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Review

Innovations and insights in environmental monitoring and assessment in port areas

Martí Puig[1] and Rosa Mari Darbra[2]

Environmental monitoring and assessment in port areas are vital for mitigating the impacts of maritime activities on surrounding ecosystems and communities. This review paper synthesizes recent literature (57 papers) from 2022 to 2024, highlighting technological advancements, case studies, and future directions. The integration of traditional and innovative approaches, such as remote sensing, Geographic Information Systems, big data analytics, and autonomous vehicles, is emphasized to enhance monitoring effectiveness. Key environmental issues, such as air and water pollution, habitat degradation, and noise pollution, are examined, alongside initiatives addressing these concerns. This review aims to inform researchers, practitioners, and policymakers about state-of-the-art techniques and emerging challenges in port environmental monitoring, contributing to sustainable port development and management.

Addresses
[1] Department of Chemical Engineering, Universitat Politècnica de Catalunya, Barcelona Tech, Diagonal 647, 08028 Barcelona, Catalonia, Spain
[2] Resource Recovery and Environmental Management (R2EM), Department of Chemical Engineering, Universitat Politècnica de Catalunya, Barcelona Tech, Diagonal 647, 08028 Barcelona, Catalonia, Spain

Corresponding author: Puig, Martí (marti.puig@upc.edu)

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Introduction

Port areas serve as vital hubs of global trade and commerce, facilitating the movement of goods and fostering economic development. However, the intensive maritime activities conducted within these zones pose significant environmental challenges, ranging from pollution to habitat destruction, impacting both marine ecosystems and adjacent communities [1]. Environmental monitoring and assessment in port areas play a pivotal role in identifying, quantifying, and mitigating these adverse impacts [2].

In recent years, there has been a notable rise in the development and adoption of advanced technologies and methodologies for environmental monitoring and assessment in port areas not only to monitor the environmental aspects generated by the port operations on land but also by the shipping activities within port areas. Innovations such as remote sensing, Geographic Information Systems, unmanned aerial vehicles (UAVs), and big data analytics have revolutionized the way environmental data are collected, analyzed, and interpreted [3]. These advancements offer unprecedented opportunities for enhancing the accuracy, efficiency, and comprehensiveness of environmental monitoring efforts in port regions [4]. An emerging and promising tool in this field is artificial intelligence (AI), which has the potential to significantly enhance data collection, analysis, and predictive capabilities in environmental monitoring.

In this context, the objective of this review paper is to provide a synthesis of significant recent developments in the field of environmental monitoring in port areas, with a particular emphasis on articles published within the past 2 years. By critically analyzing and synthesizing the latest literature, this review aims to offer insights into the current state-of-the-art techniques, emerging challenges, and future directions.

Environmental monitoring programs in ports

According to the latest European Sea Ports Organisation (ESPO) Environmental Report [5], which includes responses from 90 European ports, 92% of these ports have implemented an environmental monitoring program, demonstrating a strong commitment to sustainable practices and environmental management. In fact, monitoring is an essential element for a successful implementation of any Environmental Management System. Table 1 delineates the most commonly developed monitoring programs in these ports.

The European port sector demonstrates a robust commitment to environmental sustainability through comprehensive monitoring programs. *Water quality*

Table 1

Rate of monitoring programs implementation in ESPO respondent ports [5].

Implementation of environmental monitoring programs in European ports	Percentage
Water quality	82%
Port waste	81%
Ship waste	78%
Energy efficiency	76%
Sediment quality	73%
Water consumption	73%
Air quality	70%
Carbon footprint	65%
Noise	64%
Marine ecosystems	53%
Soil quality	48%
Terrestrial habitats	43%

monitoring, adopted by 82% of ports, focuses on preventing pollution and safeguarding marine life. *Port and ship waste* monitoring (81% and 78%, respectively) underscores efforts to manage waste effectively, enhancing compliance with environmental regulations. *Energy efficiency* monitoring (76%) aims to reduce energy consumption and improve operational efficiency, thereby minimizing environmental impact and costs. *Sediment quality* and *water consumption* monitoring (73%) highlight the importance of contamination prevention and sustainable water resource management. *Air quality* monitoring (70%) addresses emissions control from ships and port activities to protect public health. *Carbon footprint* monitoring (65%) reflects increasing efforts to reduce greenhouse gas emissions and combat climate change. *Noise* monitoring (64%) reveals concerns about the impact on marine life and local communities, necessitating effective noise management strategies.

