitalisation, and ecosystem thinking.

The most frequently identified terms within the selected corpus, as determined by keyword co-occurrence analysis, are outlined in Table 2. The column "Occurrences" indicates the number of times each term appears across the sample of articles, while "Relevance Score" reflects the term's relative importance in distinguishing thematic clusters.

Table 2. Most frequent terms in the selected articles

Term	Occurrences	Relevance Score
port	151	0.8623
innovation	84	1.0268
ecosystem	41	1.2903
sustainability	41	0.5295
strategy	38	0.2260
stakeholder	30	0.3694
collaboration	24	0.2140
sustainable development	24	0.6312
environment	21	0.3341
partnership	18	3.8733
digitalisation	15	2.4197
open innovation	14	1.2719
knowledge	13	1.0733
port authority	12	0.4488

Source: Authors' elaboration based on keyword co-occurrence analysis using VOSviewer

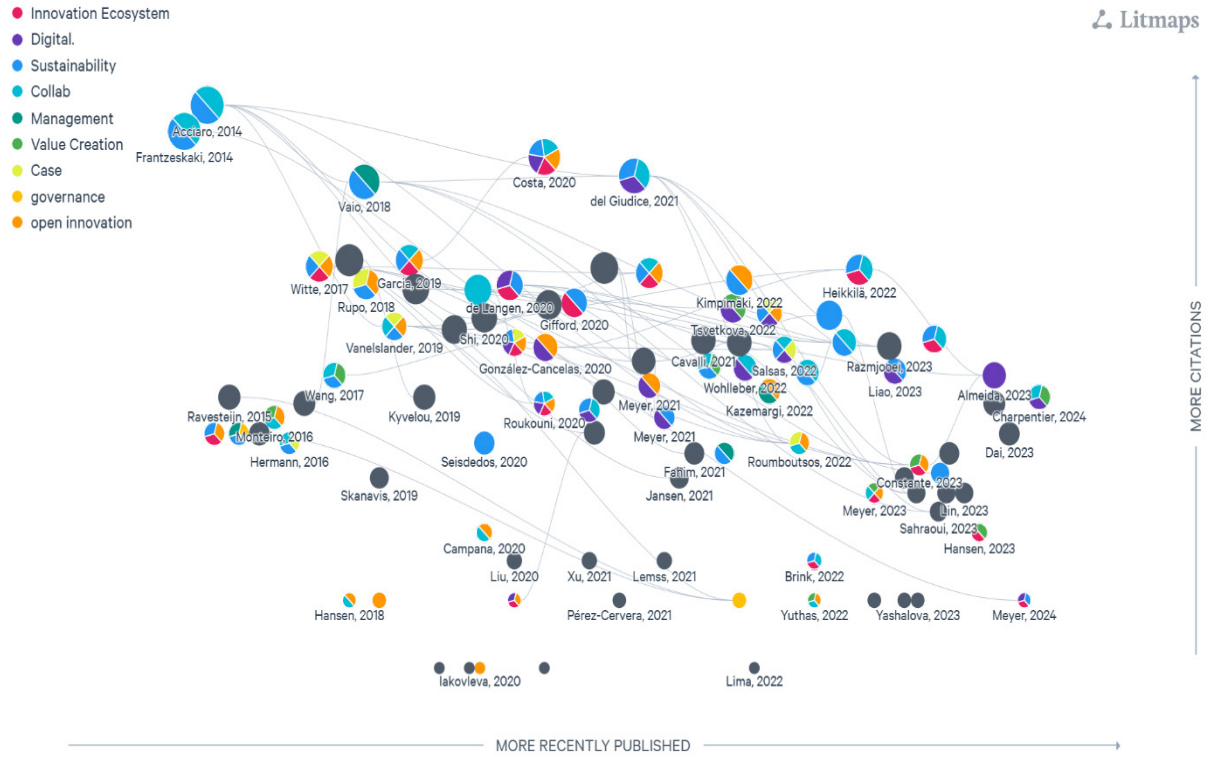
In contrast, Figures 2-4 were generated using Litmaps, which was applied to the broader set of 85 articles assessed at the full-text stage. Litmaps enables the visualisation of citation relationships, conceptual proximity, and cluster formation, thereby revealing the field's intellectual structure.

The bibliometric network, presented in Figure 2, illustrates the co-occurrence network of author

keywords, revealing three dominant colour-coded clusters: a sustainability cluster (green), a digitalisation cluster (blue), and a smaller innovation ecosystem cluster (red). The spatial distribution of nodes indicates partial overlaps between these clusters, particularly around terms such as sustainable development, innovation ecosystem, and smart port. These visual patterns reinforce the field's fragmented yet converging nature.

Figure 2. Bibliometric Map of the Selected 85 Articles and the 37 Tagged Subset

Nodes represent articles and colours indicate thematic clusters. The map shows partially overlapping clusters around sustainability, digitalisation, and ecosystem thinking, with OI appearing as a smaller but adjacent domain.

