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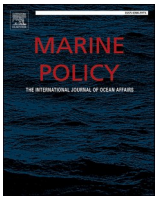

Full length article

SDG attributes: A sustainability assessment framework for Brazilian ports

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ABSTRACT

The maritime transport sector plays a vital role in Brazil's economy, yet port sustainability remains a critical challenge. In response, this study develops and applies a sustainability index model specifically designed for the port sector, aligned with the Sustainable Development Goals (SDGs 7, 8, 9, 11, 12, 13, 14, and 17). The model integrates 20 thematic dimensions and 84 indicators, enabling a quantitative assessment of port sustainability performance. It was applied to six Brazilian ports, representing 30 % of the country's cargo throughput in 2023. Results reveal that Ports B and E demonstrated the highest alignment with sustainability principles, particularly in partnerships (SDG 17) and responsible consumption (SDG 12). Conversely, significant gaps were identified in climate action (SDG 13) and clean energy adoption (SDG 7). The findings highlight strategic areas for improvement and offer a practical framework for decision-making and policy development within the port sector. By bridging operational practices and the global sustainability agenda, this model provides actionable insights to enhance governance structures and foster resilience in port operations. The study contributes to advancing sustainable maritime governance and offers a replicable tool for port authorities and policymakers aiming to align port development with international sustainability goals.

1. Introduction

The smart port functions as a logistics information centre, facilitating the intelligent management of transport and traffic systems. Port intelligence encompasses the application of advanced technologies, such as artificial intelligence and the Internet of Things, to enhance operational efficiency and optimise resource utilisation through the provision of real-time data and analytics [25]. A study conducted in Taiwan identified six key success factors for smart ports: accurate and secure delivery of cargo; accurate electronic document transfer; rapid provision of port berths to reduce ship turnaround times; convenient and comprehensive logistics and customs procedures; transparent information integration on a single platform; and the use of big data to coordinate container transport [19].

Building on the strategic importance of smart ports as data-driven logistics hubs, sustainability has emerged as a critical dimension in port performance evaluation. In a world where maritime trade continues to expand, the integration of key performance indicators is essential to guide ports towards a balanced pursuit of economic growth, social responsibility, and environmental preservation. These indicators should be explicitly aligned with sustainability goals to enable effective, coherent, and resilient port development [3].

The systematic monitoring of sustainability indicators not only promotes transparency but also enables comparability in the adoption of sustainable practices. Sustainability reports, which encompass multiple dimensions, serve as vital tools for tracking progress, benchmarking performance, and informing continuous improvement [34]. Among the available frameworks, the Global Reporting Initiative (GRI) guidelines are the most widely adopted worldwide, although regional preferences may favour the Sustainability Accounting Standards Board (SASB) or

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local stock exchange requirements [26].

Founded in Boston (USA) in 1997, the GRI published its first version (G1) in 2000, providing the first global framework for sustainability reporting. In 2016, the Global Reporting Initiative introduced guidelines that established the first international standards for sustainability reporting, known as the GRI Standards. These standards have continued to evolve, with a significant update to the Universal Standards in 2021. That same year saw the introduction of Sector Standards, beginning with Oil & Gas. Subsequently, standards for Agriculture, Aquaculture & Fishing, and Coal were released in 2022. The GRI guidelines continue to be refined, now encompassing standards for several industries [16]. However, they do not yet include the maritime and port sectors.

The Sustainability Accounting Standards Board (SASB) is an independent organisation that develops and maintains industry-specific standards to guide companies in disclosing financially material sustainability information to investors and stakeholders. SASB's standards focus on sustainability topics that have a significant impact on a company's financial performance, covering issues such as environmental impacts, social factors, and governance practices [38].

The SASB Marine Transportation Content Index provides targeted sustainability indicators for the maritime transport sector, focusing on financially material aspects relevant to investors and stakeholders, such as greenhouse gas emissions, energy efficiency, worker health and safety, and environmental risk management. While prioritising financial materiality, these metrics address key sustainability challenges within the industry, enabling ports and maritime operators to align their practices with market expectations and investor demands. This index complements other frameworks, like the GRI, by offering a model geared towards sustainable financial value creation within marine transportation [37].

The EU Taxonomy serves as a comprehensive classification system to identify economic activities that are deemed sustainable, setting a clear framework to help the European Union achieve its ambitious environmental goals. Specifically designed to steer investment and policy alignment, this taxonomy highlights economic activities that make a substantial contribution to at least one of the EU's six environmental objectives: climate change mitigation, climate change adaptation, sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, and protection and restoration of biodiversity and ecosystems. Within the port sector, the EU Taxonomy provides tailored criteria that prioritise actions aimed at reducing greenhouse gas emissions, enhancing resilience to climate impacts, promoting the sustainable use of marine resources, and minimising environmental pollution. This framework encourages ports to adopt and disclose sustainable practices, aligning operations with the EU's broader strategy toward a low-carbon and resilient economy [12].

In Brazil, ports primarily employ the *Índice de Desempenho Ambiental* (IDA), a framework developed by the Ministry of Transport, Ports and Civil Aviation, the Waterway Transport Agency (ANTAQ), and the University of Brasília. The IDA, comprising 38 specific indicators, aligns with universal standards and covers areas such as environmental governance, safety, and port operations management [2]. Although the IDA provides a structured approach to evaluating environmental performance, its focus on environmental aspects leaves social and governance dimensions underrepresented, revealing an area for improvement in the assessment of comprehensive sustainability practices.

This limitation is further compounded by the absence of port-specific indicators within the GRI framework, highlighting the need for additional models that can holistically represent the pillars of sustainability. An integrated model that encompasses social, environmental, and governance indicators is essential for aligning port activities with the broader sustainability objectives set out by the Sustainable Development Goals (SDGs).

Given the maritime industry's central role as the primary transporter of heavy cargo, it holds significant potential for contributing to the SDGs [23]. The 2030 Agenda, established by the United Nations in 2015, defined 17 SDGs with 169 targets aimed at addressing global challenges, including climate change and social inequality [24]. Consequently, ports, as key nodes in the global logistics network, are strategically positioned to drive progress towards these goals.

Integrating key performance indicators (KPIs) in ports that align with both GRI guidelines and the SDGs reinforces the importance of social responsibility. Such KPIs enable comparative assessments and help identify areas for enhancing sustainable practices [32]. Furthermore, the effective monitoring and implementation of SDG-linked indicators require the establishment of specific, measurable, achievable, and relevant targets, facilitating a structured approach to sustainability [42].

To foster greater transparency and accountability, ports require clear guidelines for communicating sustainability information to their diverse stakeholder communities. Comprehensive sustainability reports should cover social, environmental, governance, and economic pillars, thereby clarifying the sector's contributions to the SDGs. In response to this need, this article proposes a model sustainability index specifically tailored to the port sector, aligned with the SDGs, applied in the six Brazilian port terminals.

The proposed model not only identifies which SDGs are most actively addressed by port terminals, but also highlights the thematic categories within each goal that are prioritised in port operations and planning. By doing so, it offers port terminals critical insights into areas where efforts could be intensified for maximum impact, thereby enhancing their contribution to sustainable development.

This study contributes to the literature by proposing the first sustainability index framework specifically adapted to the Brazilian port sector, fully aligned with the SDGs. The framework aims to fill a critical gap by integrating environmental, social, and governance dimensions into port sustainability assessment.

2. Literature review

The port sector faces significant challenges in aligning its operations with globally recognised sustainability standards, aiming to improve both environmental and social performance. Meeting the requirements of the SDGs necessitates a broader and more integrated approach than that offered by existing frameworks [30].

To advance these objectives, a mixed-methods approach combining quantitative analysis with qualitative assessment proves beneficial. This approach deepens the understanding of critical areas such as energy efficiency, marine water quality, and sustainable technological innovations, thereby enabling decision-makers to prioritise sustainability goals more effectively [3].

Despite substantial research on sustainability indicators within the port sector, early studies predominantly focused on environmental dimensions. A computer-based tool known as Tool for the Identification and Assessment of Environmental Aspects in Ports was developed for the port sector.The methodology encompasses 17 environmental aspects, grouped into seven categories, and assessed using eight significance criteria, including frequency, duration, legal compliance, and stakeholder concerns. Although the tool is applicable to various port types and was tested using data from pilot ports, the precise number of ports involved was not disclosed [35].

A study aimed to evaluate the sustainability performance of the five largest ports in the United Kingdom by developing a comprehensive assessment model that integrates both economic and environmental dimensions. The research established a hierarchical framework incorporating indicators such as cost-efficiency, service quality, environmental policy, pollution control, energy consumption, waste management, and emergency preparedness. Several of these indicators were adapted from ISO 14001 standards, weighted accordingly, and employed to rank the ports based on their overall sustainability performance [4].

To address the previously identified gap, recent studies have adopted a more holistic approach by incorporating sustainability indicators

across the three core dimensions, environmental, social, and economic, and, in some cases, by proposing integrated frameworks. For instance, one study presented a conceptual model for sustainable port development with a specific focus on Vietnamese ports. Drawing on interviews with port authorities, the study identified key internal and external management criteria spanning all three pillars of sustainability. The findings highlight both the challenges and opportunities faced by Vietnamese ports in aligning with international sustainability standards, emphasising the importance of a comprehensive and integrated approach to port development [36].

Similarly, several models developed for Spanish ports have introduced comprehensive sustainability indices. One such model proposed a methodological framework based on synthetic indexes, enabling the integration of economic and environmental dimensions for multidimensional analysis and comparative assessments across port authorities [27]. A subsequent model expanded this framework to encompass four dimensions economic, institutional, environmental, and social. The economic pillar includes indicators such as turnover per employee, EBITDA per employee, and the ratio of third-party to public investment. Environmental indicators focus on the implementation of environmental management systems, efficient resource usage, and waste recovery practices. The social dimension comprises variables related to employment, training, gender equality, and occupational health, thereby embedding broader elements of social responsibility into port sustainability assessments [28]. A study was later applied in a longitudinal study comparing port performance across the four dimensions between 2010 and 2015, offering a valuable framework for assessing port resilience during periods of economic crisis [14].

In line with this multidimensional perspective, a study on South Korean ports developed a sustainability assessment framework that evaluated environmental, economic, and social indicators. Environmental aspects included protection initiatives, noise and pollution control, and air and water quality monitoring. Economic indicators focused on fostering growth and promoting infrastructure investment, while social dimensions addressed community involvement, employee welfare, and equity in the workplace [33].

Further contributions to the field include research on Canadian ports, which prioritised sustainability practices such as environmental policy formulation, energy management, stakeholder engagement, and the promotion of sustainable behaviours among port users [17].

A study focused on corporate social responsibility (CSR) practices within port operations, examining dimensions such as CSR reporting, employee welfare, ethical standards, and stakeholder engagement. The research underscored the critical importance of transparent disclosure concerning greenhouse gas emissions, pollutant levels, and waste management practices. The study compared three Polish ports with the Ports of Hamburg and Antwerp [32].

A broader international study analysed sustainability initiatives across thirty-six ports in North America, Europe, and the Asia-Pacific region, revealing significant variation in both adoption and implementation. Notably, European ports emerged as leaders in environmental management, air and water quality monitoring, and climate adaptation measures [18]. Furthermore, a developing methodological approach explored strategies to enhance port performance in Crete, with a particular focus on the formulation of social policies, stakeholder engagement, and educational initiatives. The study also recommended the integration of modern technologies and the adoption of renewable energy sources to further environmental objectives [3].

A model was developed to support the advancement of the marine renewable energy sector within the framework of the Blue Economy in Spanish ports. The final set of key indicators includes variables such as the evolution of total investment, investment in environmental characterisation, accident frequency rate, and port area cleanliness. The findings highlight the importance of integrating economic investment, proactive environmental management, and occupational safety measures to support strategic decision-making and foster sustainable development in the port sector [41].

A literature review study contributed to the discussion by categorising environmental indicators for ports, covering areas such as port management, energy and fuel use, maritime operations, and land-based activities. The proposed framework addresses key environmental management practices, the adoption of alternative energy sources, and technological innovations [6].

A study conducted within the context of inland ports in Europe developed a set of Environmental Performance Indicators, categorised into four key areas: environmental management, environmental monitoring, environmental priorities, and green actions. These indicators were designed to reflect both regulatory requirements and the practical realities of inland port operations, enabling ports to assess aspects such as the existence of an environmental policy, the monitoring of waste and air quality, the implementation of green technologies such as LNG bunkering and shore-side electricity, and the identification of key environmental concerns, including community engagement, air and water quality, and waste management [39].

A study examining European ports within the EcoPorts framework highlighted the widespread adoption of environmental policies and monitoring programmes, with particular attention to noise levels, sediment quality, and compliance with GRI reporting standards [34].

Recent academic literature has increasingly aligned port sustainability initiatives with the Sustainable Development Goals, reflecting a growing convergence between research and practice in this domain [8,1, 43]. However, few studies have systematically examined performance indicators explicitly linked to the SDGs, highlighting the maritime sector's pivotal role in advancing the broader global sustainability agenda [25,40].

