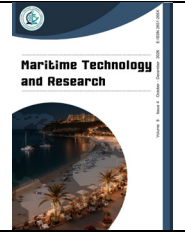




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Review Article

A review of green port indicators

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Abstract

Currently, port environmental footprints are growing due to the increase in maritime logistics activities. To address this issue, ports must become strategic actors in decarbonization and centers of sustainability governance by using “green port indicators” to measure and monitor environmental performance. This study aims to clarify dominant indicator groups, evaluation approaches, and limitations through a structured review of peer-reviewed publications and authoritative grey literature sources, as well as applying thematic synthesis to trace the evaluation of green port indicators across two conceptual periods, 2010 - 2020 and post - 2021 (2022 - 2026). The findings present that pre-2021 indicators introduced compliance-oriented localized impacts, in particular, air pollution emissions, energy consumption efficiency, governance readiness, and composite performance indices. On the other hand, the 2022 - 2026 indicators have emphasized the global climate goals, such as greenhouse gas (GHG) emissions accounting, carbon intensity assessment, electrification and energy transition progress, renewable energy integration, alternative fuel readiness, and system-level sustainability performance. However, methodological concerns remain unresolved, including inconsistent system boundaries, the limitation of port performance improvement from interventions, heterogeneous calculation methods, and overreliance on proxy readiness indicators rather than verified environmental outcomes. In conclusion, the evaluative robustness depends on harmonization improvement, transparency, and causal interpretation, as well as compliance with the environmental regulations and alignment with the global GHG emissions reduction and decarbonization targets.

1. Introduction

Since global commerce relies on maritime transportation, over 80 % of global trade involves maritime transportation (UNCTAD, 2025). Ports play a crucial role in socio-technical infrastructures that support maritime logistics more conveniently and also support regional industrial development and urban livelihoods. Moreover, ports act as gateways for coordination among stakeholders in the supply chain, including port authorities, terminal operators, shipping lines, customs agencies, and logistics services providers (Notteboom et al., 2021). Beyond their operational functions, ports are embedded in local communities and coastal ecosystems. Therefore, their performance could not be measured by cargo throughput only, but also requires safety, health, and environmental responsibility.

According to these reasons, port governance must increase its responsibility in green environmental performance and add it as a core component of competitiveness and social license, through transparent, auditable data and standardized reporting (Lam & Notteboom, 2014; Puig et al., 2014).

Currently, the expansion is motivated by the environmental and climate footprint of maritime logistics activities (Wang et al., 2023; Arof et al., 2021), particularly ports, where they record emissions from ships and cargo handling activities (Wang et al., 2023) (**Figure 1**). Although emissions mostly come from ships' propulsion, port activities, such as cargo operations, harbor craft, and dredging, also have significant effects on public and local communities (Yeh et al., 2023). Since 2022, there has been more sharpened attention on maritime logistics activities' emissions. In particular, the International Maritime Organization (IMO) set an ambitious target in 2023 to reduce carbon emissions to net-zero by 2050 (IMO, 2023), which is a significant movement and indirectly increases ports' importance in strategies as centers of cleaner energy availability, bunkering safety regimes, and infrastructure readiness.



Figure 1 Emissions from port activities.

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At the regional level, the European Union (EU) has emerged as a leading regulatory actor in the maritime green transition through integrated environmental regulatory frameworks (Khalique et al., 2025). This framework is formalized through initiatives, including the EU MRV (Monitoring, Reporting, and Verification), as well as the European Union Emission Trading System (EU ETS), whose maritime function has been integrated, aligning with FuelEU and the Alternative Fuels Infrastructure (AFIR). Therefore, in order to achieve the greenhouse gas (GHG) reduction target, there is a strong collaboration and governance system to enable intensive measurement and strengthen verification norms (IMO, 2023; ESPO, 2022; Khalique et al., 2025). Regional initiatives like FuelEU have stated that passenger and container ships must use shore connection electric power or alternative zero-emission technologies while berthing from 1 January 2030, which directly motivates relevant ports to monitor availability of onshore power supply (OPS), or another zero-emission technology at berth from 1 January 2030. This requirement encourages ports to monitor OPS availability, actual connection rates, electricity use, and emissions control (ESPO, 2022; Khalique et al., 2025; Lloyd's Register, 2024).