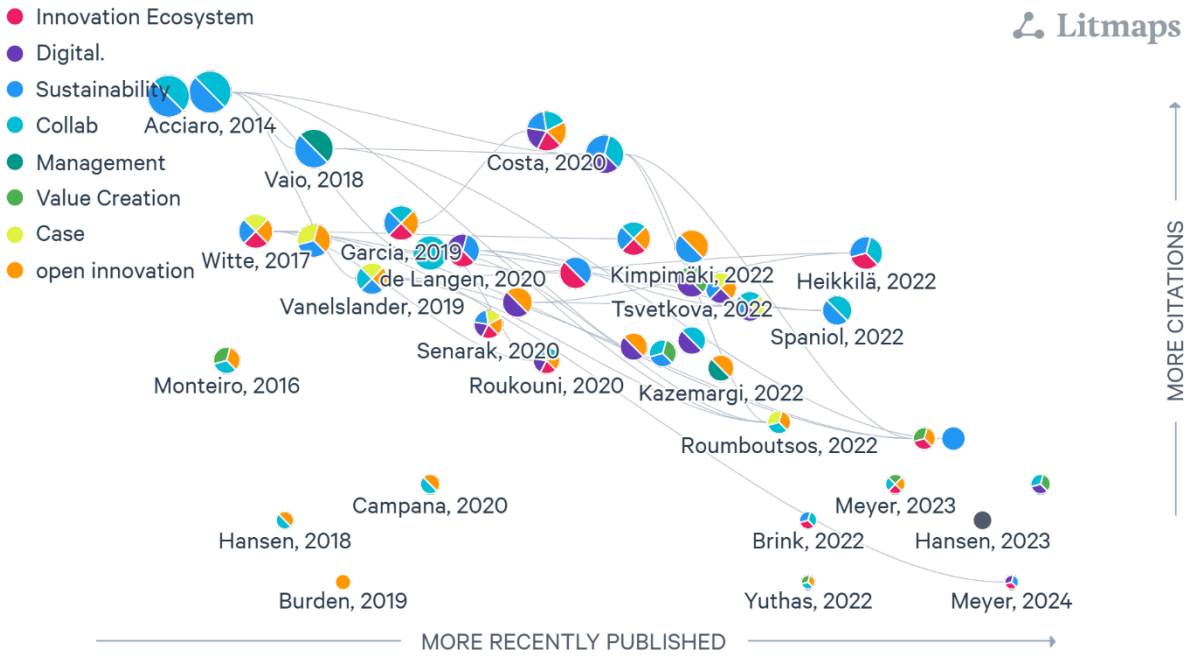


Source: Authors' elaboration based on bibliometric network visualisation using Litmaps

Citation-based connectivity among the 37 selected papers is depicted in Figure 3. Each node represents a paper, and proximity reflects shared citations or conceptual affinity. The structure positions García et al. (2019) and Costa & Matias (2020) at the centre of the sustainability–innovation interface and places digitalisation studies in a less dense, nascent subfield, underscoring the more established character of sustainability-driven innovation.

Figure 3. Connectivity Map of the 37 Selected Articles

The figure highlights citation-based proximity among the core articles, revealing several influential works that link otherwise fragmented strands on innovation ecosystems, sustainability governance, and digitalisation.

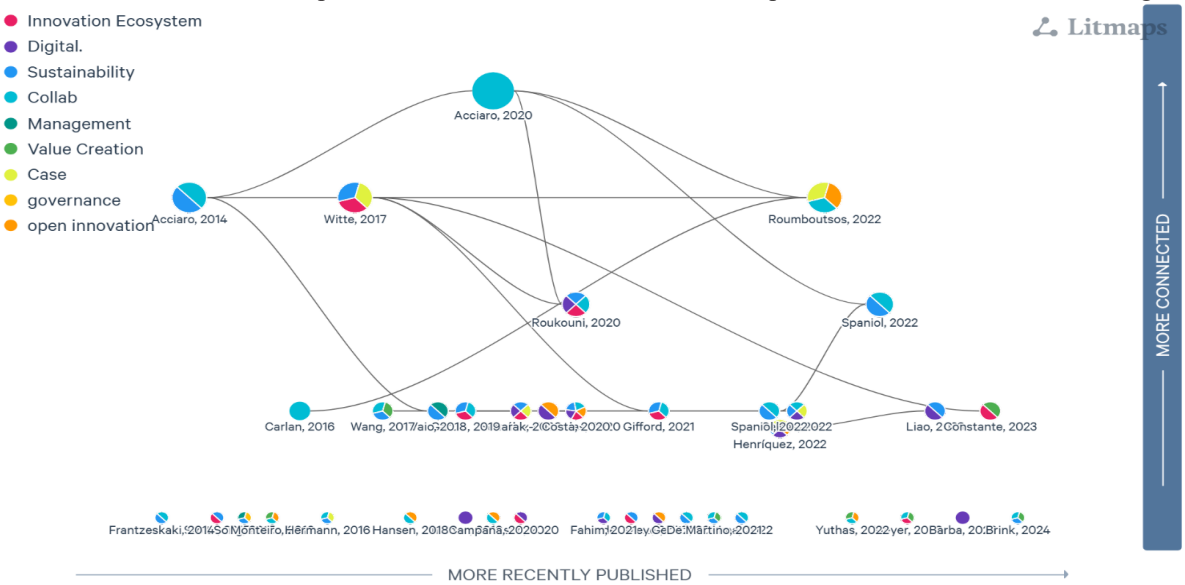


Source: Authors' elaboration based on bibliometric network visualisation using Litmaps

The citation-centrality map in Figure 4 identifies the intellectual anchors of the OSI literature. Node size represents relative citation frequency, while their vertical position indicates connectivity with other works in the field. The author impact map, which highlights a small set of central authors, such as Acciaro (2020), Witte et al. (2018), and Roumboutsos et al. (2022), positioned prominently due to their cross-cluster influence. Their contributions span sustainability, governance, and innovation domains, reinforcing their roles as conceptual bridges within the field.

Figure 4. Citation and Thematic Centrality in the OI-Sustainability-Port Literature

Node size reflects citation frequency, and vertical position indicates network centrality. A small set of highly connected articles serves as conceptual anchors around which newer, more specialised contributions have emerged.



Source: Authors' elaboration based on bibliometric network visualisation using Litmaps

The use of Litmaps for these figures ensures clarity in identifying conceptual linkages, while VOSviewer provides quantitative keyword-based insights.

By mapping scholarly interactions and thematic overlaps, the bibliometric analysis supports the robustness of the sample and clarifies the main conceptual gaps. In particular, the loose coupling between OI and sustainability-related terms underscores the absence of an integrated framework that can address knowledge flows, ecosystem governance, and triple-bottom-line outcomes simultaneously. This finding directly motivates the OSI paradigm developed in the following sections, which aims to bridge these partially connected literatures and provide a more systematic basis for theorising sustainable innovation in port ecosystems.