A qualitative content analysis was carried out based on the sustainability disclosures of 33 European ports to evaluate their alignment with the SDGs. Although the study does not propose specific indicators, it offers a comprehensive overview of strategic actions linked to each of the 17 SDGs [8].

An analysis of sustainability reports from ports and terminals across Asia, the Americas, and Europe was conducted, focusing on how the maritime industry contributes to the 17 Sustainable Development Goals. The study explores the extent to which the sustainability practices reported in these documents align with the SDG framework. A content analysis was performed to systematically examine the textual data, producing synthesised insights that inform the construction of a reality grounded in empirical evidence [43].

A comprehensive literature review contributed significantly to the academic discourse on sustainability strategies in the port sector. The study systematically categorises internal and external sustainability actions across environmental, social, and economic dimensions, and establishes their alignment with the SDGs, thereby providing a multidimensional framework to support sustainable port development [1].

A framework for the port sector, incorporating customised measures across four key dimensions (governance, environmental, social, and economic), was developed and validated through a co-design process involving officials from the Transnet National Ports Authority. It was applied to the context of South Africa's eight ports. The framework comprises a structured set of 15 sustainability outcomes and corresponding indicators, including eco-efficiency, climate resilience, institutional arrangements, community well-being, and employee satisfaction. The model enhances both local relevance and practical applicability, while also ensuring alignment with the Sustainable Development Goals [40].

A recent model comprising 22 indicators examined the contribution of port smartness to the advancement of the Sustainable Development Goals, proposing a multidimensional framework that connects smart port strategies to economic, environmental, and social sustainability. The study identified key indicators across five core dimensions: digital technology and automation, information management and integration, infrastructure and operational efficiency, governance and stakeholder

engagement, and environmental sustainability. Each dimension plays a crucial role in aligning port operations with global sustainability objectives. The analysis was based on sustainability reports from 21 ports worldwide [25].

A model comprising 16 indicators was developed to assess port city sustainability, with specific connections to SDGs 9, 11, and 12, and applied to the cases of Naples and Valencia. The environmental dimension includes indicators such as CO_2 emissions, energy consumption, waste management, green area coverage, and air and water quality. Social sustainability is evaluated through indicators related to access to public services, employment rates, quality of life, education and training, and social inclusion. The economic dimension encompasses port throughput, infrastructure investment, innovation and technology, logistics efficiency, and economic resilience [9].

Although not specifically developed for the port sector, other models have successfully established connections between sustainability indicators and the SDGs. One such model, applicable to companies across various industries, maps 178 ESG indicators to the 17 SDGs. This framework allows firms to identify the most relevant targets and evaluate their sustainability performance using a calculated ESG Relevance Index [24].

Despite recent advancements, a critical gap persists in the development of a specialised sustainability index for ports that fully integrates indicators aligned with the Sustainable Development Goals. Bridging this gap represents a strategic opportunity for further research and model development, particularly in addressing the distinctive operational, social, and environmental challenges faced by ports within the broader framework of global sustainability standards.

3. Method

The development of the SDG Attributes model followed a multidimensional approach, combining internationally recognised standards, expert feedback, and an extensive review of the academic literature. Initially, global and national frameworks, such as the Global Reporting Initiative (GRI) and the Environmental Performance Index (Índice de Desempenho Ambiental (IDA) developed by ANTAQ, were thoroughly analysed to understand prevailing practices in sustainability reporting and performance evaluation [15,2]. Additionally, sector-specific publications such as the ESPO Environmental Report [11] and the Inter-American Development Bank's Ecosistema de Innovación en Puertos [20] were instrumental in contextualising the model for the port sector, particularly in addressing the operational challenges and innovation opportunities linked to SDG 9.

To reinforce the theoretical foundation of the model, an extensive literature review was undertaken to identify key trends, best practices, and methodological advances in port sustainability. In particular, the model was informed by studies employing synthetic indices for performance evaluation, especially those applied to the Spanish port system [28,14]. These contributions provided valuable insights into the construction of multidimensional indices, enabling comparative assessments while maintaining contextual relevance, particularly with respect to SDGs 8, 11, and 12. Additional references incorporated into the framework include studies focused on environmental management systems, institutional governance, and integrated sustainability strategies in port operations [8,18,1,17,32,33,34,39].

The design of the model was informed by the integration of various sources and aimed to be comprehensive, up-to-date, and specifically aligned with the needs of the port sector. The selection of Sustainable Development Goals (SDGs) incorporated into the SDG Attributes model was guided by two key studies. The first study emphasised the alignment of SDGs 8, 9, 12, and 14 with the core commercial activities of maritime companies and port operations, positioning these goals as central responsibilities in sustainability efforts. The second study highlighted the relevance of SDGs 7, 11, and 13 for the port sector. Additionally, SDG 17 was incorporated due to its emphasis on transparency in indicator disclosure and its overarching connection across all sustainability dimensions [10,43].

The final model encompassed SDGs 7, 8, 9, 11, 12, 13, 14, and 17, with linkages across 20 thematic areas tailored to the port sector's specificities. It incorporated 84 indicators aligned with the targets of these SDGs. For each SDG, thematic categories were defined, with each encompassing two to three specific areas. Fig. 1 illustrates the 20 areas included in the model, reflecting the unique characteristics of the port sector.

The model employs a quantitative approach to evaluate sustainability performance. To assess performance across the selected Sustainable Development Goals (SDGs), a scoring system ranging from 0 to 3 was applied to each indicator. This scale was designed to capture the degree of implementation, maturity, and effectiveness of sustainability practices within the participating ports. The scoring criteria are defined as follows: 0: No evidence of action: The port does not address the indicator, has not implemented any related measures, or lacks available information. 1: Initial action: The port has initiated activities related to the indicator, but these actions are limited in scope, pilot-based, or not yet systematically integrated into operations. 2: Consolidated action: The port has implemented consistent and structured measures addressing the indicator, with evidence of operational integration and ongoing activities. 3: Best practice: The port demonstrates comprehensive, systematic, and advanced implementation of the indicator, aligned with international best practices and supported by performance monitoring and reporting. The specific metrics applied to each indicator within the model are detailed in Annex I.

The study targeted the 20 most active ports and terminals in Brazil in 2023. Invitations to participate were sent via email, resulting in responses from six ports. Participation was voluntary, and respondents were informed about the purpose of the study. Data confidentiality was ensured by anonymising port identifiers, and the research was conducted in accordance with ethical guidelines for organisational research.

The proposed model was applied to a representative sample of six Brazilian ports, collectively accounting for approximately 30 % of the country's total port throughput in 2023. The selected sample comprises ports and terminals located across Brazil's three principal port regions: the Southeast, Northeast, and South. Data were collected through the administration of a structured questionnaire conducted between April and October 2024. Prior to full deployment, a pilot test was conducted with two port sector experts to ensure the clarity, relevance, and validity of the questionnaire items. To preserve participant confidentiality and ensure compliance with ethical research standards, the identities of the ports have been anonymised and are referred to as Ports A, B, C, D, E, and F throughout the study.

The proposed framework was subsequently applied empirically to six ports and terminals, illustrating its applicability and potential to inform strategic decision-making in the field. The indicators were derived from an extensive review of the literature and validated through expert consultations, thereby ensuring both conceptual rigour and practical relevance.

The model was developed using Power BI software, and all visual elements were generated by the authors. The study results are accessible via a web application created using Streamlit, a Python library for interactive web applications. A beta version of the application, which allows ports to simulate outcomes for SDGs 7 and 13, is available through links provided in the data availability section.

The decision to develop a framework for assessing sustainability in the Brazilian port sector was informed by several key considerations. Although the IDA model, developed in Brazil, provides valuable contributions, its scope remains predominantly focused on environmental aspects. It does not incorporate the economic, social, or institutional dimensions that are vital for a comprehensive and multidimensional sustainability assessment. Moreover, it lacks explicit alignment with the SDGs, which have become a central reference point for guiding sustainability strategies across diverse sectors and regions.

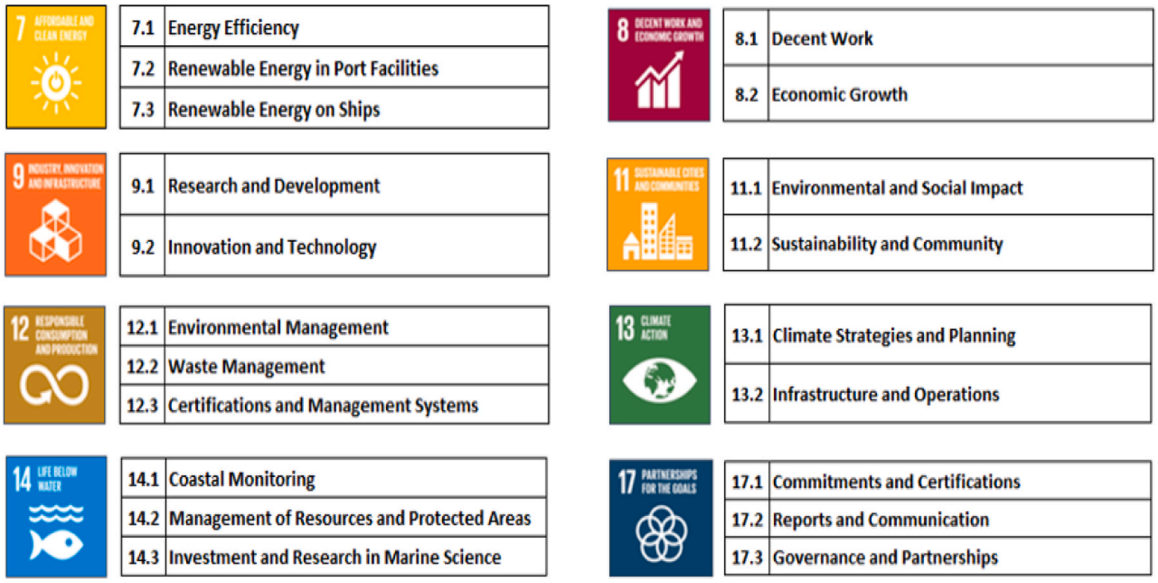

Fig. 1. SDGs and linked areas.

Additionally, while the academic literature offers a broad spectrum of relevant indicators across areas such as operational efficiency, governance, social equity, and environmental performance, these indicators are rarely organised or interpreted in direct connection with the SDGs. This disconnection reduces their practical utility for institutions and policymakers seeking to align port sustainability initiatives with global development agendas. Therefore, the development of a context-specific and SDG-oriented model is essential to enable a more balanced, integrative, and forward-looking approach to sustainability evaluation in the Brazilian port context.

4. Results

The results of this study reveal distinct sustainability profiles among

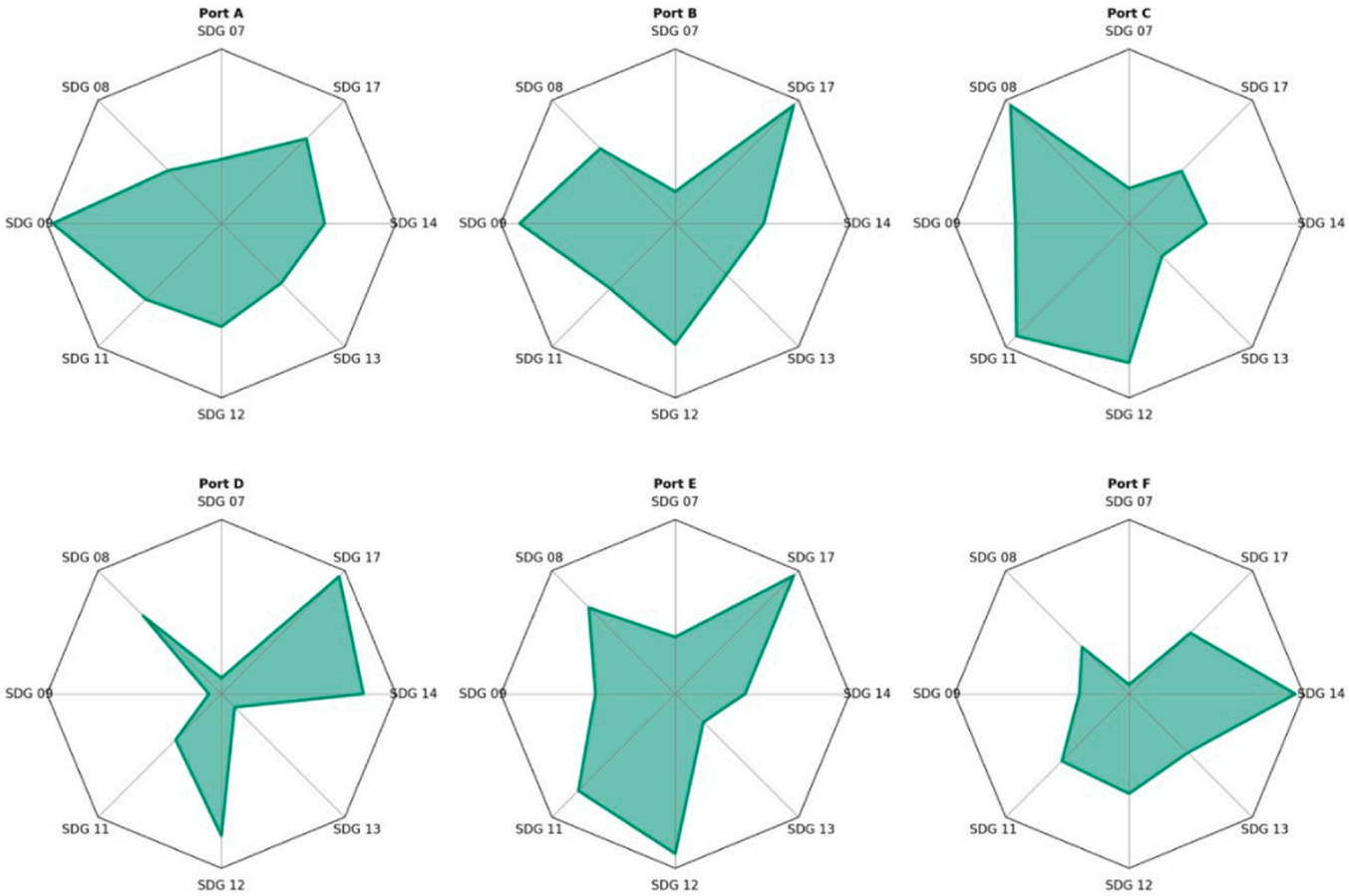

Fig. 2. SDGs selected for the SDG Attributes model.