The context of “Green port” refers to a port that systematically minimizes its environmental footprint through the adoption of environmental management practices, performance monitoring frameworks, and sustainability governance mechanisms (Lam & Notteboom, 2014; Puig et al., 2014). This concept primarily presents a policy and operational aspiration that ports aim to achieve rather than a binary classification of either success or failure (Arof et al., 2021; González-Laxe et al., 2024). According to Green Marine (2024), over 200 certified stakeholders across North America, including ports, shipowners, and terminal operators, participate in the green evaluation, while the European Sea Ports Organization (ESPO) EcoPorts program has over 100 member ports actively engaged in structured environmental self-assessment (ESPO, 2022).

“Green port indicators” are both quantitative and qualitative measures for monitoring, evaluating, and reporting the environmental performance of port activities. These indicators are generally organized around core sustainability dimensions, including air quality, energy efficiency, carbon emissions, governance readiness, and transition preparedness. Together, they enable ports to demonstrate progress toward environmental targets and sustainability governance objectives (Arof et al., 2021; Puig et al., 2014; Lam & Notteboom, 2014).

As of 2026, there are several factors that shape performance monitoring, including emissions accounting regimes, decarbonization infrastructure readiness and utilization indicators, and environmental management and benchmarking systems within the ports sector (Hardianto et al., 2023). Regional and global initiatives, such as the EcoPorts reporting scheme, are also reinforcing pressures for indicator harmonization while progressively extending coverage to climate and alternative energy concerns in ports (ESPO, 2022; IAPH, 2024). Furthermore, some parallel projects, like Green Marine, demonstrate that indicator systems have been increasing in combination with management practices through quantified results, that shifting from activity-based indicators toward impact-and-performance-based ones instead (Green Marine, 2024).

In general, although there have been several studies on green port indicators, several research gaps remain. Firstly, due to inconsistent carbon calculation methods, there is a lack of a harmonized index framework that is both methodologically sound and comparable to real-world situations. Secondly, indicators from 2022 - 2026 limit the ability to assess the true impact, focusing only on governance efforts. Thirdly, there is a lack of detailed research on causal factors such as economic shifts or policy changes, leading to a lack of integration and complexity. This paper aims to synthesize past indicators and update green port indicator domains for 2022 - 2026, as well as identify the limitations that impact comparative and decision-making. The study not only updates reporting indicators but also acts as an instrument in port investments and operational levers to measurable environmental outcomes.

This paper reviews the evolution of green port indicators across two periods, including pre-2021 (approximately 2010 - 2021) and post-2021 (2022 - 2026); the justification for this threshold is further detailed in Section 2 [2.2]. Its findings present the evolution of the indicators across five dominant groups, as well as evaluation approaches, key methodological problems, and emerging trends. Finally, the study presents the methodological implications and offers recommendations for future research, followed by a conclusion of key contributions and limitations of green port indicator frameworks from 2022 to 2026.

2. Materials and methods

2.1 Data collection and searching method

This study adopted a structured literature review approach to identify, collect, and analyze indicators published from 2010 to 2026 by using pre-2021 literature as a baseline. Data collection was undertaken through structured searches from major peer-reviewed academic databases, including Scopus and Google Scholar, in areas of maritime logistics and environmental management research (refer to the details in **Table 1**). Additionally, the research also complemented the policy-driven evolution of green port indicators by authoritative grey literature from international organizations,

regulatory bodies, and port-sector associations, as well as reports, technical guidelines, and sustainability frameworks.

Table 1 Research criteria.

Keywords	Inclusion Criteria	Year	Language	Source Type
- Green Port Indicators	- Journals	- Pre-2021 - 2022 - 2026	English	Peer-reviewed
- Green Port	- Articles			
Performance	- Proceeding reports			
- Green Ports	- Policy guidelines			Grey literature
- Sustainable Ports	- Regulatory Frameworks			

Note: Created by Authors

2.2 Data analysis and synthesis

The documents used in this research were selected through a structured qualitative synthesis approach beginning with an initial database search in Scopus and Google Scholar, which retrieved a total of 63 candidate documents using the keywords according to **Table 1**. After a structured screening process, 41 documents were excluded from pre-defined exclusion criteria, such as studies primarily applying quantitative efficiency without developing an indicator framework, studies that focused on specific technology or equipment assessment rather than indicator design, etc.