3. 2. EVIDENCE FROM THE LITERATURE

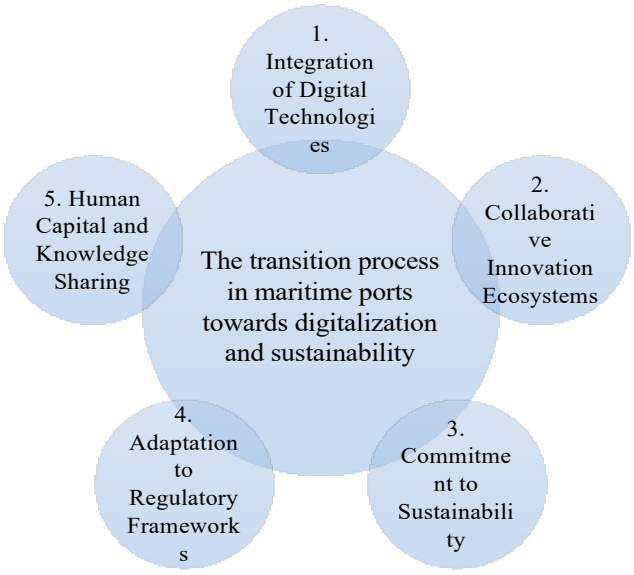
This section synthesises the main theoretical and empirical contributions at the intersection of OI, sustainability, and port ecosystems. It first characterises the dual transition towards digitalisation and sustainability in maritime ports and then examines how OI mechanisms have been operationalised in this context. Building on this discussion, the OSI paradigm is introduced and, finally, the managerial and technological conditions required for its implementation are explored.

3. 2. 1. THE DIGITAL AND SUSTAINABLE TRANSITION IN MARITIME PORTS

Innovation has become a cornerstone of industrial transformation, particularly in sectors facing mounting environmental, regulatory, and technological pressures. Maritime ports, as key nodes in global logistics networks, are undergoing a structural shift to balance operational efficiency with sustainability objectives. This transition, summarised in Figure 5, is driven by the interplay of five interrelated factors: the integration of digital technologies, the formation of collaborative innovation ecosystems, a strong commitment to sustainability principles, adaptation to evolving regulatory frameworks, and the development of human capital and knowledge sharing.

Figure 5. Key Characteristics of digital and Sustainable transition in Maritime Ports

The diagram synthesises five interrelated drivers—digital technologies, collaborative innovation ecosystems, sustainability commitments, regulatory adaptation, and human capital and knowledge sharing—that jointly shape port transformation.



Source: Author's own construction

First, the integration of digital technologies plays a foundational role. The adoption of digital technologies such as the Internet of Things (IoT), blockchain, and 5G networks has signifi-

cantly enhanced operational efficiency and facilitated real-time data sharing among port ecosystems. As Cavalli et al. (2021) demonstrate, 5G infrastructure can serve as a bridge between the United Nations Sustainable Development Goals (SDGs) and key performance indicators (KPIs) for ports, enabling better measurement of the benefits of innovative technologies for port operations. Furthermore, the implementation of Terminal Operating Systems (TOS) has been shown to increase productivity and streamline operations, as evidenced by research conducted in developing countries (De Martino, 2021). Similarly, the adoption of innovative port technologies has been shown to optimise supply chain processes, enhancing overall efficiency and sustainability (González-Cancelas et al., 2020; Meyer et al., 2021).

However, technological advancement alone does not ensure systemic change. The formation of collaborative innovation ecosystems, through Port Community Systems (PCS) and inter-organisational platforms, exemplifies a move towards collaborative governance models. These ecosystems enable participatory governance by engaging multiple stakeholders, including port authorities, logistics firms, technology providers, and regulatory agencies (Garcia et al., 2019; Mendes Constante et al., 2023). The interaction among these participants facilitates knowledge transfer and collaborative strategies that support the efficient implementation of new technologies and sustainable practices (De Martino, 2021).

The third element, a commitment to sustainability, reflects both external regulatory pressures and internal strategic shifts. As Meyer et al. (2021) observe, European Commission mandates are reshaping port governance, pushing sustainability to the core of strategic planning. This shift is operationalised through initiatives such as waste management and energy-efficiency enhancements, often guided by Balanced Scorecard frameworks (Suárez-Gargallo & Zaragoza-Sáez, 2023) or grounded in circular economy principles (de Langen et al., 2020; Meyer et al., 2023). These mechanisms promote institutional alignment around sustainability goals and provide accountability metrics for continuous improvement.

Closely related is the adaptation to regulatory frameworks, which constitutes the fourth component of the transition. Ports must now respond to increasingly stringent environmental regulations related to emissions, climate resilience, and biodiversity impacts. Garcia et al. (2019) show that aligning strategies with anticipated regulatory trends allows ports to move from reactive compliance to proactive sustainability leadership. Long-term sustainability planning, anchored in climate legislation and environmental monitoring, is therefore not merely a regulatory requirement but also a strategic differentiator (Meyer et al., 2021).

Finally, human capital and knowledge sharing are consistently underscored to sustain this transformation. Organisational culture, learning platforms, and cross-sectoral knowledge networks form the "soft infrastructures" needed to institutionalise innovation (Roumboutsos et al., 2022). Empirical works by Mendes Constante et al. (2023) and Witte et al. (2018) emphasise that ports such as Rotterdam and Valencia have leveraged learning and inclusive innovation practices to overcome cultural inertia and embed sustainability into day-to-day operations.

Collectively, these five dimensions can constitute an interdependent architecture for transformation. They suggest that closed and insular innovation models are no longer fit for purpose. Instead, the path forward lies in embracing open, collaborative, and digitally mediated strategies that reconcile efficiency with environmental and social responsibility. This logic sets the stage for a deeper exploration of open approaches to sustainable innovation, discussed in the following subsection.