the Brazilian ports surveyed, reflecting their varied approaches to integrating the Sustainable Development Goals (SDGs) into their operations. By analysing the prioritisation of SDGs and their associated indicators, this section aims to highlight the strategic focus areas of each port and identify commonalities and divergences in their sustainability efforts.

Fig. 2 illustrates the distribution of these SDGs through a graphical scheme designed to facilitate comparative analysis between different port facilities, considering both the SDGs and the indicators that constitute the tool. The figure indicates that the Brazilian ports surveyed prioritise different SDGs, each reflecting a unique focus within their sustainability strategies. Ports A, B, and E demonstrate a balanced approach.

Port A places particular emphasis on SDG 09 (Industry, Innovation, and Infrastructure), while Port B prioritises both SDG 17 (Partnerships for the Goals) and SDG 09, highlighting a commitment to fostering innovation and collaborative initiatives. Port E prioritises SDG 17, along with SDG 12 (Responsible Consumption and Production) and SDG 11 (Sustainable Cities and Communities), indicating a well-rounded approach to promoting sustainable production, urban sustainability, and collaborative networks. Port C focuses on SDG 08 (Decent Work and Economic Growth) and SDG 11. Port D shows a strong focus on SDG 14 (Life Below Water) and SDG 17, suggesting a dedication to marine conservation and partnership-building efforts. Port F primarily emphasises SDG 14, reflecting its focus on preserving marine life.

Overall, these distinctions in SDG priorities illustrate the diverse sustainability profiles among Brazilian ports, with each port concentrating on specific goals to address its unique environmental and operational contexts.

SDG 7 (Affordable and Clean Energy) aims to ensure universal access to affordable, reliable, sustainable, and modern energy. In alignment with this goal, the maritime industry is expected to lead investments, research, and innovation in sustainable energy technologies specifically designed for the sector [43].

The indicators of SDG 7 are essential tools for monitoring the adoption of sustainable practices in three key areas: energy efficiency, renewable energy in port facilities, and renewable energy on vessels. In the area of renewable energy within port facilities, the focus is on the procurement and production of renewable energy, the use of biofuels, innovation, and the diversity of renewable sources. These efforts further promote clean energy and support the implementation of charging stations for electric vehicles. The significance of these initiatives becomes even more apparent considering recent studies in the field.

In the segment of renewable energy on vessels, the focus is on supplying renewable energy to ships, encouraging sustainable technological innovations, and monitoring the percentage of ships adopting renewable sources, thus promoting clean energy practices.

Table 1 provides a comprehensive framework of indicators linked with SDG 7. These indicators offer a structured approach to evaluating and enhancing the energy sustainability performance of ports, focusing on three main areas. The first area addresses Energy Efficiency, covered by indicators 7.1, 7.2, and 7.3, which emphasise efforts to optimise energy use through targeted programmes and innovative practices. The second area focuses on Renewable Energy in Port Facilities, including indicators 7.4, 7.5, 7.6, 7.7, 7.8, and 7.9, highlighting the adoption and integration of sustainable energy solutions, diversification of energy sources, and promotion of clean energy partnerships. The third area centres on Renewable Energy in Ships, represented by indicators 7.10, 7.11, 7.12, 7.13, and 7.14, reflecting efforts to supply clean energy to vessels, incentivise environmentally responsible practices, and develop innovative energy services for maritime operations.

This categorisation provides a clear and actionable framework for ports to monitor their progress, align their activities with global sustainability goals, and contribute to the transition towards clean energy systems.

Fig. 3 highlights the limited adherence of the study ports to SDG 7. Port E demonstrates a stronger alignment with this SDG, exhibiting a more balanced distribution across the indicators (7.2, 7.4, and 7.7). Similarly, Port A performs well on specific indicators (7.4 and 7.7). The average chart provides an aggregated perspective, with the results indicating a notably stronger alignment with indicator 7.2 (Number of energy efficiency management programmes).

SDG 7 showed limited adherence across the ports, with Port E and Port A standing out through stronger performance in energy efficiency initiatives. However, widespread adoption of renewable energy solutions remains low, indicating a critical area for improvement.

The growing energy demands of the maritime industry further underscore the urgency of achieving this objective. A study reported a 1.6 % annual increase in energy demand within the sector between 2000 and 2015. This rising demand, combined with escalating energy costs and an intensified global focus on climate change mitigation, has led many ports to prioritise energy efficiency within their operational strategies [21].

The collaboration between efficient navigation practices and the port sector is increasingly recognised as a pivotal driver for global stability and sustainable development. In this context, the proposed model offers an analytical tool for assessing a port's alignment with the Sustainable Development Goals (SDGs). It enables a detailed evaluation of the SDGs that receive the most strategic attention from port administrations [43].

Ports are increasingly leveraging renewable energy sources, such as solar, wind, and wave power, to meet their operational energy demands in a more sustainable manner. The integration of advanced energy management technologies, including smart grids and Onshore Power Supply (OPS), enhances energy efficiency and significantly reduces reliance on fossil fuels. These developments directly contribute to achieving decarbonisation targets and align with the objectives of SDG 7, which promotes access to affordable, reliable, sustainable, and modern energy [7].

However, despite the global ambition to promote a diverse and multi-fuel transition in the maritime sector, the current fleet of

Table 1
Indicators SDG 7.

7.1 Number of awareness programmes on rational energy use
7.2 Number of energy efficiency management programmes
7.3 Number of technological innovation initiatives in energy efficiency
7.4 Percentage of renewable energy contracted and produced in port facilities
7.5 Percentage of biofuels in electrical and mechanical loads
7.6 Number of technological innovation initiatives in renewable energy
7.7 Diversity of renewable energy sources in port facilities
7.8 Number of partnerships for the promotion of clean energy
7.9 Number of charging stations for electric vehicles
7.10 Percentage of renewable energy supply to ships
7.11 Percentage of LNG fuelling
7.12 Number of technological innovation initiatives in electrical and energy services for ships
7.13 Number of ships using renewable energy in the port
7.14 Differentiated tariffs for ships performing above environmental standards

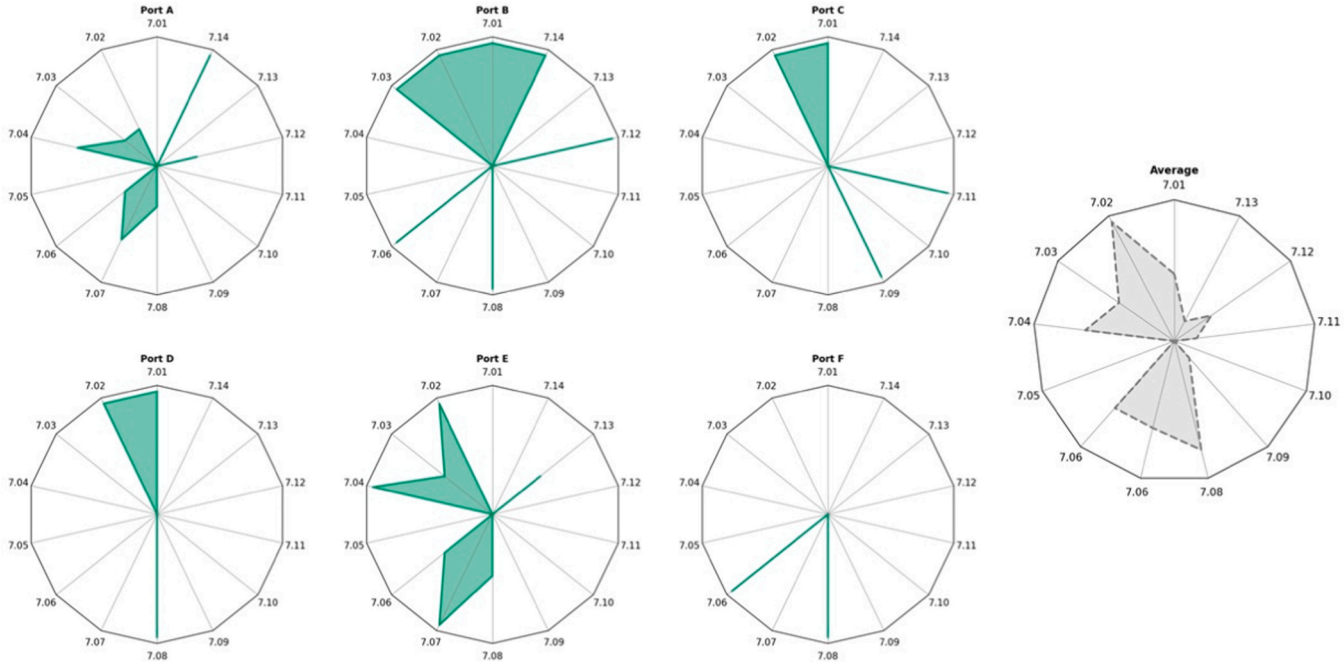

Fig. 3. Indicators linked to SDG 7.

alternative-fuel vessels remains relatively homogeneous and technologically narrow. Most of these vessels continue to rely on liquefied natural gas (LNG) and share comparable propulsion systems, such as dual-fuel internal combustion engines. This suggests that the widespread adoption of a broader range of low- and zero-carbon fuels, such as green ammonia, hydrogen, and methanol, is still in its nascent stages and faces significant technological, infrastructural, and regulatory barriers [13].

SDG 8 (Decent Work and Economic Growth) seeks to promote sustained, inclusive, and sustainable economic growth, ensuring full, productive employment and decent work for all. This goal is structured around specific indicators that monitor its progress and effectiveness, focusing on two primary areas: economic growth and decent work. By balancing economic and social dimensions, SDG 8 provides a comprehensive framework for development that prioritises growth benefiting everyone.

Table 2 presents a detailed framework of indicators aligned with SDG 8. These indicators provide a structured methodology for assessing and enhancing efforts towards promoting sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all. The framework is organised into two main areas. The first area focuses on Decent Work, encompassing nine indicators (8.1–8.9), which evaluate various aspects of employment quality, labour rights, and workplace conditions. The second area addresses Economic Growth, consisting of seven indicators (8.10–8.17), which measure progress in fostering economic productivity, innovation, and sustainable business practices.

Fig. 4 highlights the adherence of the studied ports to SDG 8, with Ports B, E, and D demonstrating particularly strong alignment. The average chart indicates a relatively balanced approach across the indicators, with slightly higher alignment observed in indicators 8.16 (Diversity of Types of Cargo Handled), 8.13 (Quantity of Tons Handled), and 8.12 (EBITDA Margin Value). This suggests that the ports are contributing positively to the economic growth dimensions of SDG 8 while reflecting its emphasis on inclusive and sustainable practices.

SDG 8 was relatively well-addressed, with Ports B, E, and D displaying strong economic and employment performance. Indicators related to cargo handling and revenue growth were particularly robust, although social aspects like employee diversity showed less emphasis.

Occupational health and safety represent a critical component of social sustainability in the port sector, directly contributing to the goals of SDG 8, which promotes decent work and economic growth. The adoption of digital technologies, including smart sensors and monitoring

Table 2
Indicators SDG 8.