The remaining documents, 22 peer-reviewed publications, including journal articles, conference proceedings, and book chapters, were retained as the primary analytical corpus for thematic synthesis of green port indicator evolution. During the synthesis phase, an additional 36 peer-reviewed sources were identified and incorporated through backward citation tracking by reviewing the reference lists of selected articles and forward citation analysis from newer studies that cited them, yielding a total of 60 references cited in this study. In summary, the total number of documents used in this study can be clarified as 51 papers being peer-reviewed academic publications, and another 7 authoritative grey literature sources, including policy strategies, sustainability reports, and technical guidelines, which are issued by international organizations. However, the grey literature sources were used to capture the policy-driven evolution of indicators, not treated as primary analytical sources in the thematic synthesis (as shown in **Figure 2**).

This study distinguishes between two conceptual periods of green port indicator development to ensure analytical clarity by pre-2021 (covering 2010 - 2020) and post-2021 (2022 - 2026), which were adopted as a conceptual rather than a strictly chronological distinction. The year 2021 has been selected as the analytical watershed for three converging reasons. First, according to the ambitious target of the IMO's revised 2023 GHG strategy to achieve net-zero by 2050, it was formally accelerated through the MEPC 76 intersessional working group deliberations in 2021, shifting toward mandatory decarbonization alignment (IMO, 2023).

Next, the introduction of Fit for 55 from the EU legislative in July 2021 has initiated the formal integration of shipping into the EU Emission Trading System (EU ETS) and launched the FuelEU, which has reshaped European ports' indicators toward carbon accounting and alternative fuel readiness (Khalique et al., 2025; Lloyd's Register, 2024). Lastly, the post-COVID pandemic from 2021 onward accelerated port sustainability reporting and ESG investment commitments globally, presenting the movement in the system-level and transition-oriented indicator framework (ESPO, 2022; IAPH, 2024). Therefore, these regulatory, institutional, and policy developments in 2021 are the core reasons that influenced a conceptual inflection point in the evolution of green port indicators rather than an arbitrary calendrical division.

In addition, the study primarily focuses on commercial ports, which are engaged in international maritime trade, including container terminals, multipurpose terminals, and general cargo

facilities, due to being the most extensively represented in the green port indicator literature (Arof et al., 2021; Fei et al., 2025). Specialized ports, such as bulk cargo, cruise, ferry, fishing, and oil and gas terminals, are not in the mandatory area of this study because the differential in the regulatory frameworks and environmental impact profiles requires dedicated indicator systems beyond the study's scope (Notteboom et al., 2021; Taljaard et al., 2024).