3. 2. 2. OPEN APPROACHES TO SUSTAINABLE INNOVATION IN PORT ECOSYSTEMS

Port transformation processes increasingly rely on open, collaborative models that go beyond firm-level innovation. OI enables various stakeholders within the port ecosystem, including firms, academic institutions, and even customers, to co-create solutions by leveraging external knowledge and resources (Wohlleber et al., 2024). This collaboration enhances problem-solving capabilities and drives more effective innovation outcomes (Campana et al., 2020; Roukouni et al., 2020). Furthermore, OI fosters transparency and coordination by facilitating the sharing of data and resources among port actors. This interconnectedness improves operational efficiency and the development of previously unattainable innovative applications (Vanelslander et al., 2019).

A key advantage of OI is its support for the growth of start-ups within the port ecosystem. By granting smaller firms access to the resources and expertise of larger organisations, OI creates a symbiotic relationship that accelerates technology transfer and the adoption of new ideas (Witte et al., 2018). This dynamic enhances innovation processes and drives the long-term evolution of port operations (Henríquez et al., 2022; Jansen & Hein, 2023).

While these practices illustrate the shift from firm-level innovation to ecosystem-level collaboration, a more comprehensive theoretical framework is needed to explain how open and sustainable goals are jointly pursued. The following section introduces the OSI paradigm as a response to this need.

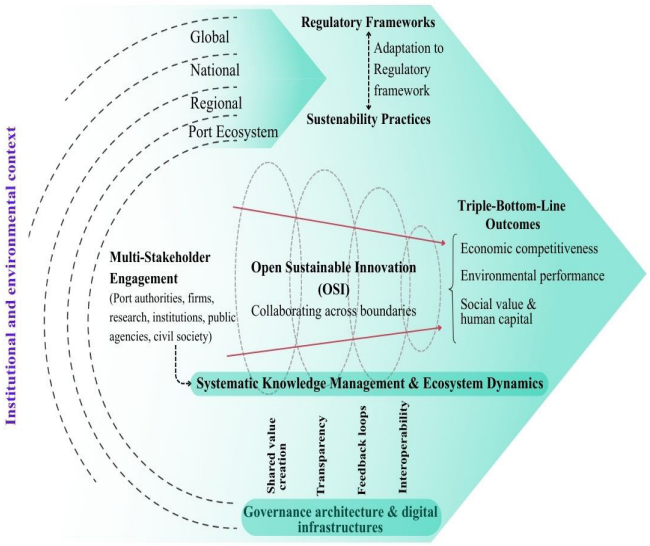
3. 2. 3. OPEN SUSTAINABLE INNOVATION PARADIGM

The transition from OI to OSI reflects a paradigmatic shift grounded in five theoretical components: (1) cross-boundary knowledge flows (Meyer et al., 2021); (2) sustainability-oriented triple-bottom-line objectives (environmental, social, and economic objectives) (Adams et al., 2016; Rupo et al., 2018); (3) multi-stakeholder engagement (Garcia et al., 2019); (4) systematic knowledge management (Gifford & McKelvey, 2019); and (5) shared-value creation, balancing economic gains with broader societal benefits and reduced environmental impacts (De Martino, 2021; Kimpimäki et al., 2022). Within port ecosystems, this shift manifests in collaborative frameworks that align co-creation with sustainability imperatives, such as decarbonisation, social equity, and resilient infrastructure (Rupo et al., 2018), while necessitating governance models that distribute innovation responsibility across public, private, and civil society actors (Tijan et al., 2021).

The proposed OSI framework, depicted in Figure 6, positions institutional and environmental context, together with regulatory frameworks and sustainability practices, as the broader arena within which ports operate. At the core lies OSI, understood as cross-boundary collaboration enabled by digital platforms and collaborative arrangements. OSI is mediated by multi-stakeholder engagement (port authorities, firms, research institutions, public agencies, and civil society) and by systematic knowledge management and ecosystem dynamics (data governance, learning mechanisms, evaluation and collaborative innovation ecosystems). These mechanisms are embedded in a governance architecture and digital infrastructures that aim to create shared value through transparency, feedback loops and interoperability. In combination, they lead to triple-bottom-line outcomes in port ecosystems, namely economic competitiveness, environmental performance, and social value and human capital.

Figure 6. Open Sustainable Innovation (OSI) framework

The figure summarises the OSI framework for port ecosystems, linking institutional and environmental contexts, multi-stakeholder engagement, systematic knowledge management, and governance architecture to triple-bottom-line outcomes through cross-boundary knowledge flows.



Source: Author's own construction

In this context, open eco-innovation emerges as a critical dimension of OSI, operationalising sustainability through collaborative environmental innovation. Open eco-innovation specifically addresses the intersection of OI and ecological value creation, as observed in port-centric literature (Garcia et al., 2019; Hermann & Wigger, 2017). This concept reflects one of OSI's core value-creation mechanisms, where multi-stakeholder networks (e.g., governments, NGOs, suppliers) navigate tensions between economic and environmental goals (Costa & Matias, 2020; De Martino, 2021; Monteiro, 2016). Garcia et al. (2019) further emphasise its multi-level dynamic spanning firm, inter-organisational, and ecosystem tiers, to amplify societal and environmental impacts through boundary-spanning knowledge flows. Thus, in complex, resource-intensive sectors like maritime transport, open eco-innovation exemplifies the application of OSI's theoretical components to reconcile sustainability with OI.

The OSI theoretical lens illuminates the structural requirements for aligning OI with sustainability goals. However, its successful application hinges on effective management practices, particularly in digitally transforming environments.

3. 2. 3. 1. MANAGING OPEN SUSTAINABLE INNOVATION IN THE DIGITAL ERA

The profound influence of digital technologies increasingly shapes the transition towards OSI in port ecosystems. Managing OSI in this context requires the orchestration of collaborative processes and the integration of digital infrastructures that foster transparency, responsiveness, and multi-level coordination.