8.1 Absences due to health-related absenteeism
8.2 Leave due to occupational diseases
8.3 Leave due to accidents
8.4 Number of accidents
8.5 Fatal accidents
8.6 Percentage of local workers in management positions
8.7 Percentage of female employees
8.8 Percentage of young employees (14–24 years old)
8.9 Percentage of employees with disabilities
8.10 Annual Revenue Growth Rate Adjusted for Inflation
8.11 Port Revenue Target
8.12 EBITDA Margin Value
8.13 Quantity of Tons Handled
8.14 Revenue per Employee
8.15 Position in the ANTAQ Cargo Movement Ranking
8.16 Diversity of Types of Cargo Handled
8.17 Number of Inclusive and Social Policies Implemented

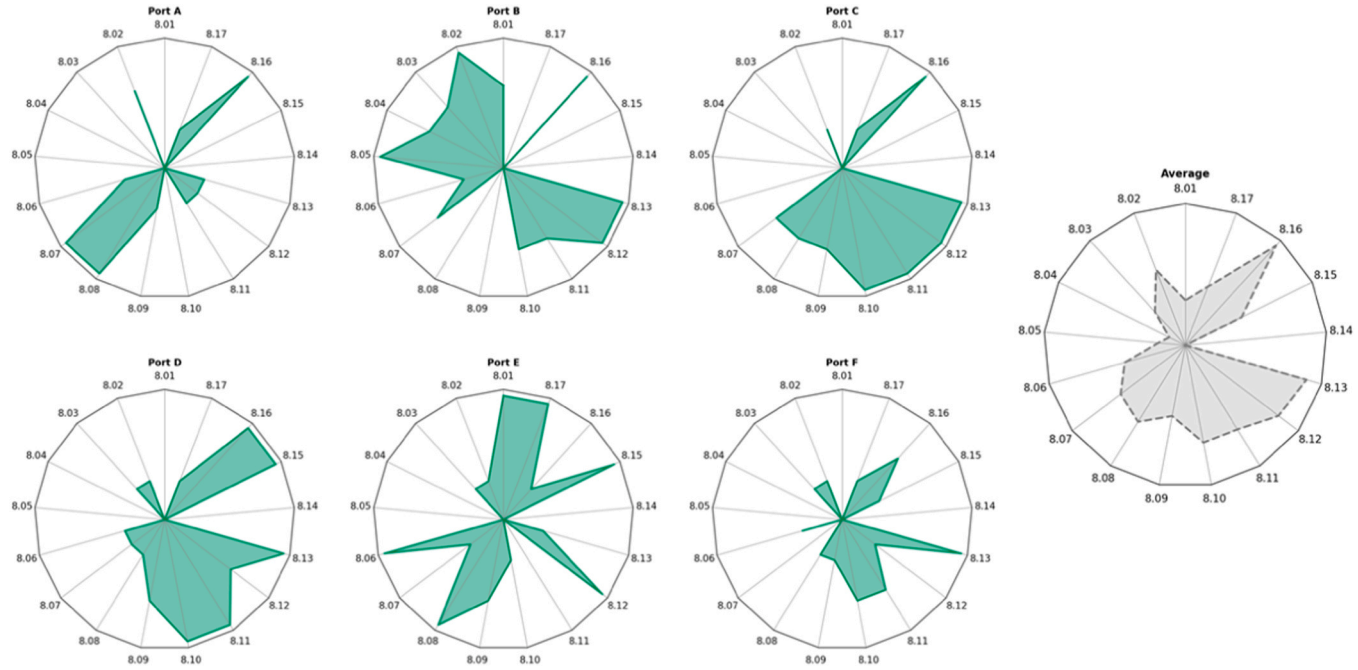

Fig. 4. Indicators linked to SDG 8.

systems, can significantly enhance occupational health and safety practices. Moreover, digital platforms facilitate the delivery of training and awareness programmes, equipping workers with essential knowledge and skills. Digitalised tools also strengthen communication and collaboration among port workers, thereby improving operational efficiency and fostering a safer and more cohesive working environment [25].

SDG 9 (Industry, Innovation, and Infrastructure) seeks to build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation. This goal is measured through specific indicators that track progress in infrastructure development, industrial inclusivity, and advancements in innovation. As such, SDG 9 provides a holistic view of development that balances economic growth with technological and infrastructural advancements, highlighting the importance of creating a robust foundation for sustainable development.

Table 3 provides a comprehensive framework of indicators linked with SDG 9. These indicators establish a structured methodology for evaluating and enhancing efforts to promote sustainable industrialisation, foster innovation, and advance research and technological development. The framework is divided into two key areas.

The first area, Research and Development, encompasses three indicators (9.1, 9.2, and 9.3) that focus on measuring investments, capacity-building, and advancements in research activities. The second area, Innovation and Technology, includes nine indicators (9.4–9.12) that assess the adoption of innovative practices, technological advancements, and infrastructure development to support sustainable growth.

Fig. 5 illustrates that Ports B and A demonstrate strong adherence to SDG 9, whereas the other ports do not prioritise this goal to the same extent. Port B adopts a more comprehensive approach, with a balanced distribution across most indicators, suggesting that it addresses multiple facets of SDG 9 effectively. Similarly, Port A also stands out, exhibiting a broad and balanced distribution across several indicators of SDG 9. This approach indicates that both Port A and Port B address key aspects essential for promoting resilient infrastructure, inclusive industrialisation, and sustainable innovation, which are the core pillars of SDG 9.

The average chart reveals a relatively balanced approach across the indicators, with slightly higher alignment observed in indicators 9.7 (Percentage of automated operations in the port), 9.9 (Number of external researchers from the port institution or university linked to innovation projects), and 9.10 (Number of partner companies in innovation projects).

SDG 9 highlighted Port B and Port A as leaders in innovation initiatives and technology adoption. Nevertheless, other ports lagged behind in research development and partnerships, suggesting a gap in fostering sustainable industrialisation.

Environmental protection is becoming increasingly important. Global warming, air pollution, and greenhouse gas emissions are exerting a detrimental influence on the environment and are likely to continue doing so for future generations. Consequently, there is a

Table 3
Indicators SDG 9.

9.1 Number of patents filed and assigned at the INPI (National Institute of Industrial Property)
9.2 Number of publications in high-impact journals funded by the port
9.3 Number of awards and quality seals related to Innovation
9.4 Position in the port sector innovation ranking
9.5 Average level of innovation maturation per project
9.6 Diversity of knowledge areas in applied research projects
9.7 Percentage of automated operations in the port
9.8 Number of agreements with universities and research centres or funded projects
9.9 Number of external researchers from the Porto institution or university linked to innovation projects
9.10 Number of partner companies in innovation projects
9.11 Number of supported startups focused on innovative solutions
9.12 Number of agreements with other ports or terminals for the promotion of innovation

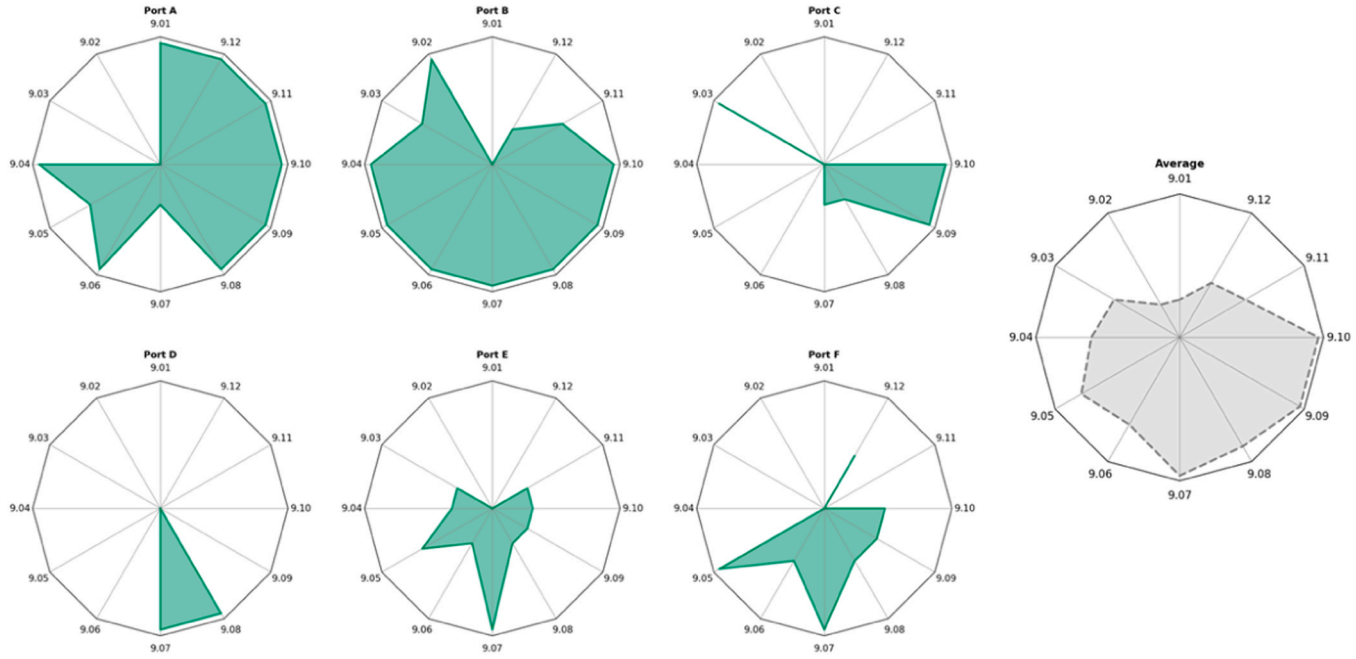

Fig. 5. Indicators linked to SDG 9.

growing imperative to promote environmental sustainability within maritime transport [31]. Aligned with Sustainable Development Goal 9, which emphasises the importance of fostering innovation and building resilient infrastructure, the port sector is witnessing an increasing demand for environmentally driven technological advancements. In this context, investments in innovations such as autonomous vehicles, blockchain technology, knowledge databases, and data-sharing platforms are becoming essential. These technologies not only contribute to environmental protection but also modernise port infrastructure, enhancing operational efficiency and improving the overall quality of services [8].

In alignment with these needs, SDG 11 (Sustainable Cities and Communities) aims to make cities and human settlements inclusive, safe, resilient, and sustainable. This goal is structured around indicators that monitor the progress and effectiveness of urban and regional development initiatives. By focusing on these areas, SDG 11 provides a comprehensive perspective on sustainable urbanisation, balancing environmental, social, and economic dimensions to improve the quality of life for all.

Table 4 outlines a detailed framework of indicators aligned with SDG 11. These indicators provide a structured methodology for assessing and enhancing efforts to create inclusive, safe, resilient, and sustainable urban environments.

The framework is organised into two main areas. The first area, Environmental and Social Impact, comprises two indicators (11.1 and 11.2) that evaluate the extent of investments, capacity-building efforts, and initiatives aimed at mitigating environmental and social challenges within urban settings. The second area, Sustainability and Community, includes five indicators (11.3–11.7) that focus on fostering innovative practices, technological advancements, and community-oriented infrastructure to support sustainable development.

Fig. 6 illustrates that Ports B, E, and F demonstrate a moderate connection to SDG 11. The average chart indicates a relatively balanced approach across the indicators, with slightly higher alignment observed in indicators 11.1 (Number of complaints related to the environmental and social impact of the port), 11.3 (Number of sustainability projects targeted at the community), and 11.7 (Number of community engagement initiatives by the port). These findings reflect a notable focus on specific areas within the collective performance of the ports, highlighting their contributions to sustainable urban development and community engagement.

SDG 11 reflected moderate alignment across most ports, with Ports B, E, and F demonstrating notable community engagement and environmental impact mitigation efforts.

Sustainable cities and communities rely on a reliable supply chain to support their development and resilience. The maritime industry plays a critical role in maintaining global logistics infrastructure by enhancing maritime safety and security, which is essential for sustaining these supply chains [43].

Smart ports must also prioritise community engagement, in line with the objectives of SDG 11, which advocates for inclusive, safe, resilient, and sustainable communities. The use of social media, web-based platforms, and other digital communication tools allows ports to interact more effectively with local populations, disseminate information about ongoing projects, and collect public feedback. These practices foster greater community participation and enhance transparency in port operations [25].

SDG 12 (Responsible Consumption and Production) focuses on

Table 4
Indicators SDG 11.