Lower implementation rates for monitoring *marine ecosystems* (53%), *soil* (48%), and *terrestrial habitats* (43%) suggest areas needing greater focus and resource allocation for comprehensive environmental protection.

When comparing these results with a similar report for ports outside Europe [6], the performance of the ESPO respondent ports is lower. However, it should be noted that the number of participating non-European ports is smaller, with only 33 ports included, compared to the 90 ESPO ports.

Building on these primary concerns, extensive research was conducted to identify and select the most compelling recent papers. The primary databases used for the literature search, chosen for their extensive coverage of scientific and technical literature, included Web of Science, Scopus, and Google Scholar. This initial search identified over 100 papers. A rigorous scrutiny process was then undertaken, selecting articles based on their relevance to the key themes of the review, such as technological advancements in environmental monitoring. Papers not focused on port areas or environmental monitoring were discarded. To ensure the quality and reliability of the information, only peer-reviewed articles published in journals identified in the Journal Citation Reports were included. Additionally, the research focused on articles published between 2022 and 2024 to cover the most recent advancements and research trends in the field. Despite the extensive search, some topics yielded fewer articles, reflecting the slower pace of technological advancements in certain areas compared to others. While some fields within environmental monitoring have seen rapid innovation and numerous studies, others have progressed more slowly, resulting in fewer publications.

After this scrutiny, a total of 57 articles were selected. These articles were reviewed in detail, extracting information regarding the methodologies used, findings, and implications for environmental monitoring in port areas. The selected articles were categorized based on the specific environmental aspect they addressed (e.g. air quality, water quality, noise pollution) to facilitate a structured and focused review. Figure 1 outlines the specific research topics and indicates, in brackets, the number of selected papers within each category, which are detailed in the subsequent section.

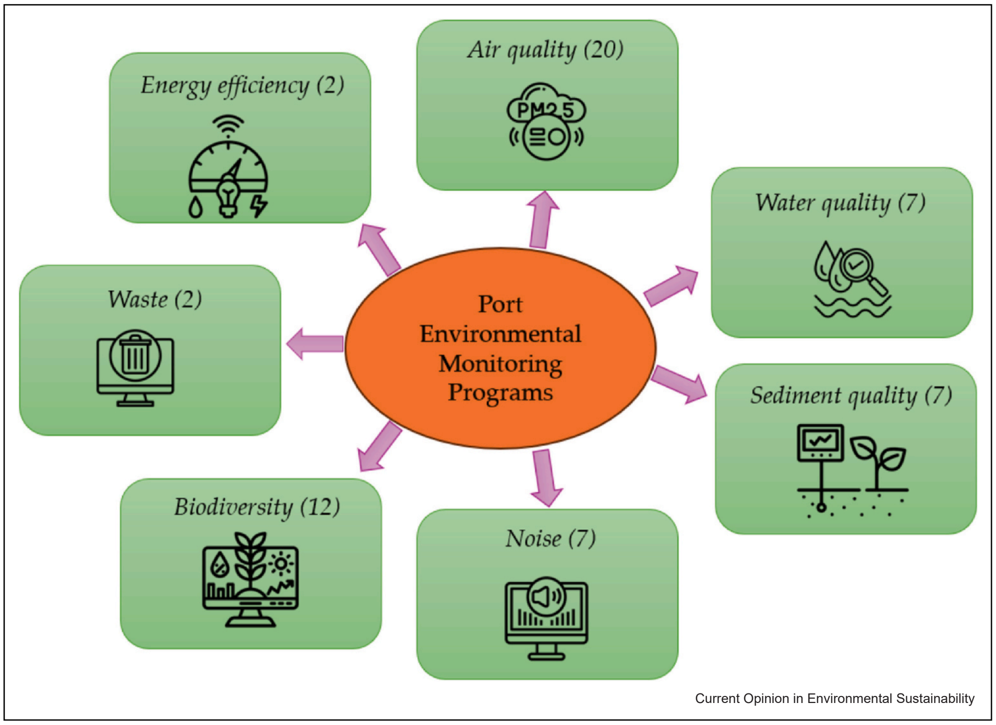
Research findings on proposed monitoring programs

Air quality monitoring

Air quality monitoring focuses on measuring emissions from ships, port machinery, and vehicles to control pollutants. This research includes a comprehensive review of 20 papers, with key findings summarized to highlight best practices and advanced strategies in air quality monitoring in port regions.