The successful implementation of OSI demands a multi-level theoretical framework, encompassing organisational, regional, national, and global dimensions (Kimpimäki et al., 2022). At each level, specific actors, mechanisms, and dynamics shape innovation trajectories. This approach underscores that sustainability and openness are not mutually exclusive objectives; instead, they are interdependent forces catalysed by digital transformation (Kimpimäki et al., 2022). The prominence of transparency and feedback loops in this model highlights the importance of digital tools in enhancing trust and reliability across innovation ecosystems.

Digitalisation has significantly expanded OI's potential by enabling large-scale collaboration through platforms like open-source systems and crowdsourcing tools (Acciaro & Sys, 2020; Monteiro, 2016; Roukouni et al., 2020). The case study of collaboration between Fincantieri, one of the largest shipbuilding groups globally, and the National Research Council of Italy (CNR) illustrates the successful implementation of open-source and crowdsourcing approaches to harness external expertise, leading to significant advancements in technological development and competitiveness (Campana et al., 2020). Technologies such as blockchain enhance governance by ensuring transparency and data integrity in complex ecosystems (Meyer et al., 2021).

From a managerial standpoint, Costa and Matias (2020) emphasise the importance of ecosystemic coordination, where companies, public institutions, academia, government bodies, and civil society collaborate to build platforms for innovation. These ecosystems enable cross-fertilisation of ideas, aligning environmental and social goals with market-based innovation. In this context, digital transformation serves as both a catalyst and an enabler, breaking down traditional silos and fostering a fluid exchange of knowledge.

As highlighted by Campana et al. (2020) in their case study in the maritime sector, Fincantieri, a leading shipbuilder, effectively collaborates with universities and public research institutions to co-develop digital innovations that enhance operational performance and sustainability outcomes. Projects such as E-Cabin and E-Navigation integrate real-time monitoring, augmented reality, and virtual dashboards to personalise user experiences and optimise energy efficiency. These initiatives exemplify how digital tools enable ongoing feedback, enabling companies to align their strategies with ecological and market demands. Moreover, the management model adopted by Fincantieri underscores the need for clear leadership structures that align technical innovation with strategic goals.

The multi-level framework further reinforces the need for alignment across scales (Kimpimäki et al., 2022):

- **At the individual level**, digital platforms empower users to contribute ideas and participate in solution development.
- **At the organisational level**, firms use co-creation tools to enhance product development cycles; **At the city and regional levels,** digital governance infrastructures such as smart port initiatives support integrated planning and stakeholder engagement.
- **Across these levels,** data transparency and feedback mechanisms become critical to fostering inclusion and iterative learning.

In summary, managing OSI in the digital age is a fundamentally dynamic and systemic endeavour. It necessitates the capacity to align technological advancement with sustainability imperatives across various governance levels and institutional domains. When effectively arranged, digital infrastructures enhance innovation capabilities and embed sustainability as a core operating principle within port ecosystems and beyond.

3. 3. ILLUSTRATIVE CASE EVIDENCE

This section analyses how OSI is operationalised in a set of **illustrative European seaports**. The cases of Rotterdam, Valencia, Barcelona, and Motril-Granada were selected because they are recurrently cited in the literature as exemplars of collaborative and sustainability-oriented initiatives, while differing in size, governance structures, and digital maturity. Together, they illustrate contrasting pathways—from global hubs to peripheral ports — through which OSI-related mechanisms can be mobilised in practice using secondary data alone.

Rotterdam

The Port of Rotterdam stands out as a frontrunner in ecosystem orchestration. Through initiatives such as the Port Innovation Barometer and various labs (e.g., RAMLAB, BlockLab, PortXL) support the development and testing of sustainable technologies (Jansen & Hein, 2023; Mendes Constante et al., 2023). Moreover, with international collaborative platforms, Rotterdam positions itself not only as a logistics hub but also as a knowledge port (Witte et al., 2018). Strong partnerships between universities, research institutes, and industry players characterise Rotterdam's ecosystem. For instance, initiatives such as the Rotterdam Mainport Institute and the PortCityFutures programme connect educational institutions with practical maritime and technological activities (Jansen & Hein, 2023; Roukouni et al., 2020; Witte et al., 2018). These collaborations encourage the migration of knowledge, transforming the port into a centre of innovation rather than just a physical location for cargo handling. These structures enable multilevel collaboration among academia, startups, and government bodies, facilitating the deployment of innovative technologies and circular-economy strategies. The city´s open digital infrastructure, such as real-time data sharing systems and innovation barometers, enhances transparency and provides a fertile ground for experimentation and scaling. Importantly, the Port Authority plays a central role as innovation orchestrator, reinforcing the governance capacity required for systemic OSI implementation (Mendes Constante et al., 2023).

Valencia

In contrast, Valencia´s model centres on human capital development and institutional learning, orchestrated primarily through the Fundación Valenciaport. This innovation intermediary connects port stakeholders with European funding programmes, training schemes, and collaborative R&D platforms (Mendes Constante et al., 2023). Rather than positioning itself through digital infrastructure alone, Valencia invests in cultural change, building a shared innovative mindset across all actors. This softer but strategic approach is especially relevant in environments where cultural resistance and institutional inertia persist, a phenomenon documented by Roumboutsos et al. (2022) as a key barrier to sustainable innovation diffusion in port settings. Another challenge highlighted is aligning short-term and long-term objectives. The trade-off between rapid deployment of solutions and the need for co-created, robust innovation outcomes can create friction among stakeholders. Such differences in timeline expectations often discourage deep collaboration and the sharing of valuable insights over time (Mendes Constante et al., 2023). These challenges highlight a multifaceted set of barriers that stakeholders in port innovation ecosystems must overcome.