11.1 Number of Complaints Related to the Environmental and Social Impact of the Port
11.2 Value of the Port Noise Control Index
11.3 Number of sustainability projects targeted at the Community
11.4 Quantity of green areas or public spaces developed or maintained by the Port
11.5 Total value of investments in local community infrastructure (roads, lighting, sanitation, others)
11.6 Number of programmes or partnerships for sustainable mobility
11.7 Number of community engagement initiatives by the Port

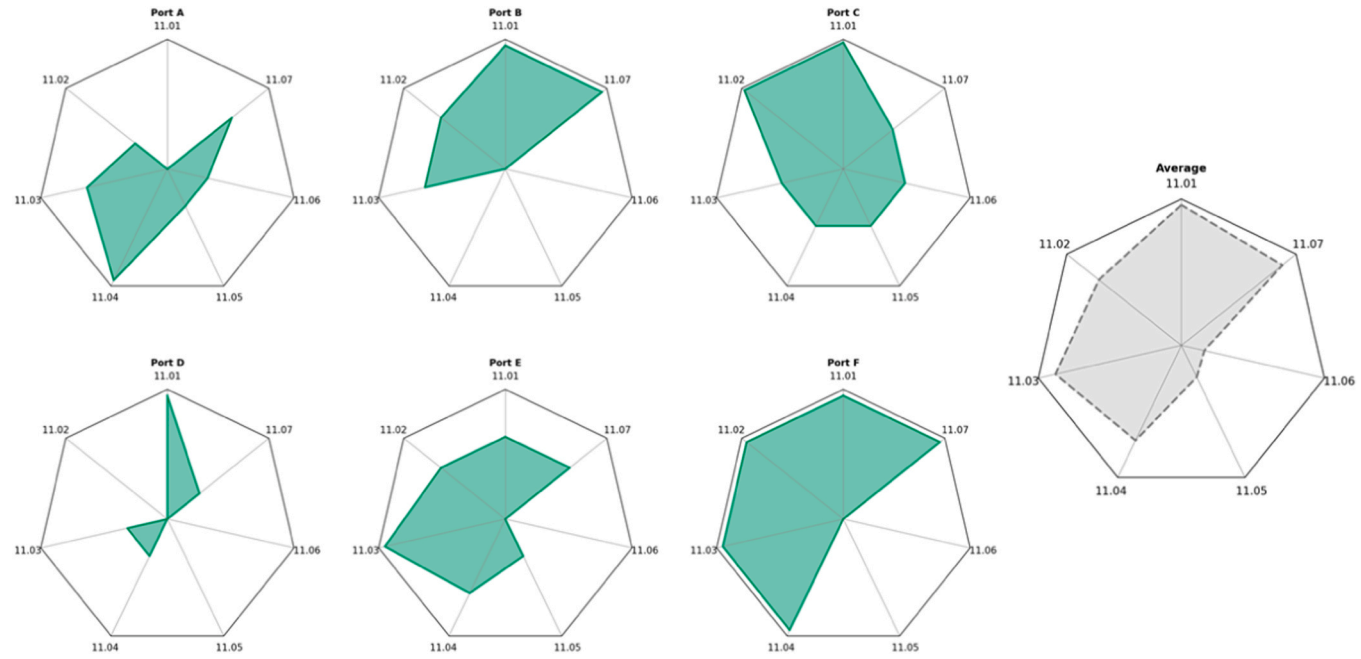

Fig. 6. Indicators linked to SDG 11.

ensuring sustainable consumption and production patterns, aiming to reduce waste and promote efficient use of resources. This goal is structured around indicators that track the progress of sustainable practices and resource efficiency in production processes, with an emphasis on minimising environmental impact. As such, SDG 12 provides a comprehensive view of sustainable development, balancing economic growth with responsible consumption to protect the environment.

Table 5 presents a detailed framework of indicators aligned with SDG 12, offering a structured methodology for evaluating and enhancing efforts to promote sustainable practices, efficient resource use, and reduced environmental impacts. The framework is organised into three main areas.

The first area, Environmental Management, comprises four indicators (12.1–12.4) that assess investments, capacity-building efforts, and initiatives aimed at improving environmental stewardship and addressing sustainability challenges. The second area, Waste Management, includes two indicators (12.5 and 12.6) that focus on innovative waste management practices, technological advancements, and the development of infrastructure to support sustainable consumption and production patterns. The third area, Certifications and Management Systems, encompasses two indicators (12.7 and 12.8) that evaluate the adoption of recognised certifications and the implementation of robust management systems to enhance sustainability performance.

Fig. 7 illustrates that Port E exemplifies a more comprehensive approach, displaying a balanced distribution across most indicators for SDG 12. This suggests that Port E addresses multiple aspects of SDG 12, reflecting a strong commitment to sustainable consumption and production practices. Additionally, Ports B and D demonstrate a moderate connection to SDG 12, with greater participation from other ports also observed in relation to this SDG.

The average chart reveals a relatively balanced approach across the indicators, with slightly higher alignment observed in indicators 12.7 (Use of Environmental Management System) and 12.8 (ISO 14000 Certification Status).

SDG 12 indicated a growing commitment, especially in environmental management and ISO certification, with Port E exhibiting the strongest overall alignment.

Table 6 presents a comprehensive framework of indicators linked with SDG 13 (Climate Action), providing a structured methodology for assessing and enhancing efforts to address climate change, promote sustainable practices, and reduce environmental impacts. The framework is organised into two main areas.

The first area, Climate Strategies, comprises five indicators (13.1–13.5) that evaluate strategic investments, capacity-building initiatives, and programmes aimed at mitigating climate-related risks and improving environmental stewardship. These indicators focus on fostering resilience, advancing adaptation measures, and implementing effective climate policies. The second area, Infrastructure and Operations, includes three indicators (13.6–13.8) that assess the integration of technological advancements, innovative operational practices, and the development of infrastructure designed to support sustainability goals and reduce greenhouse gas emissions.

Fig. 8 highlights that, similar to SDG 7, SDG 13 receives relatively little attention from the ports surveyed. However, Ports F, A, and B demonstrate a higher-than-average focus on this SDG. The average chart reveals stronger alignment with indicators 13.2 (Emissions Inventory) and 13.4 (Climate Monitoring Programme), reflecting a predominance of interest in these specific areas. This limited engagement with SDG 13

Table 5
Indicators SDG 12.

12.1 Air Pollutant Concentration Value
12.2 Total Volume of Water Used
12.3 Total Volume of Water Reused
12.4 Number of Internally Recorded Environmental Accidents
12.5 Amount of Waste Generated
12.6 Percentage of Waste Recycled and/or Reused
12.7 Use of Environmental Management System
12.8 ISO 14000 Certification Status

Fig. 7. Indicators linked to SDG 12.

Table 6
Indicators SDG 13.

13.1 Status of Climate Change Strategy Plan
13.2 Emissions Inventory
13.3 Carbon Credit Management Programme
13.4 Climate Monitoring Programme
13.5 Number of Collaborations and Partnerships for Climate Action
13.6 Climate-Resilient Infrastructure
13.7 Cargo Traffic Efficiency Index
13.8 Percentage Reduction of Emissions Through New Technology Implementation

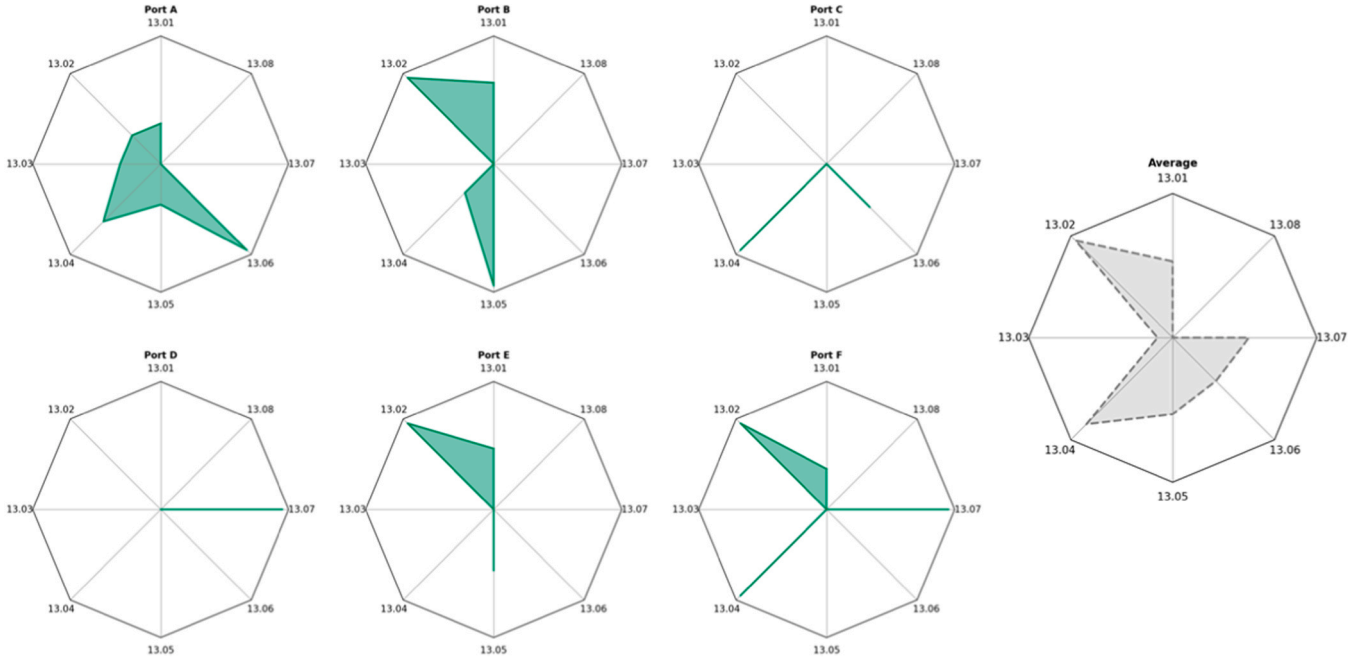

Fig. 8. Indicators linked to SDG 13.

suggests that while some ports are addressing climate-related challenges, there is significant room for improvement in integrating comprehensive climate action across the sector.

SDG 13 revealed significant weaknesses, with most ports displaying limited integration of climate resilience strategies and carbon management practices, highlighting a major area for strategic enhancement. Maritime ports and the shipping industry face a wide range of impacts resulting from marine hazards and extreme weather events. Among these, more intense rainfall can cause delays in the loading and unloading of cargo, while the increased frequency of storms has the potential to disrupt port activities, increasing risks to navigation and docking manoeuvres [22,29]. These challenges underscore the critical need for ports to integrate resilience measures and climate action into their operational strategies.

SDG 14 (Life Below Water) aims to conserve and sustainably use marine resources, emphasising the importance of responsibly managing marine and coastal ecosystems to minimise significant adverse impacts. This SDG can be divided into three key areas: coastal monitoring, resource management and protected areas, and marine investment and research. By addressing these areas, ports can play a pivotal role in safeguarding marine biodiversity and promoting sustainable practices.

Table 7 outlines a comprehensive framework of indicators consistent with SDG 14, offering a structured methodology for evaluating and enhancing efforts to protect marine ecosystems, promote sustainable practices, and minimise environmental impacts. The framework is organised into three key areas.

The first area, Coastal Monitoring, comprises four indicators (14.1–14.4) that evaluate strategic investments, capacity-building initiatives, and programmes aimed at mitigating risks to coastal environments and enhancing resilience. These indicators focus on advancing adaptation strategies, improving environmental stewardship, and implementing effective policies to safeguard coastal ecosystems.

The second area, Management of Resources and Protected Areas, includes two indicators (14.5 and 14.6) that assess the integration of technological innovations, the adoption of sustainable operational practices, and the development of infrastructure to support marine conservation and the sustainable use of resources.

The third area, Investment and Research in Marine Science, encompasses two indicators (14.7 and 14.8) that focus on promoting scientific research, fostering technological advancements, and supporting the implementation of robust management systems to enhance sustainability performance in marine environments.

Fig. 9 illustrates that Port F exemplifies a comprehensive approach, with a balanced distribution across most indicators. This reflects a strong commitment to various aspects of marine conservation and sustainable resource management, demonstrating proactive efforts to align with the objectives of SDG 14. Similarly, Ports D and B also perform well on this SDG, showcasing notable efforts to address marine sustainability through targeted initiatives.

The average chart highlights higher alignment with indicators 14.3 (Quality of marine sediment, in accordance with regional legislation), 14.2 (Average concentration of pollutants in coastal water, in accordance with regional legislation), and 14.1 (Number of invasive exotic species registered). These findings suggest a collective focus on monitoring and improving key environmental parameters, reinforcing the importance of safeguarding marine ecosystems as a critical component of port operations.

SDG 14 was prioritised by Ports F, D, and B, which showed strong efforts in monitoring coastal and marine ecosystems. Focus on ballast water management and marine research investment, however, remains insufficient across the sample.

Investment in and research on marine monitoring are both essential and timely. A recent study of Brazilian ports reveals persistent gaps in key areas, including environmental noise monitoring, the protection of Permanent Preservation Areas (PPAs) such as mangroves, and the limited application of Environmental DNA (eDNA) techniques for biodiversity assessment. Strengthening efforts in these domains could significantly improve the sector's environmental management capacity, support more effective ecosystem conservation, and enhance the quality of environmental data [5].