Several case studies on air quality highlight the importance of localized monitoring for public health and environmental management. For instance, a study in *Rhodes port* (Greece) [7] investigated PM2.5, NO_2, and O_3 concentrations, emphasizing the role of vehicle traffic, anthropogenic activities, and meteorological conditions on air quality and health risks. In the *Port of Albany* (USA) [8], real-time monitoring revealed significant daytime pollutant concentrations, particularly during rush hours, suggesting substantial contributions from industrial and vehicular sources. In Port of Paranaguá (Brazil) [9], Volatile Organic Compounds (VOC) emissions, specifically benzene, toluene, ethylbenzene, xylenes (as BTEX) concentrations were evaluated, with toluene being the most dominant compound and ethylbenzene posing a moderate cancer risk. Shanghai Port (China) [10] showed higher PM1 and PM10 concentrations on roads used by heavy-duty diesel vehicles.

Figure 1



Main environmental monitoring programs implemented in ports.

The research on air quality in northern Adriatic ports (Rijeka, Trieste, Koper, and Venice) [11] found that increased container throughput did not reduce urban air quality, suggesting mobile sensors for better measurement. In *Piraeus Port* (Greece) [12], the study on non-methane hydrocarbons identified fugitive emissions (72%), traffic (13%), and diesel-related emissions (15%) as primary sources.

Advanced models have been developed to estimate ship-related emissions, providing insights into pollutant sources and distribution patterns. In the Port of Split (Croatia) [13], a ship-related emissions inventory identified Ro-Ro ferries as major contributors to annual emissions, particularly during the tourist season. In Busan Port (South Korea) [14], emissions of various pollutants were calculated using open-source data, estimating the social environmental costs. *Taiwan Ports* [15] developed an activity-based model revealing that small vessels generate most emissions, while larger vessels have higher unit emissions, with green policies slightly reducing CO_2 and SO_x emissions. The *Port of Naples* (Italy) [16,17] conducted an experimental campaign to measure local-scale emissions. The results were overlapped with maritime traffic data based on Automatic Identification System (AIS) data to study vessel traffic and calculate emission rates. In the *Belgian North Sea area* [18], airborne monitoring of SO_x emissions from over 4500 ocean-going vessels showed high compliance with sulfur emission regulations, increasing from 83% in 2015 to over 95% in 2019.

Integrated strategies combining various monitoring tools have proven effective for managing air quality in port areas. Port of Castelló (Spain) [19] presents a strategy for selecting monitoring locations, using low-cost sensors for PM2.5, passive dosimeters for NO_2, and high-end instruments for short-term monitoring, alongside aerosol chemical analysis. In an *eastern China port* [20], a robust optimization model to design an air pollution monitoring buoy network was developed, considering ship exhaust emissions and wind conditions, with the objectives of maximizing monitoring capacity and minimizing costs. Liu et al. [21] created an optimization method for designing an air quality monitoring network in coal ports under uncertain operational efficiency and wind conditions, with a case study in a ***northern China coal port.***

Recent advancements in air quality monitoring technologies have significantly enhanced environmental management in port areas. Chen et al. [22] designed a *UAV* for VOCs monitoring in the atmosphere, overcoming the limitations of traditional atmospheric monitoring methods, enhancing the ability to assess air quality in challenging and dynamic environments, such as ports, where fixed monitoring stations may not capture the full scope of emissions. Another innovative approach, *AIS-Based Scenario Simulation* [23], evaluated various 'what-if' emission reduction options, demonstrating that shore power supply can significantly reduce carbon emissions more than speed policies. The *Grammatical Evolution for CO (carbon monoxide) classification* [24] (GenClass) outperformed an advanced classification technique that supports better air quality management and helps in addressing the health and environmental impacts of CO pollution more effectively. Finally, another study on *Sustainable Monitoring of Ship Operations* [1] focused on solutions for monitoring environmental elements and hazardous ship operations. This includes the use of cloud-based systems, digital twins, and indirect methods for measuring jet velocities. A key outcome from a recent review of air pollution monitoring technology for ports [25] is the development and application of *Differential Optical Absorption Spectroscopy and gas sensors*. These technologies offer precise and cost-effective solutions for detecting air pollutants in extensive port areas.

Water quality monitoring

Water quality monitoring involves testing for pollutants, such as oil, heavy metals, chemicals, and nutrients, alongside parameters such as pH, temperature, salinity, dissolved oxygen, and turbidity to assess marine health. A review of seven papers examined various methodologies used in monitoring water quality in port areas.