Barcelona

Barcelona´s approach leverages the city-port interface to foster digital innovation, inclusive governance, and socio-environmental integration. Through initiatives such as cloud-based Port Community Systems and dedicated spaces like Pier01 and PierNext, Barcelona has created open-data policies and flexible governance platforms that support co-creation among government, private firms, and startups (Garrido Salsas et al., 2022; Henríquez et al., 2022). The port's open-data approach involves sharing vast amounts of data generated from port operations with digital solution providers. This transparency invites innovative ideas and applications that can help design more sustainable practices. While benchmarking against leading ports provides a basic framework, the Port of Barcelona takes it a step further by engaging with external stakeholders through joint ventures and partnerships. The emphasis on digital twins, decarbonisation strategies, and participatory workshops reflects a commitment to embedding sustainability within digital transformation. The Spanish government´s direct involvement further reinforces institutional legitimacy and resource availability, enabling innovation beyond the boundaries of

port administration to foster open digital innovation. The city-port interface is key in supporting startups and enabling co-creation (Henríquez et al., 2022).

Motril-Granada

Meanwhile, the case of Motril-Granada, although smaller in scale, demonstrates how peripheral or resource-constrained ports can still mobilise OSI through strategic alignment with the blue economy agenda (Seisdedos & Carrasco, 2020). It uses insights from collaborative projects to streamline its activities in line with European blue economy policies. This involves assessing current operations and designing new work methods that are both sustainable and economically beneficial. Motril-Granada focuses on coastal protection, infrastructure retrofitting, and the preservation of local ecosystems. While its funding is more fragmented and often reliant on EU project cycles, the port exemplifies the importance of contextual adaptation and niche positioning. This echoes findings by Garcia et al. (2019), who highlight the need for flexible governance and tailored value propositions in small and medium-sized ports.

These insights are synthesised in Table 3 by mapping the key OI mechanisms, sustainability priorities, and institutional support structures characterising each case. However, the comparative value lies in identifying best practices and understanding how local conditions shape the translation of OSI principles into practice.

Table 3. OSI practices in port ecosystems

Port	Key OI Mechanisms	Sustainability Focus	Institutional Support
Rotterdam	Innovation hubs (PortXL), hackathons, Port Innovation Barometer, start-up incubation, international collaboration and networking (Mendes Constante et al., 2023; Witte et al., 2018)	Smart port tech, energy transition, circular economy	Municipality, Port Authority, Port Development Companies (PDCs), academic institutions, research entities, and incubators
Valencia	Fundación Valenciaport, training and innovation ecosystem, OpenTop initiatives and collaborative events, cluster development (Mendes Constante et al., 2023)	Human capital, green logistics, and research internationalisation	Public-private cluster, EU funding, universities, incubators
Barcelona	Open-data policies, Pier01 innovation hub, Portic PCS digitalisation, resilient and flexible governance models, inclusive workshops, government start-up support (Garrido Salsas et al., 2022; Henríquez et al., 2022)	Digital twin, decarbonisation, stakeholder co-creation, green energy and renewable resources, digitalisation with a sustainability lens, customised logistic models, integrated socio-economic and environmental perspective	Port Authority, Spanish government
Motril-Granada	Blue Economy strategy, infrastructure improvements, green port initiatives (Seisdedos & Carrasco, 2020)	Coastal protection, circular practices	Local engagement, regional development funds

Source: Author's own construction

Taken together, the four cases reveal both common enablers and divergent trajectories of OSI. Large hubs such as Rotterdam and Barcelona leverage strong institutional capacity, dense networks of intermediaries, and advanced digital infrastructures to position themselves as innovation orchestrators. Valencia illustrates the importance of human capital development and cul-

tural change, showing how a dedicated intermediary (Fundación Valenciaport) can gradually embed openness and sustainability in a previously conservative environment. Motril-Granada, by contrast, demonstrates how smaller and resource-constrained ports can adopt a niche strategy, aligning with blue-economy agendas and EU projects to pilot circular and coastal-protection initiatives. Across all cases, the extent to which OSI unfolds depends on how governance arrangements, digital platforms, and intermediary organisations collectively translate OI principles into concrete sustainability outcomes.

4. DISCUSSION

The findings of this review suggest that OSI in port ecosystems is not yet a fully consolidated domain, but rather an emergent, multi-scalar paradigm shaped by diverse theoretical and empirical influences. While the literature exhibits growing interest in the convergence between OI and sustainability, this relationship remains unevenly theorised and operationalised. In what follows, we first discuss how the OSI lens reframes port innovation, then examine the institutional and governance conditions that enable or constrain systemic application and finally outline key research gaps and limitations that define a future agenda for the field.

The bibliometric evidence (Figs. 2–4) reveals shared conceptual spaces centred on ecosystem thinking, stakeholder engagement, and digital governance, as reflected in earlier contributions by García et al. (2019), Monteiro (2016), and Roumboutsos et al. (2022). These studies highlight the importance of collaboration, inter-organisational knowledge exchanges, and knowledge-intensive services as foundational mechanisms shaping innovation practices in ports. At the same time, the bibliometric network illustrates significant fragmentation: only a subset of studies explicitly and coherently integrates OI and sustainability (Costa & Matias, 2020; Kimpimäki et al., 2022; Rupo et al., 2018), suggesting the conceptual novelty and evolving nature of the OSI lens.

The illustrative case evidence supports and contextualises these patterns, demonstrating how institutional, organisational, and contextual conditions shape the operationalisation of OSI principles across different port ecosystems. Rotterdam, Valencia, and Barcelona exemplify advanced ecosystem orchestration capabilities, enabled by intermediary organisations, collaborative governance structures, and robust digital infrastructures (Henríquez et al., 2022; Jansen & Hein, 2023; Mendes Constante et al., 2023; Witte et al., 2018). These cases align with prior findings on the role of boundary-spanning agents, absorptive capacity, and institutional learning in enabling collaborative innovation (Garcia et al., 2019; Monteiro, 2016). Conversely, smaller ports such as Motril-Granada illustrate adaptive strategies grounded in territorial specificities and niche positioning (Seisdedos & Carrasco, 2020), reinforcing the argument that OSI trajectories remain context-dependent and sensitive to resource availability, governance maturity, and institutional alignment.