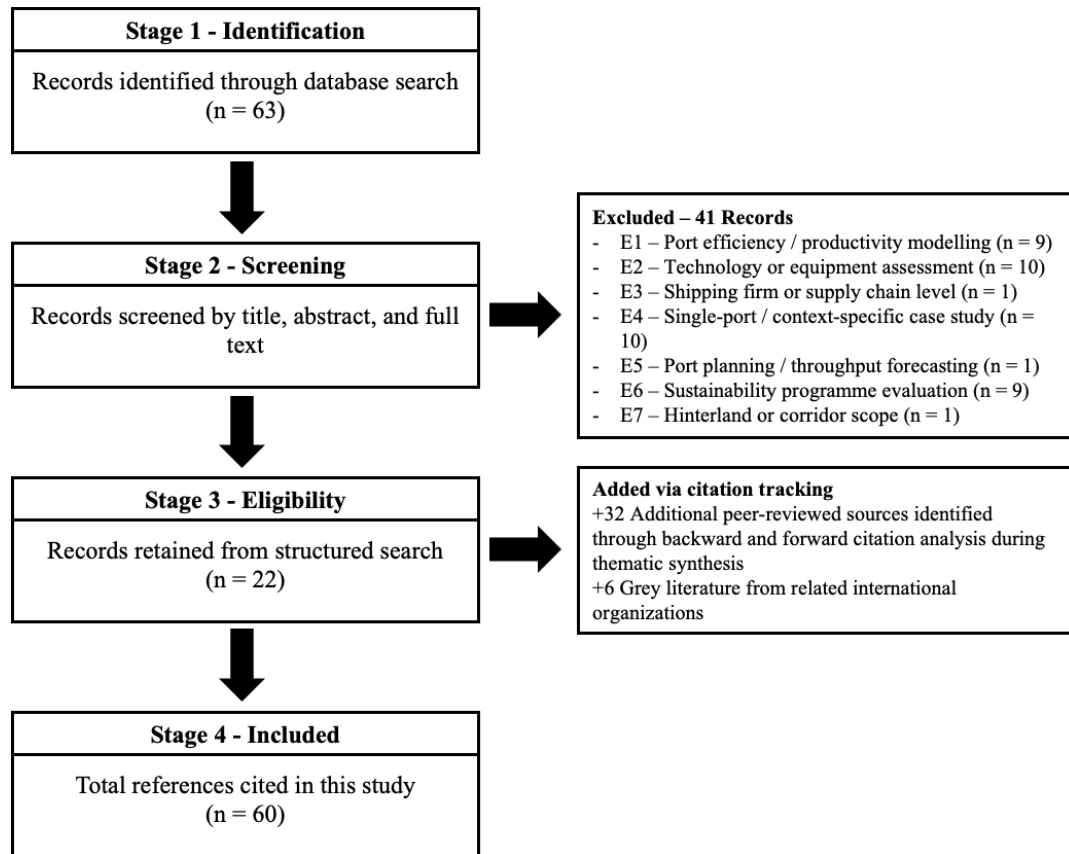


Figure 2 PRISMA flow diagram.
 Adapted from: Moher et al. (2009)

3. Green port indicators

Green port evaluation requires green indicators to monitor and evaluate sustainable performance across port activities. The indicators play a crucial role in converting environmental complexity impacts to observable and manageable variables in order to support the port's environmental context, including regulations, operational efficiency, strategic planning, and communication among port stakeholders. Moreover, green port indicators are significantly adopted within the environmental management systems (EMS) in ports, particularly ISO 14001, which emphasizes continuous improvement through objective setting, monitoring, and review (Lee & Wu, 2014; Puig et al., 2020).

According to the literature review from previous studies, ports, where ship berthing, cargo handling, storage, and hinterland connection occur, have intensive nodes of environmental impacts in maritime supply chains (Alamouch et al., 2021; Dinwoodie et al., 2011). Therefore, the indicators significantly focused on spatially concentrated impacts and politically visible issues, such as air emissions, noise, and waste generation in ports. However, the conceptual framing of indicators has evolved, from narrow pollution-control measures toward wider sustainability and performance-based approaches. In order to clarify the evolution, the following sections differentiate between past indicators (until 2021) and post-2021 indicators (2022 - 2026) to demonstrate the evolution of

indicators that conform to the global GHG emission reduction target. This conceptual distinction reflects a convergence of regulatory and governance shifts from 2021 onward.

3.1 Past indicators

3.1.1 Air and climate emission indicators

In the past, the air pollution indicators were primarily considered for application in many studies due to their clear maturity metrics. Ports are consistently identified as atmospheric pollutant sources through ship and shore-side operational activities (Lun, 2011; Lee & Wu, 2014), which made early indicator frameworks prioritize air pollutant measures, including NO_x, SO_x, particulate matter (PM), and other combustion-related pollutant emissions (Winkel et al., 2016). In general, these indicators are estimated by combining fuel consumption with emission coefficients and are evaluated against regulatory thresholds or temporal trends to assess the effectiveness of mitigation (Lee & Wu, 2014).

Therefore, early air pollution and emissions indicators prioritized addressing local environmental and public health impacts, particularly in port cities (Gobbi et al., 2020). However, there are several variations in emissions estimation and an inconsistent system, reducing comparability across ports (Arof et al., 2021). Additionally, the scope limitations of these indicators affect long-term environmental transformation and limit strategic relevance beyond compliance (Castellano et al., 2020).

3.1.2 Energy use and transition indicators

In early 2021, the energy-related indicators were primarily measured by total energy consumed and the intensity of cargo handled per unit. Lirn et al. (2013) and Munim et al. (2020) revealed that these indicators are widely used at the terminal and port level for benchmarking studies, where energy efficiency is interpreted as a proxy for environmental performance and cost effectiveness. Generally, these indicators are used for comparison, based on the ability to minimize energy inputs while maintaining performance, with a focus on relative efficiency (Duin et al., 2017). Moreover, previous studies found that operational energy efficiency improvements, including equipment optimization, infrastructure upgrades, and energy management, could directly support cost reduction and operational competitiveness (Acciaro et al., 2014; Puig et al., 2014; Sdoukopoulos et al., 2019).