Two studies focus on assessing water quality and pollution levels in port areas. In southern Vietnam [26], a study analyzed 17 water quality indicators across 58 locations using multicriteria statistical approaches, revealing contamination from organics, nutrients, and iron. Similarly, the study on *Port Qasim* (Pakistan) [27] analyzed seawater samples for physicochemical characteristics and heavy metal content, finding significant pollution from industrial sources, including high organic loads and elevated levels of chromium and lead. This study highlighted the urgent need to address pollution threatening coastal biodiversity due to untreated industrial discharges and indiscriminate effluent disposal.

Several studies introduce advanced technologies for monitoring and addressing pollution in port waters. The *Unmanned Surface Vehicle Port Oil Spill Cleanup study* [28] presents a hybrid method combining global path planning for multidestination oil spills with reinforcement learning-based coverage path planning, enhancing cleanup efficiency. The *Parallel Intelligent Monitoring System based on the* Artificial systems, Computational experiments, and Parallel execution (*ACP*) *method* [29] integrates real and artificial monitoring systems to control water pollutants more effectively using real-time data and predictive models. In the Port of Palma de Mallorca (Spain), a study evaluates *neural networks and computer vision* [30] for image classification to detect surface spills and floating waste, demonstrating the potential for automated real-time monitoring. Another study introduces a model combining the entropy weight method, gray relational analysis, and TOPSIS method to *assess the ecological quality of port sea areas* [31], providing a comprehensive evaluation framework for seawater quality, sediments, and marine organisms.

Biomonitoring studies, such as the *EU Interreg Project* '*GEREMIA*' [32], use fish as bioindicators to assess the environmental status of port waters. By examining the health of Mugilidae fish through chemical analyses, biomarkers, and histopathology, the study highlights differences between the polluted Port of Genoa (Italy) and the natural environment of the S'Ena Arrubia fishpond. This multidisciplinary approach underscores the importance of biological indicators in understanding the broader ecological impacts of port activities and pollution.

Sediment quality monitoring

Monitoring sediment quality in port areas is essential due to the environmental impact of port operations, such as dredging, industrial discharges, and maritime traffic. Sediments often contain pollutants such as heavy metals and organic compounds, which can harm marine ecosystems and human health. This section explores recent studies and innovative approaches in sediment quality monitoring.

The investigation of antifouling organotin compounds and booster biocides in sediments from Samsun Port (Turkey) [33] highlights the first-time detection of these compounds in this area, indicating the ongoing pollution challenges faced by port ecosystems. The research on organophosphate esters (OPEs) in sediments from fishing ports in Dalian (China) [34] reveals that the concentrations and composition profiles of sediment OPEs were highly variable among ports, indicating differing anthropogenic impacts on OPE pollution. On the Brazilian equatorial margin, *an assessment of metal contamination in sediments and macroalgae in mangroves and port complexes* [35] utilized geochemical indices to evaluate pollution vulnerability. This study provided essential baseline data for future monitoring efforts aimed at safeguarding these sensitive ecosystems. Contrarily, at Prahovo Port (Serbia), *study on heavy metal(loid)s and polycyclic aromatic hydrocarbons* [36] indicated contaminant levels below regulatory limits.

The study on water column spatiotemporal monitoring in Mediterranean harbors [37] demonstrated that continuous monitoring of trace metals and organotin compounds offers critical insights beyond one-time sediment assessments. This approach reveals temporal variability and distribution patterns of pollutants, providing a comprehensive understanding of environmental health in harbor areas. The study on the effects of long-lasting massive dumping of dredged material during the Barcelona port expansion [38] provided a thorough analysis of sediment and water turbidity changes. It identified frequent peaks in suspended sediment concentrations and the formation of shock waves, along with a thin laminated deposit extending beyond the dumpsite. Persistent elevated suspended sediment concentrations postdumping indicated enduring environmental impacts. Finally, innovative monitoring technologies were also explored in the evaluation of a mobile unmanned platform for water and sediment sampling in the Port of Gdynia (Poland) [39]. The study concluded that HydroDron-1 provides sample quality comparable to traditional boat-based methods but with reduced costs and increased safety, highlighting its potential for advancing monitoring practices in port environments.