Despite encouraging evidence, persistent challenges continue to constrain OSI implementation. Regulatory fragmentation, short-term funding cycles, organisational inertia, and misalignment between long-term sustainability objectives and short-term operational priorities remain recurrent barriers (Campana et al., 2020; Tsvetkova & Hellström, 2022; Vanelslander et al., 2019). These issues confirm earlier arguments that institutional path dependencies, uneven digital maturity, and weak coordination capacity can inhibit cross-boundary collaboration and hinder systemic innovation within port ecosystems (Garcia et al., 2019; Witte et al., 2018). Furthermore, impact assessment mechanisms for sustainability-oriented innovation—particularly social and environmental outcomes—remain underdeveloped, as highlighted by Meyer et al. (2021; 2023).

This discussion synthesises the implications of these findings across three interrelated dimen-

sions: (i) the reframing of innovation through the OSI paradigm; (ii) the institutional and governance conditions that enable or constrain systemic OSI implementation; and (iii) the theoretical, methodological, and empirical gaps that define the future research agenda for this emerging field.

4. 1. REFRAMING PORT INNOVATION THROUGH THE OSI PARADIGM

The OSI paradigm represents a conceptual shift in how port innovation is understood and enacted. Traditional innovation models in the maritime and logistics sectors have typically followed closed, firm-centric approaches, relying on internal R&D, proprietary technologies, and piecemeal, project-based interventions (Acciaro & Sys, 2020; Vanelslander et al., 2019). As Chesbrough (2003) and Chesbrough & Bogers (2014) argue, such models are increasingly inadequate for addressing complex sustainability challenges that require knowledge exchange, collaborative governance, and systemic adaptability. The OSI paradigm addresses these limitations by explicitly integrating openness—through cross-boundary knowledge flows and stakeholder inclusion—with sustainability-oriented objectives grounded in environmental, social, and economic dimensions (Adams et al., 2016; Rupo et al., 2018).

This conceptual integration aligns with systemic innovation frameworks, notably the quadruple and quintuple helix models (Carayannis et al., 2021), which emphasise co-evolutionary interactions between firms, governments, academia, civil society, and ecological systems. In the port context, OSI reframes innovation as a collaborative and socially embedded process aimed at co-creating shared value (De Martino, 2021; Tsvetkova & Hellström, 2022). Successful OSI implementation thus requires long-term vision, embedded learning structures, and governance architectures capable of coordinating diverse actors, as illustrated in recent comparative studies of Rotterdam and Valencia (Mendes Constante et al., 2023).

At the same time, OSI foregrounds several tensions and open questions. Ports must balance openness with commercial confidentiality, safety, and security; operationalise sustainability goals without reducing them to narrow operational metrics; and integrate digital transformation as both an enabler and a potential source of new inequalities. These challenges reflect earlier observations in the literature concerning the institutional constraints and cultural barriers to collaboration (Garcia et al., 2019; Monteiro, 2016; Roumboutsos et al., 2022). Moreover, as highlighted by Meyer et al. (2021; 2023), knowledge transfer and continuous learning underpin sustainable innovation, reinforcing the need for multi-level coordination across ecosystems.

4. 2. INSTITUTIONAL CONDITIONS FOR SUCCESSFUL IMPLEMENTATION

While the conceptual potential of OSI is widely recognised, its translation into practice depends heavily on institutional conditions. Multi-stakeholder governance frameworks are essential, as ports sit at the intersection of public authority, private logistics operators, digital innovation actors, and environmental regulators. Fragmented or hierarchical governance structures inhibit knowledge flows, joint problem-solving, and long-term strategic planning (de Langen et al., 2020; Tijan et al., 2021).

Intermediary organisations—such as Fundación Valenciaport and SmartPort Rotterdam—play a pivotal boundary-spanning role by facilitating collaboration, reducing transaction costs, enabling access to funding, and aligning diverse strategic agendas (Mendes Constante et al., 2023; Witte et al., 2018). These intermediaries institutionalise learning and support ecosystem orchestration, both of which are core attributes of OSI.

Digital infrastructures also constitute a foundational enabler. Port Community Systems, open-data environments, digital twins, and cloud-based platforms support transparency, interoperability, and collaborative decision-making (Carlan et al., 2016; Monteiro, 2016; Wohlleber et al., 2024). However, disparities in digital maturity—particularly among small and medium-sized

ports—intensify asymmetries and may limit the inclusiveness of OSI (Meyer et al., 2024).

Cultural and organisational factors further influence OSI implementation. A culture of openness, tolerance for ambiguity, and commitment to long-term sustainability goals are essential precursors to system-level innovation. For example, Valencia's transition towards a more collaborative, learning-oriented innovation culture underscores the need to overcome entrenched mentalities resistant to change (Mendes Constante et al., 2023). Barcelona's use of inclusive governance tools, stakeholder participation forums, and joint ventures illustrates how cultural alignment supports co-creation and trust-building (Garrido Salsas et al., 2022; Henríquez et al., 2022).

Nonetheless, several structural constraints persist, including short-term funding horizons, regulatory misalignment, and the absence of robust sustainability indicators (Acciaro & Sys, 2020; Garcia et al., 2019; Vanelslander et al., 2019). These limitations highlight the risk that OSI platforms devolve into isolated pilot projects without strategic continuity—an issue exacerbated by political turnover, institutional inertia, and policy fragmentation (Costa & Matias, 2020).

Overall, institutionalising OSI requires governance flexibility, digital capacity, intermediary coordination, cultural openness, and policy coherence. Without these enabling conditions, OSI struggles to achieve systemic relevance.