SDG 17 (Partnerships for the Goals) emphasises the importance of partnerships and global cooperation in the pursuit of sustainable development. It recognises that achieving the other 16 goals is intrinsically linked to mobilising means of implementation, which extend beyond financial resources to include technology and capacity building. This SDG can be divided into three key areas: commitments and certifications, reporting and communication, and governance and partnerships.

Table 8 outlines a comprehensive framework of indicators consistent with SDG 17, providing a structured methodology for evaluating and enhancing collaborative efforts, promoting sustainable practices, and minimising environmental impacts. The framework is organised into three key areas.

The first area, Commitments and Certifications, comprises three indicators (17.1–17.3) that assess strategic investments, capacity-building initiatives, and commitments to internationally recognised standards and certifications. These indicators focus on fostering resilience, strengthening institutional capacities, and advancing policies that enhance environmental stewardship and align with global sustainability objectives.

The second area, Reports and Communications, includes four indicators (17.4–17.7) that evaluate the effectiveness of sustainability reporting, transparency in communication, and the adoption of innovative tools and practices to support data-driven decision-making. This area emphasises the importance of accurate reporting and open dialogue in promoting accountability and driving sustainable development.

The third area, Governance and Partnerships, encompasses three indicators (17.8–17.10) that assess the establishment of collaborative frameworks, the integration of robust governance mechanisms, and the implementation of management systems designed to improve sustainability performance and foster global partnerships.

Fig. 10 highlights a greater balance in the adoption of SDG 17 among the ports studied, particularly for Ports B, A, E, and F. Port B stands out with a comprehensive and balanced approach across most indicators, demonstrating strong engagement with various aspects of SDG 17. This performance suggests that Port B prioritises global cooperation and effective governance, which are essential elements for fostering sustainable partnerships.

The average chart reveals higher alignment with indicators 17.5 (Disclosure of the position in the IDA) and 17.7 (Recording and

Table 7
Indicators SDG 14.

14.1 Number of invasive exotic species registered
14.2 Average concentration of pollutants in coastal water, in accordance with regional legislation
14.3 Quality of marine sediment, in accordance with regional legislation
14.4 Number of environmental events recorded on the coast of the region
14.5 Monitoring of ballast water
14.6 Total area of marine habitats protected in the port's area of operation
14.7 Total value invested in sustainable marine resource research
14.8 Number of marine research projects funded by the port

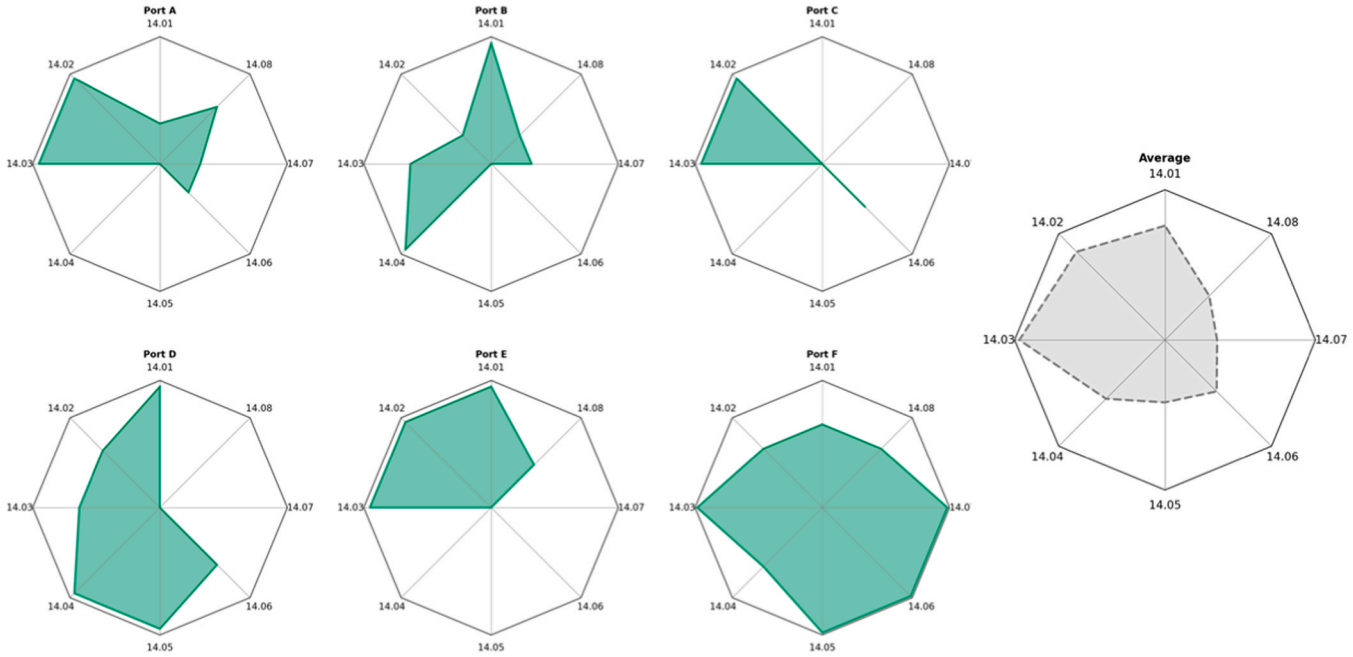

Fig. 9. Indicators linked to SDG 14.

Table 8
Indicators SDG 17.

17.1 Status as a signatory of the UN Global Compact
17.2 Alignment of the SDGs with IDA and GRI indicators
17.3 Existence of ECOPORTS certification
17.4 Publication of the sustainability report
17.5 Disclosure of the position in the IDA
17.6 Publication of sustainability indicators
17.7 Recording and communication of environmental incidents
17.8 Number of independent members on the board of directors
17.9 Number of partnerships established with NGOs and other entities for sustainability initiatives
17.10 Listing of active communication channels with stakeholders

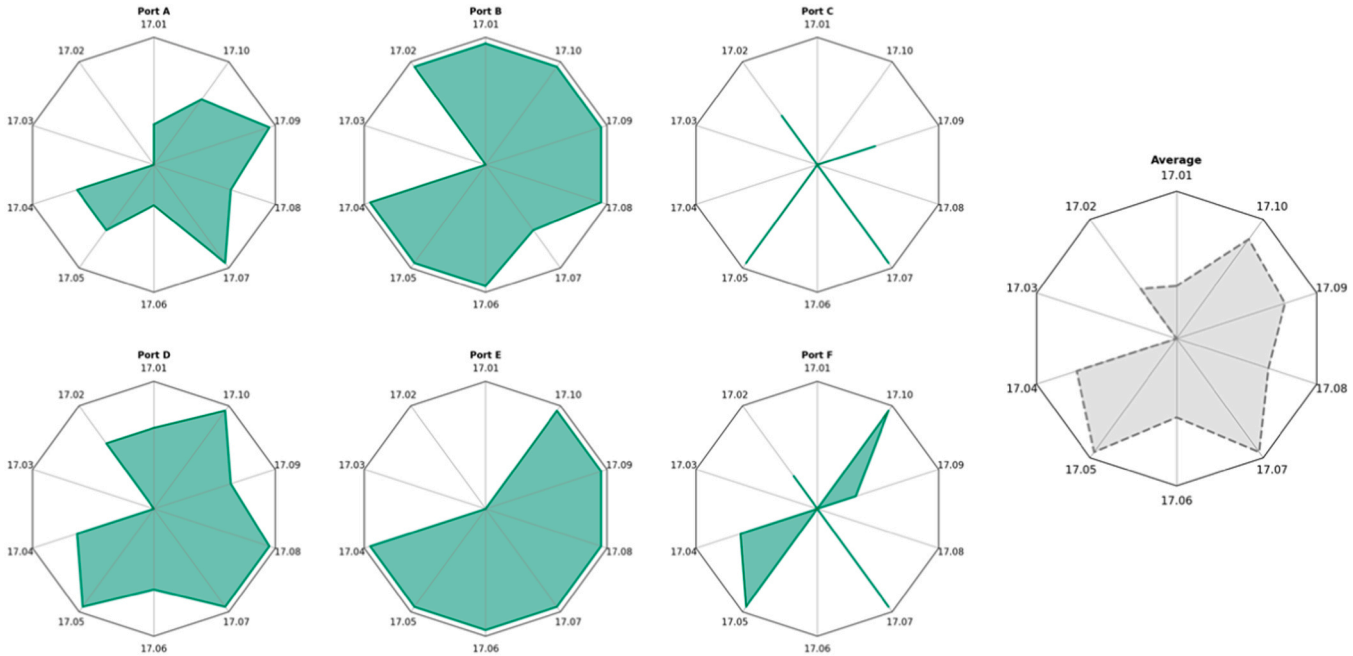

Fig. 10. Indicators linked to SDG 17.

communication of environmental incidents), emphasising a collective focus on governance structures, reporting practices, and strategic partnerships across the ports. These efforts highlight the importance of collaboration and transparency in advancing the objectives of SDG 17.

SDG 17 plays a crucial role in advancing sustainability within the port sector. By fostering partnerships, it promotes a holistic approach that broadens the scope of sustainability beyond environmental factors to encompass economic, social, and governance dimensions. This inclusive perspective is essential for aligning port operations with all aspects of sustainable development, facilitating a balanced integration of the Sustainable Development Goals [3,8,18,1].

Given the interconnected nature of the SDGs, a holistic approach is essential, as ports increasingly recognise the value of addressing how individual SDGs can reinforce one another. This integrated perspective fosters sustainability practices that not only generate direct benefits but also leverage emerging synergies, thus contributing meaningfully to the global sustainability agenda [8].

The partnerships encouraged by SDG 17 enable ports to leverage shared knowledge, resources, and technology, enhancing their capacity to address complex challenges, including emissions reduction, which is crucial for advancing decarbonisation efforts. Collaboration with diverse stakeholders provides the port sector with the support and innovation needed to implement sustainable practices effectively. Through these partnerships, ports can drive impactful, multi-dimensional sustainability initiatives that support their transformation into more resilient and responsible economic entities.

SDG 17 emerged as the most consistently addressed SDG, with Ports B, A, E, and F particularly active in establishing partnerships, enhancing transparency, and improving governance structures.

The heatmaps of SDG indicators reveal a predominance of red cells across multiple targets, indicating significant data gaps in several areas. Notably, SDGs 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), and 13 (Climate Action) display a lower density of reported indicators, suggesting limited engagement or availability of information related to these goals. In particular, SDGs 13 and 7 appear to be comparatively underrepresented, underscoring critical dimensions that require increased attention within port sustainability strategies (Fig. 11).

A stronger focus on these goals would enhance the role of ports in advancing clean energy transitions and building climate resilience. To address these gaps, future research should explore actionable pathways to reinforce port commitments, including investments in low-carbon infrastructure, the deployment of renewable energy solutions, and the integration of climate adaptation measures tailored to local environmental risks.

In alignment with this concern, a study evaluating the adoption of sustainability initiatives across 36 major ports in North America, Europe, and Asia-Pacific, based on 25 predefined indicators, revealed that climate change adaptation (25 %) and the use of renewable energy were among the least implemented actions. Nevertheless, the Port of Los Angeles and the Port of Gothenburg distinguished themselves by adopting 23 out of the 25 indicators, demonstrating higher levels of commitment to sustainability practices [18].

5. Conclusions

This paper presented a specialised model tailored to the port sector, addressing a critical gap in the literature by proposing a sustainability index linked with the Sustainable Development Goals (SDGs) and applying it to a sample of six Brazilian ports. The model integrates SDGs 7, 8, 9, 11, 12, 13, 14, and 17, establishing connections across 20 key thematic areas that reflect the unique operational, environmental, and social characteristics of the maritime sector. This approach provided a comprehensive and sector-specific framework for evaluating sustainability performance, ensuring that the selected SDGs could be meaningfully operationalised within port management practices.