Noise monitoring

Noise pollution is a critical environmental issue in port areas, affecting both human communities and marine ecosystems. This section synthesizes findings from seven studies, highlighting innovative approaches to monitoring and assessing noise in port environments.

The study on the Port of Split (Croatia) offers a *multifaceted analysis of airborne noise impacts* [40] from cargo terminals. It classifies noise sources, presents strategic noise maps and simulations, and calculates the economic costs associated with noise pollution.

The ANCHOR LIFE Project focuses on creating *guidelines for a common approach to port noise monitoring and assessment* [41]. It uses the expansion project at Melilla port (Spain) as a case study, highlighting the significance of consistent methodologies and accurate algorithms in noise mapping. The paper *development of key performance indicators for noise monitoring networks* [42] provides stakeholders with tools to evaluate the effectiveness of their monitoring systems, using the ports of Cagliari, La Spezia, and Livorno (Italy) as case studies.

Several studies investigate underwater noise, often neglected in noise assessments. The research on *coastal underwater soundscapes in the Port of Newport and in a protected marine reserve* (Oregon, USA) [43] examines the variability and sources of underwater noise over 5 years. It contrasts noise variability and sources between a port area with high vessel activity and a quieter marine reserve, underscoring the need for tailored noise management strategies in diverse marine environments. Another study characterizes *underwater noise from a tidal turbine in the Port of Portsmouth* (UK) [44], concluding that the turbine's acoustic emissions were minimal, remaining below ambient sound levels and causing negligible impact on overall underwater noise levels. This finding supports the sustainable integration of renewable energy technologies in port environments.

Innovative mapping techniques are crucial for understanding and managing noise pollution in ports. The paper on *source characterization guidelines for noise mapping* [45], developed as part of the INTERREG Maritime program, promotes a common methodology for acoustic mapping of port environments. This approach facilitates comparable noise mapping across different ports, enhancing the effectiveness of noise management strategies. The introduction of Noise Source Predominance and Intensity Noise Source Predominance maps [46] represents a novel way to visualize main noise sources and their intensity levels. These maps aid in understanding noise sources, identifying responsibility for noise limits, and strategically locating monitoring stations.

Biodiversity monitoring

Monitoring biodiversity in port areas is crucial for assessing the ecological impacts of industrial activities and shipping on marine and terrestrial ecosystems. This summary consolidates findings from 12 studies that emphasize the importance of tracking the presence, abundance, and health of species within and around port environments.

Several studies focus on the impacts of chemical contaminants on marine organisms within port areas. The research on *green turtles in Port Curtis* (Australia) [47] reveals increasing cytotoxicity levels over time due to organic chemical exposure, suggesting potential negative effects on turtle health.

Similarly, a study in eastern ports of China focuses on *organotin compounds in marine organisms* [48], identifying phenyltins as dominant pollutants. This poses health risks through seafood consumption, particularly for children. In Kandla Port (India), research on *phytoplankton community structure* [49] examines seasonal and spatial variations, noting significant presence of toxic/harmful species influenced by environmental conditions, impacting marine ecosystem health. Similarly, the investigation of *zooplankton in the ballast water of ships at Shahid Rajaee Port* (Iran) [50] identifies 57 species, with correlations between environmental factors and zooplankton communities.

Monitoring invasive species is critical for maintaining biodiversity in port areas. The study on *fouling communities on mooring lines in the Port of Livorno* (Italy) [51] highlights their efficacy as a rapid and cost-effective tool for assessing nonindigenous species (NIS) presence. The study reveals that colonization time and harbor type significantly influence fouling communities, with touristic harbors exhibiting faster colonization rates and higher abundance of NIS. Innovative approaches such as a *new sampling device for metabarcoding surveillance* [52] are introduced as practical and cost-effective methods for standardized biodiversity monitoring in marine environments. This device provides comparable biodiversity assessments to traditional settlement plates, making it invaluable for detecting NIS and other organisms in port areas.

Advanced techniques, such as environmental DNA (eDNA) surveys, are utilized to monitor threatened species. A *study on scalloped hammerhead sharks in Apra Harbor* (Guam) [53] uses eDNA and open ecological data to determine their local distribution and habitat preferences. The findings reveal that hammerhead sharks are most frequently detected in January and prefer sites with high turbidity and sediment-dominated benthos. Research on *fish assemblages in coastal wetlands within the industrial port of Altamira* (Mexico) [54], monitored seasonally over 5 years, reveals ecosystems that may have reached an alternate steady state. In the Port of Miami (USA), a study on *coral persistence* [55] describes diverse coral communities that persist despite extreme environmental conditions, providing valuable insights into how corals can tolerate various anthropogenic stressors, with implications for their future survival.