4. 3. RESEARCH GAPS AND FUTURE THEORETICAL DIRECTIONS

Despite increasing scholarly interest in OSI, several conceptual and methodological gaps remain. One critical gap concerns the fragmented nature of existing terminologies and frameworks. As Kimpimäki et al. (2022) note, a shared conceptual vocabulary for OSI remains lacking, hindering cumulative theorisation and interdisciplinary dialogue.

While the literature acknowledges that OI facilitates sustainability transitions (Adams et al., 2016; Meyer et al., 2021), its integration with environmental and social objectives remains insufficiently theorised (De Martino, 2021; Garcia et al., 2019). Many studies privilege economic outcomes or technological efficiencies, while underexploring social equity, governance dynamics, and long-term ecological impacts. This imbalance reinforces earlier critiques that sustainability is often subordinated to operational imperatives (Rupo et al., 2018).

Another underdeveloped area concerns the role of institutional actors—particularly universities—in shaping OSI. Despite their recognised importance in innovation ecosystems, their potential contributions to sustainability-oriented innovation remain underexplored (Costa & Matias, 2020). This limitation intersects with the inadequacy of policy instruments that prioritise traditional innovation metrics over societal impact.

Power asymmetries and value-distribution mechanisms also require closer examination. Studies by De Martino (2021) and Mendes Constante et al. (2023) underscore how inequalities in influence, legitimacy, and resource access can undermine inclusivity and skew sustainability outcomes. These issues resonate with broader debates on the political economy of innovation and warrant deeper investigation in the context of OSI.

Furthermore, much of the empirical literature relies on cross-sectional or case-specific designs, limiting the ability to trace innovation trajectories, institutional learning, and feedback loops over time. Longitudinal analyses grounded in transition management, institutional theory, and critical innovation studies could help illuminate how OSI evolves, consolidates, or fails within port ecosystems (de Langen et al., 2020; Henríquez et al., 2022).

Despite these gaps, OSI holds significant promise as a theoretical and practical lens for reimagining innovation in port ecosystems. Future research should build integrative models that reflect the multi-level, multi-actor, and multi-dimensional nature of OSI, providing clearer conceptual boundaries, operational mechanisms, and evaluation metrics.

5. LIMITATIONS AND RESEARCH AGENDA

Building on the methodological constraints outlined in Section 2.5, this section broadens the focus to conceptual, empirical, and methodological gaps that define a future research agenda on OSI in port ecosystems.

Conceptually, the literature remains fragmented across separate strands on smart and digital ports, green ports, and innovation ecosystems. Few studies develop integrative frameworks that explicitly link cross-boundary knowledge flows, sustainability goals, and ecosystem governance or address how power asymmetries and value distribution shape OSI processes. Future research could advance this agenda by elaborating multi-level theoretical models that connect micro-level practices, meso-level ecosystem dynamics, and macro-level institutional change.

Empirically, the evidence reviewed is concentrated in European ports, reflecting both the geographical bias of existing research and the prominence of EU policy initiatives. This focus limits the generalisability of the findings. Comparative studies involving ports in Asia, Africa, and the Americas—especially those operating under different regulatory and governance regimes—are needed to test, refine, and possibly challenge the OSI framework proposed here.

From a research design perspective, most of the reviewed contributions adopt cross-sectional or single-case approaches. There is considerable scope for longitudinal and mixed-method studies that trace OSI processes over time, combine qualitative insights (e.g., interviews, ethnographies, participatory observation) with quantitative indicators (e.g., emissions, throughput, innovation outputs), and examine how conflicts, trade-offs, and negotiations around sustainability goals unfold in practice. Such approaches would provide a richer basis for assessing the effectiveness and transformative potential of OSI in maritime port ecosystems.

6. CONCLUSION

This review has examined the evolving relationship between OI and sustainability in maritime port ecosystems and proposed OSI as a conceptual and operational bridge between these two imperatives. By combining bibliometric mapping with qualitative synthesis and illustrative case analysis, the study shows that OSI is not yet a consolidated domain but rather a dynamic, heterogeneous arena of experimentation, negotiation, and institutional learning.

From a theoretical perspective, the article contributes by articulating OSI as an evolution of traditional OI, in which cross-boundary knowledge flows, multi-stakeholder engagement, systematic knowledge management, and digital infrastructures are explicitly aligned with triple-bottom-line objectives. The bibliometric and conceptual analysis reveals how current research remains fragmented across separate strands on smart ports, green ports, and innovation ecosystems, underscoring the need for integrative frameworks that address governance, power, and value distribution in a unified way.

In terms of managerial and policy implications, the comparative evidence from Rotterdam, Valencia, Barcelona, and Motril-Granada indicates that successful OSI implementation depends on the interplay between governance flexibility, intermediary organisations, digital capacity, cultural openness, and long-term policy coherence. Ports that aspire to move beyond isolated pilot projects towards systemic, sustainability-aligned innovation need to invest in enabling digital infrastructures, cross-sectoral funding mechanisms, inclusive governance arrangements, and learning-oriented cultures. Viewing ports as innovation ecosystems—rather than merely logistical nodes—can support broader urban, regional, and global sustainability agendas.

Finally, the study outlines a future research agenda centred on three priorities: (i) developing integrative theoretical models that reconcile openness, sustainability, and ecosystem governance;

(ii) conducting longitudinal and mixed-method empirical studies that capture the temporal and political dynamics of OSI implementation, including value distribution and power asymmetries; and (iii) extending the geographical scope of analysis beyond Europe to include diverse port regions, particularly in the Global South. Addressing these challenges will be essential to harnessing the transformative potential of OSI and to positioning ports as key actors in the transition towards more sustainable, resilient, and inclusive socio-technical systems.

Declaration of generative ai and ai-assisted technologies in the writing process

During the preparation of this work, the author(s) used app.litmaps.com to visualise how papers relate to one another and to discover relevant new papers. We also used Scite.ia and Scispace.ia to organise and chat with the documents, getting answers and explanations. After using this tool/service, the author(s) reviewed and edited the content as needed and take full responsibility for the publication's content.

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