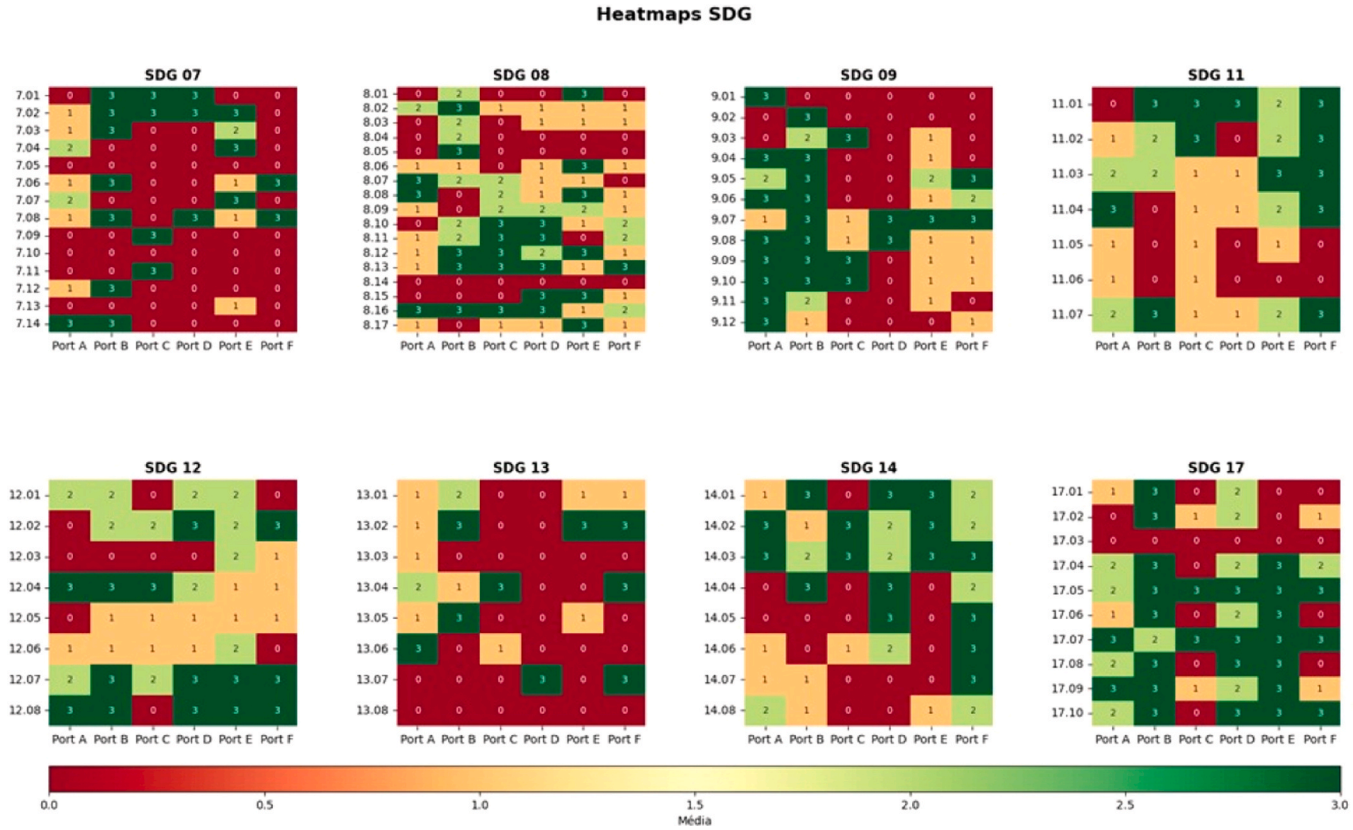

Fig. 11. Heatmaps of SDG Indicators Across Analysed Ports.

The resulting port sustainability index identified strategic areas of focus, including renewable energy for vessels, decent work and economic growth, innovation, climate planning, investment in marine research, environmental certifications, international agreements, governance, and multi-stakeholder partnerships. Among the analysed ports, Ports B and E demonstrated broader alignment with key sustainability dimensions, achieving the highest overall scores and reflecting comparatively stronger sustainability performance.

Notably, SDGs 17 (Partnerships for the Goals) and 12 (Responsible Consumption and Production) received the highest average scores across the sample. In the port context, partnerships are pivotal in addressing complex sustainability challenges, such as carbon emission reduction, resource efficiency, and community engagement. By fostering collaborative networks among government bodies, private sector actors, and local communities, ports can mobilise shared resources, knowledge, and technologies to implement more effective and impactful sustainability strategies.

The SDGs 13 (Climate Action) and 7 (Affordable and Clean Energy) were comparatively underrepresented in the data, underscoring critical areas that merit increased attention within port sustainability initiatives. Greater focus on these dimensions would enhance ports' contributions to clean energy transitions and climate resilience. Future research should explore actionable pathways for strengthening port commitments in these areas, including investment in low-carbon infrastructure and adaptation strategies for climate-related risks.

The principal aim of this study was to provide a practical yet analytically robust tool to support decision-making within the port sector. By enhancing stakeholders' understanding of the relationships between port-specific sustainability indicators and the SDGs, the proposed model offers a valuable framework for guiding sustainability assessment and strategic planning. Furthermore, the model's flexibility allows for potential adaptation across different sectors and contexts, both nationally and internationally.Nonetheless, several methodological limitations must be acknowledged. The model did not encompass all 17 SDGs. Rather, a deliberate selection was made to prioritise those most relevant to the port sector while maintaining feasibility, given the inclusion of 84 indicators. This decision reflects a balance between analytical depth and practical applicability, aiming to encourage implementation without imposing excessive resource burdens on port authorities.

The sample, composed of six ports and terminals representing approximately 30 % of Brazil's total throughput, may not capture the full diversity of the national port system. Notably, the absence of ports from the North region limits the geographical scope. The study primarily engaged port authorities and terminal operators, with limited input from other key stakeholders such as civil society organisations, environmental groups, and trade unions. This restricted engagement may have constrained the depth of analysis, particularly concerning the social and governance dimensions of sustainability.

To address these limitations, future research should seek to expand the sample to encompass a more diverse range of ports across all Brazilian regions. A stratified sampling approach would improve representativeness, while a longitudinal design would enable the tracking of sustainability performance over time and facilitate the identification of emerging trends in SDG integration.

Moreover, methodological triangulation, incorporating structured questionnaires, semi-structured interviews, document analysis, and field observations, would enhance data validity and richness. Broader stakeholder involvement, including academia, industry representatives, and local communities, is essential to capture the multifaceted nature of port sustainability.

Finally, comparative analyses with international ports recognised for sustainability excellence could provide valuable benchmarks, helping Brazilian ports contextualise their progress and adopt best practices aligned with global standards.

In conclusion, this study represents a significant step towards embedding the SDGs within the operational and strategic fabric of the port sector. By bridging conceptual frameworks with practical implementation, the proposed sustainability index offers a clear pathway for ports to advance their sustainability agendas and contribute meaningfully to the broader transformation towards a more inclusive, resilient, and sustainable maritime industry.

CRediT authorship contribution statement

Markus Dannyllo Carneiro Costa: Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Clóvis Bôsco Mendonça Oliveira:** Supervision, Conceptualization. **Darliane Ribeiro Cunha:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Newton Narciso Pereira:** Writing – review & editing, Writing – original draft, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Annex I. SDG Attributes

SDG 7	
Area: Energy Efficiency	
7.1 Number of awareness programmes on rational energy use	0: No programme in operation. 1: Up to 2 programmes in operation, reaching up to 100 people. 2: 3–5 programmes in operation, reaching 101–500 people. 3: More than 5 programmes in operation, reaching over 500 people.
7.2 Number of energy efficiency management programmes	0: No programme in operation. 1: At least one programme, resulting in up to 5 % reduction in energy consumption. 2: At least one programme, resulting in a reduction greater than 5 % and less than or equal to 10 % in energy consumption 3: At least one programme with energy consumption reductions exceeding 10 %.

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7.3 Number of technological innovation initiatives in energy efficiency	0: No initiative. 1: Up to 2 technological initiatives implemented. 2: 3–5 technological initiatives implemented. 3: More than 5 initiatives implemented.
Area: Renewable Energy in port facilities	
7.4 Percentage of renewable energy contracted and produced in port facilities	0: No use of renewable energy. 1: Up to 10 % of the energy used is renewable. 2: More than 10 % up to 50 % of the energy used is renewable. 3: More than 50 % of the energy used is renewable.
7.5 Percentage of biofuels in electrical and mechanical loads	0: No use of biofuels. 1: Less than 5 % of the loads are operated with biofuels. 2: 5–20 % of the loads are operated with biofuels. 3: More than 20 % of the loads are operated with biofuels.
7.6 Number of technological innovation initiatives in renewable energy	0: No initiative. 1: Up to 2 initiatives in the planning or pilot phase. 2: 3–5 initiatives in the implementation phase with preliminary results. 3: More than 5 initiatives in full operation with proven results.
7.7 Diversity of renewable energy sources in port facilities	0: No use of renewable sources. 1: Use of 1 different type of renewable energy. 2: Use of 2 different types of renewable energy. 3: Use of 3 or more different types of renewable energy.
7.8 Number of partnerships for the promotion of clean energy	0: No partnership established. 1: Up to 2 partnerships established with a focus on clean energy. 2: 3–5 partnerships established with a focus on clean energy. 3: More than 5 partnerships established with a focus on clean energy.
7.9 Number of charging stations for electric vehicles	0: No charging station available. 1: Up to 5 charging stations available. 2: 6–15 charging stations available. 3: More than 15 charging stations available.
Area: Renewable Energy on ships	
7.10 Percentage of renewable energy supply to ships	0: No supply of renewable energy to ships. 1: Less than 10 % of the energy supply to ships comes from renewable sources. 2: Between 10 % and 30 % of the energy supply to ships comes from renewable sources. 3: More than 30 % of the energy supply to ships comes from renewable sources.
7.11 Percentage of LNG fuelling	0: No LNG fuelling. 1: Less than 5 % of the total fuel supply is with LNG. 2: Between 5 % and 20 % of the total fuel supply is with LNG. 3: More than 20 % of the total fuel supply is with LNG.
7.12 Number of technological innovation initiatives in electrical and energy services for ships	0: No initiative. 1: Up to 2 technological innovation initiatives in planning or pilot phase. 2: 3–5 initiatives in the implementation or efficacy evaluation phase. 3: More than 5 initiatives in full operation, with proven efficacy results.
7.13 Number of ships using renewable energy in the port	0: No ships use renewable energy. 1: Up to 5 % of the ships in the port use renewable energy. 2: 5–15 % of the ships in the port use renewable energy. 3: More than 15 % of the ships in the port use renewable energy.
7.14 Differentiated tariffs for ships performing above environmental standards	0: No application of differentiated tariffs. 1: Up to 5 % discount on port tariffs. 2: 5–15 % discount on port tariffs. 3: More than 15 % discount on port tariffs.
SDG 8	
Area: Decent Work	
8.1 Absences due to health-related absenteeism	0: Absences greater than 5 % of total worked hours. 1: Absences between 3 % and 5 %. 2: Absences between 1 % and 3 %. 3: Absences less than 1 %.
8.2 Leave due to occupational diseases	0: Leave greater than 10 cases per 100 employees. 1: Leave between 6 and 10 cases. 2: Leave between 2 and 5 cases. 3: Leave less than 2 cases.
8.3 Leave due to accidents	0: Leave greater than 10 cases per 100 employees. 1: Leave between 6 and 10 cases. 2: Leave between 2 and 5 cases. 3: Leave less than 2 cases.
8.4 Number of accidents	0: Accidents greater than 15 per 100 employees. 1: Accidents between 10 and 15. 2: Accidents between 5 and 10. 3: Accidents less than 5.
8.5 Fatal accidents	0: Any fatal accident. 1: No fatal accidents, but high rate of serious accidents (> 5 per 100 employees). 2: Low rate of serious accidents (1–5 per 100 employees). 3: No serious accidents
8.6 Percentage of local workers in management positions	0: Menos de 20 %. 1: Entre 20 % e 30 %. 2: Entre 30,1 % e 40 %. 3: Mais de 50 %.