The study on *microbial contamination in recreational coastal beaches neighboring shipping ports in the Adriatic Sea* [56] assesses the impact of ports on surrounding recreational areas. The findings indicate that the port of Rijeka (Croatia) is more microbiologically loaded than the port of Pula (Croatia), highlighting the potential for ballast water to transfer pathogens and the need for effective management strategies.

Effective biodiversity monitoring in ports involves robust management strategies. The paper on *ballast water management in ports* [57] provides guidance on developing monitoring, early warning, and response measures to prevent biodiversity loss and risks to human health. These measures include species identification, port monitoring, and early warning systems to detect and mitigate the introduction of harmful species through ballast water. The research *ballast water quality in Onne Harbor* (Nigeria) [58] highlights noncompliance with ballast water management standards due to varying concentrations of heavy metals and other parameters. This underscores the need for policymakers and regulators to monitor ballast water quality and develop management strategies to mitigate these risks.

Waste management monitoring

The management of waste in port environments has gained significant attention due to its critical impact on marine ecosystems and the operational efficiency of ports. Two recent studies have been selected as valuable insights into different aspects of port waste monitoring. The first one investigates the *characteristics of microplastics in the surface waters of the Port of Gdynia* (Poland) [59], revealing concentrations ranging from 0.082 to 0.524 mg/m³ in surface waters. It identifies fragments, fibers, and polyolefins as the predominant types of microplastics, highlighting the widespread nature of this pollution within controlled port settings. The second paper focuses on *Submerged Marine Debris (SMD) collection projects in major Korean ports* [60], assessing the effectiveness of current management practices and identifying areas for improvement. The study recommends policy enhancements such as more comprehensive collection strategies and stricter regulations to better manage SMD and reduce its impact on marine environments.

Energy efficiency monitoring

Enhancing energy efficiency in port operations is crucial since the growing environmental concerns in the maritime industry. Two recent studies provide valuable insights into strategies aimed at reducing CO_2 emissions in ports.

One study emphasizes *adopting renewable energy sources, clean fuels, and energy-saving techniques to meet* International Maritime Organization *(IMO) sustainability targets* [61]. It discusses integrating smart technologies, such as energy management and automated control systems, to optimize energy use and minimize emissions, aiming for net zero CO_2 emissions in maritime shipping. Another study proposes using Internet of Things (*IoT*) *technology to enhance energy efficiency in the administrative buildings of the Port of Durres* (Albania) [62]. By implementing smart sensors, real-time data analytics, and automated energy management systems, the study aims to reduce energy consumption by 25–50%. This approach not only improves energy efficiency but also provides a scalable model for other ports.

Conclusions

This review highlights the significant advancements in environmental monitoring and assessment in port areas through the integration of innovative technologies and methodologies. The use of advanced tools, such as remote sensing and UAVs, combined with comprehensive monitoring programs, has greatly enhanced the ability to assess and mitigate the environmental impacts of port activities. These technologies provide unique opportunities for detailed environmental assessments and real-time data analysis, leading to more effective management practices. An exciting area for future research is the application of AI in environmental monitoring. AI has the potential to improve the efficiency and accuracy of monitoring practices through advanced data analytics, machine learning algorithms, and predictive modeling.

The review reveals that air quality monitoring receives the most attention from the scientific community, followed by biodiversity issues, indicating a strong commitment to public health and marine life protection. Equivalent numbers of monitoring initiatives are found for water, sediment, and noise, while there are fewer recent publications on energy efficiency and waste management, indicating varying rates of technological advancements. The 2-year publication window may be found as a limitation, as it may not fully capture long-term trends and developments.

Overall, the findings emphasize the need for ongoing efforts and improvements to achieve long-term environmental sustainability. This includes continued innovation, integration of new technologies, interdisciplinary collaboration, investment in infrastructure, and collaborative efforts among stakeholders, along with strict policy enforcement. Such measures can help port areas significantly reduce their environmental footprint and promote sustainable activities.

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CRediT authorship contribution statement

Martí Puig: Formal analysis; Investigation; Writing – original draft. **Rosa Mari Darbra:** Conceptualization, Writing – review & editing, Supervision.

Data Availability

No data were used for the research described in the article.

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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