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8.7 Percentage of female employees	0: Less than 20 %. 1: Greater than or equal to 20 % and less than 30 %. 2: Greater than or equal to 30 % and less than 50 %. 3: Greater than or qual to 50 %.
8.8 Percentage of young employees (14–24 years old)	0: Less than 5 %. 1: Greater than or equal to 5 % and less than 10 %. 2: Greater than or equal to 10 % and less than 15 %. 3: Greater than or equal to 15 %.
8.9 Percentage of employees with disabilities	0: Less than 2 %. 1: Greater than or equal to 2 % and less than 4 %. 2: Greater than or equal to 4 % and less than 6 %. 3: Greater than or equal to 6 %.
Area: Economic Growth	
8.10 Annual Revenue Growth Rate Adjusted for Inflation	0: Real growth $<$ 1 % or negative. 1: Real growth between 1 % and 4 %. 2: Real growth between 5 % and 8 %. 3: Real growth $>$ 8 %.
8.11 Port Revenue Target	0: No port revenue target set. 1: More than 2 % below the target. 2: Between 2 % below and 2 % above the target. 3: More than 2 % above the target.
8.12 EBITDA Margin Value	0: No EBITDA target set. 1: More than 2 % below the target. 2: Between 2 % below and 2 % above the target. 3: More than 2 % above the target.
8.13 Quantity of Tons Handled	0: No target stipulated. 1: More than 2 % below the target. 2: Between 2 % below and 2 % above the target. 3: More than 2 % above the target.
8.14 Revenue per Employee	0: No target stipulated. 1: More than 2 % below the target. 2: Between 2 % below and 2 % above the target. 3: More than 2 % above the target.
8.15 Position in the ANTAQ Cargo Movement Ranking	0: No target stipulated. 1: More than 2 % below the target. 2: Between 2 % below and 2 % above the target. 3: More than 2 % above the target.
8.16 Diversity of Types of Cargo Handled	0: No monitoring of cargo types. 1: Between 1 and 3 types. 2: Between 4 and 6 types. 3: More than 6 types.
8.17 Number of Inclusive and Social Policies Implemented	0: No policies in place. 1: Between 1 and 5 policies. 2: Between 6 and 10 policies. 3: More than 10 policies.
SDG 9	
Area: Research and Development	
9.1 Number of patents filed and assigned at the INPI (National Institute of Industrial Property)	0: No patents filed in the year. 1: Up to 2 patents filed in the year, with patents assigned. 2: 3–5 patents filed in the year, with patents assigned. 3: More than 5 patents filed in the year, with patents assigned.
9.2 Number of publications in high-impact journals funded by the port	0: No initiatives or significant results. 1: Up to 2 publications in high-impact journals. 2: 3–5 publications in high-impact journals. 3: More than 5 publications in high-impact journals.
9.3 Number of awards and quality seals related to Innovation	0: No initiatives or significant results. 1: Receipt of up to 2 awards or quality seals in innovation. 2: Receipt of 3–5 awards or quality seals in innovation. 3: Receipt of more than 5 awards or quality seals in innovation.
Area: Innovation and Technology	
9.4 Position in the port sector innovation ranking	0: Position in the fourth quartile in the innovation ranking. 1: Position in the third quartile in the innovation ranking. 2: Position in the second quartile in the innovation ranking. 3: Position in the first quartile in the innovation ranking.
9.5 Average level of innovation maturation per project	0: No project. 1: Projects in the initial concept or development phase with low level of maturation. 2: Projects in the prototyping or pilot stage with medium level of maturation. 3: Projects with final products or implemented solutions with a high level of technological maturity (Technology Readiness Levels).
9.6 Diversity of knowledge areas in applied research projects	0: No knowledge areas involved in the projects. 1: Up to 2 knowledge areas involved in the projects. 2: 3–5 different knowledge areas involved in the projects. 3: More than 5 different knowledge areas involved in the projects.
9.7 Percentage of automated operations in the port	0: No automated operations. 1: Up to 25 % of operations automated. 2: 25–50 % of operations automated. 3: More than 50 % of operations automated.

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9.8 Number of agreements with universities and research centres or funded projects	0: No agreement or project. 1: Up to 2 agreements or projects. 2: 3–5 agreements or established projects. 3: More than 5 agreements or projects.
9.9 Number of external researchers from the Porto institution or university linked to innovation projects	0: No external researcher linked. 1: Up to 3 external researchers linked. 2: 4–6 external researchers linked. 3: More than 6 external researchers linked.
9.10 Number of partner companies in innovation projects	0: No partner companies. 1: Up to 2 partner companies involved. 2: 3–5 partner companies involved. 3: More than 5 partner companies with effective collaboration and significant contributions.
9.11 Number of supported startups focused on innovative solutions	0: No startup. 1: Support to up to 2 startups. 2: Support to 3–5 startups. 3: Support to more than 5 startups.
9.12 Number of agreements with other ports or terminals for the promotion of innovation	0: No agreement. 1: Up to 2 agreements. 2: 3–5 agreements. 3: More than 5 agreements.
SDG 11	
Area: Environmental and Social Impact	
11.1 Number of Complaints Related to the Environmental and Social Impact of the Port	0: More than 10 annual complaints. 1: 5–10 annual complaints, with mitigation actions. 2: 2–4 annual complaints, with mitigation actions. 3: Up to 1 annual complaint, with mitigation actions.
11.2 Value of the Port Noise Control Index	0: No measurement of the index. 1: Index above the legally permitted limit. 2: Index within the legally permitted limits. 3: Index 10 % below the legally permitted limit.
Area: Sustainability and Community	
11.3 Number of sustainability projects targeted at the Community	0: No project. 1: Up to 2 ongoing projects. 2: 3–5 ongoing projects, with initial proven impact. 3: More than 5 ongoing projects, with significant and sustainable proven
11.4 Quantity of green areas or public spaces developed or maintained by the Port	0: No green area. 1: Less than 10 % of the total space. 2: 10–30 % of the total space. 3: More than 30 % of the total space.
11.5 Total value of investments in local community infrastructure (roads, lighting, sanitation, others)	0: No investments. 1: Total investment represents less than 5 % of the Port's budget. 2: Total investment represents 5–10 % of the Port's budget. 3: Total investment represents more than 10 % of the Port's budget.
11.6 Number of programmes or partnerships for sustainable mobility	0: No programme. 1: Up to 2 programmes or established partnerships. 2: 3–5 programmes or established partnerships. 3: More than 5 programmes or established partnerships.
11.7 Number of community engagement initiatives by the Port	0: No initiative. 1: Up to 3 engagement initiatives. 2: 4–6 engagement initiatives. 3: More than 6 engagement initiatives with broad coverage, high community participation.
SDG 12	
Area: Environmental Management	
12.1 Air Pollutant Concentration Value	0: No pollutant measurement. 1: Pollutant concentrations up to 10 % above established standards. 2: Pollutant concentrations within established standards. 3: Pollutant concentrations 10 % below established standards.
12.2 Total Volume of Water Used	0: No control over water use. 1: Water use above the granted limit. 2: Water use equal to the granted limit. 3: Water use 10 % below the granted limit.
12.3 Total Volume of Water Reused	0: No water reuse. 1: Less than 10 % of the total water used is reused. 2: Between 10 % and 25 % of the total water used is reused. 3: More than 25 % of the total water used is reused.
12.4 Number of Internally Recorded Environmental Accidents	0: No measurements for recording environmental accidents. 1: Two or more accidents recorded in the year. 2: One accident recorded in the year. 3: No environmental accident recorded in the year.
Area: Waste Management	
12.5 Amount of Waste Generated	0: No waste management system. 1: Reduction of up to 5 % in waste generation compared to the previous year. 2: Reduction of 5–10 % in waste generation compared to the previous year. 3: Reduction of more than 10 % in waste generation compared to the previous year.
12.6 Percentage of Waste Recycled and/or Reused	0: No recycling and/or reuse of waste. 1: Less than 30 % of the generated waste is recycled and/or reused.

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	2: 30–60 % of the generated waste is recycled and/or reused. 3: More than 60 % of the generated waste is recycled and/or reused.
Area: Certifications and Management Systems	
12.7 Use of Environmental Management System	0: No system implemented. 1: System implemented but not fully integrated into daily operations. 2: System implemented and partially integrated into daily operations. 3: System fully implemented and integrated into daily operations.
12.8 ISO 14000 Certification Status	0: No certification initiative. 1: Not certified or in the process of obtaining certification. 2: Certified, but without annual reviews or continuous improvements. 3: Certified with annual reviews and continuous improvements implemented.
SDG 13	
Area: Climate Strategies and Planning	
13.1 Status of Climate Change Strategy Plan	0: No strategies. 1: Strategy plan under development, no actions implemented. 2: Strategy plan implemented, with some actions in practice. 3: Fully operational strategy plan, with regular review and updates.
13.2 Emissions Inventory	0: Emissions inventory not carried out. 1: Emissions inventory conducted, but outdated. 2: Emissions inventory conducted, updated more than a year ago. 3: Emissions inventory updated annually and actively used for emissions management.
13.3 Carbon Credit Management Programme	0: No Carbon Credit Programme. 1: Programme in initial phase, without credits generated or purchased. 2: Active programme, with carbon credits being generated or purchased. 3: Well-established programme, with carbon credits being actively managed.
13.4 Climate Monitoring Programme	0: Non-existent programme. 1: Programme in implementation phase. 2: Programme implemented, but data used in a limited way. 3: Programme implemented and integrated into a climate response and planning system.
13.5 Number of Collaborations and Partnerships for Climate Action	0: No collaboration or partnership established. 1: Up to 2 collaborations or partnerships established. 2: 3–5 collaborations or partnerships with initial results. 3: More than 5 collaborations or partnerships with significant and measurable impact on climate action.
Area: Infrastructure and Operations	
13.6 Climate-Resilient Infrastructure	0: No infrastructure assessed as climate resilient. 1: Less than 25 % of infrastructure assessed as climate resilient. 2: 25–50 % of infrastructure assessed as climate resilient. 3: More than 50 % of infrastructure assessed as climate-resilient and adapted.
13.7 Cargo Traffic Efficiency Index	0: Index not calculated. 1: Efficiency index below the industry average. 2: Efficiency index at the industry average. 3: Efficiency index above the industry average, with continuous improvements.
13.8 Percentage Reduction of Emissions Through New Technology Implementation	0: No emission reduction programmes. 1: Less than 5 % reduction in emissions through new technologies. 2: 5–10 % reduction in emissions through new technologies. 3: More than 10 % reduction in emissions through new technologies.
SDG 14	
Area: Coastal Monitoring	
14.1 Number of invasive exotic species registered	0: No programme for identifying species. 1: Identification of a number of invasive species in the region greater than in the previous period. 2: Identification of a number of invasive species in the region equal to the previous period. 3: Identification of a number of invasive species in the region fewer than in the previous period.
14.2 Average concentration of pollutants in coastal water, in accordance with regional legislation.	0: No measurements of pollutants in the water. 1: Pollutant concentrations more than 10 % above the established standards. 2: Pollutant concentrations within the established standards. 3: Pollutant concentrations 10 % below the established standards.
14.3 Quality of marine sediment, in accordance with regional legislation.	0: No assessments of sediment quality. 1: Sediment quality below acceptable standards, with the presence of contaminants. 2: Sediment quality within acceptable standards. 3: Sediment quality above standards, with low levels of contaminants.
14.4 Number of environmental events recorded on the coast of the region	0: No monitoring of events. 1: More than 5 environmental events recorded in the year. 2: 2–5 environmental events recorded in the year. 3: 0–1 environmental event recorded in the year, with rapid and effective responses.
Area: Management of Resources and Protected Areas	
14.5 Monitoring of ballast water	0: No monitoring in place. 1: Inconsistent monitoring. 2: Regular monitoring. 3: Systematic monitoring.
14.6 Total area of marine habitats protected in the port's area of operation	0: No protection programmes in place. 1: Less than 10 % of marine habitats are under protection. 2: 10–25 % of marine habitats are under protection. 3: More than 25 % of marine habitats are under protection, with active conservation programmes.
Area: Investment and Research in Marine Science	
14.7 Total value invested in sustainable marine resource research	0: No investments. 1: Investment less than 5 % of the total research budget.

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	2: Investment of 5–10 % of the total research budget. 3: Investment greater than 10 % of the total research budget.
14.8 Number of marine research projects funded by the port	0: No projects. 1: Up to 2 projects funded in the year. 2: 3–5 projects funded in the year. 3: More than 5 projects funded in the year, with collaborations from HEIs or research.
SDG 17	
Area: Commitments and Certifications	
17.1 Status as a signatory of the UN Global Compact	0: Not a signatory. 1: Signatory, without progress report. 2: Active signatory. 3: Active signatory, with annual progress report and targets for continuous improvement.
17.2 Alignment of the SDGs with IDA and GRI indicators	0: No documented alignment. 1: Partial alignment with the SDGs. 2: Partial alignment and regular reports on SDG progress. 3: Full alignment and regular reports on SDG progress.
17.3 Existence of ECOPORTS certification	0: Not certified. 1: In the process of certification. 2: Certified, without regular renewal. 3: Certified, with regular renewal and compliance with all criteria.
Area: Reports and Communications	
17.4 Publication of the sustainability report	0: Report not published. 1: Report in implementation. 2: Report published, but not in accordance with GRI standards or equivalent. 3: Report published and in compliance with GRI standards or equivalent.
17.5 Disclosure of the position in the IDA	0: Position in the IDA not disclosed. 1: Position in the IDA publicly disclosed without action plans for improvement. 2: Position in the IDA publicly disclosed. 3: Position in the IDA publicly disclosed with action plans for improvement.
17.6 Publication of sustainability indicators	0: Indicators not published. 1: Indicators in the implementation phase. 2: Indicators published, but without detail or context. 3: Indicators published with detail, context, and performance comparisons.
17.7 Recording and communication of environmental incidents	0: No follow-up for records. 1: Non-systematic recording and communication. 2: Systematic recording, internal communication. 3: Systematic recording and communication, public and with response actions.
Area: Governance and Partnerships	
17.8 Number of independent members on the board of directors	0: No independent members. 1: Less than 25 % of members are independent. 2: 25–50 % of members are independent. 3: More than 50 % of members are independent.
17.9 Number of partnerships established with NGOs and other entities for sustainability initiatives	0: No partnership established. 1: Up to 2 partnerships established. 2: 3–5 partnerships established. 3: More than 5 partnerships established with ongoing projects.
17.10 Listing of active communication channels with stakeholders	0: No communication channel. 1: Limited or ineffective communication channels. 2: Some communication channels established and active. 3: Various communication channels established, active, and with regular feedback.

Data availability

The data that has been used is confidential.

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