However, there are several limitations to measuring in practice because the energy-related indicators mostly focus on consumption rather than environmental impact; environmental improvement does not reduce energy intensity if the energy supply remains releasing carbon (Arof et al., 2021). Also, the early indicators limited the ability to sustainably transition from distinguishing between fossil-based and low-carbon energy sources (Castellano et al., 2020). Therefore, ports should play an increasingly active role in the renewable energy system transformation and infrastructure in a broader transition perspective (Damman & Steen, 2021). In conclusion, pre-2021 energy-related indicators focused on operational optimization and incremental efficiency improvements rather than systematic transformation and transition readiness.

3.1.3 Composite and strategic performance indicators

According to previous studies of Lirn et al. 2013 and Munim et al. (2020), the general evaluation variables, including environmental, operational, and economic, were combined and interpreted as the composite and strategic performance indicators to measure the environmental performance outcomes of port activities. These indicators are developed through many tools, such as Data Envelopment Analysis (DEA), Multi-Criteria Decision-Making (MCDM), and sustainability index frameworks, in order to solve the limitations of single-indicator systems (Cullinane & Wang, 2010; Puig et al., 2014; Lim et al., 2019). In other words, the performance evaluation outcomes and policy interpretation are typically influenced by indicator selection, weighting structure, and

normalization method (Arof et al., 2021; Castellano et al., 2020; Lim et al., 2019). These approaches integrate economic efficiency, environmental impact, and operational productivity, reflecting the multidimensional nature of port sustainability.

However, these composite indicators remain a challenge in methodology, even though they offer analytical sophistication and comparability. For instance, the indicators often obscure causal relationships with specific environmental actions and outcomes, which leads to a limit of usefulness for target environmental management (Munim et al., 2020; Puig et al., 2014; Bjerkan & Seter, 2019). Therefore, although composite and performance-based indicators provide an improvement in benchmarking capacity and provide a holistic perspective on port sustainability, these indicators frequently reduce interpretability, decision-making, and strategic environmental governance.

3.1.4 Governance and environmental management indicators

In the early era of green ports, governance and environmental management indicators occupy a dominant position in the literature. The common indicators include environmental policy adoption, EMS, voluntary environmental programs, sustainability reporting practices, and stakeholder engagement mechanisms (Lee & Wu, 2014; Walker, 2016; Teslya & Gutman, 2020), which are widely adopted due to their institutionally standardized and relative ease to compare across ports through observation. Moreover, governance indicators are normally used to assess organizational capacity, institutional commitment, and managerial readiness in order to address environmental challenges (Lun, 2011; Lee & Wu, 2014; Lam & Notteboom, 2014). These indicators provide insight into the structure and necessary processes of ports that are required to support environmental management, including monitoring systems and formalized procedures.

However, some studies from Aróf et al. (2021) and Castellano et al. (2020) cautioned that governance indicators primarily play a role as process-based proxies rather than direct measures of environmental performance. Furthermore, the literature highlights a persistent disconnect between strong governance frameworks and measurable environmental improvement; for instance, ports demonstrate extensive institutional arrangements while having limited reductions in emissions or environmental risk achievement (Arof et al., 2021). Notably, governance indicators are increasingly interpreted as enabling conditions rather than performance outcomes. Thus, transparency, accountability, and organizational learning could be supported by governance-related indicators, but these do not provide robust environmental effectiveness evidence (Walker, 2016; Teslya & Gutman, 2020).

3.2 Post-2021 Indicators (2022 - 2026)

3.2.1 Air and climate emission indicators

According to global climate concerns and the UN Sustainable Development Goals (SDGs) targets, GHG emissions and carbon currently play a crucial core dimension for green port performance assessment. The recent research presents a significant increase in quantification approaches to evaluate CO₂-equivalent emissions, emissions intensity, and emissions contributions from port activities, such as ships at berth, cargo handling, and port energy systems (Wang et al., 2025; Pradana et al., 2023; Lafta & Aletaiby, 2025). This offers a fundamental transformation from pollutant-specific monitoring toward a climate-oriented sustainability approach. Thus, air emissions-related indicators became a primary index to measure and offer a practically explicit outcome-based information by focusing on emissions baselines, reduction trajectories, and long-term decarbonization pathways (Wang et al., 2025; Ye et al., 2025).

This shifting is influenced by the global maritime climate governance framework, particularly the IMO, which sets the strategic direction in GHG emissions reduction and encourages ports to develop decarbonization monitoring systems and infrastructures to align with the global climate target (IMO, 2023; ESPO, 2022). However, these indicators present the opposite view from earlier indicators that required transparency boundary definition, consistent emission factors, and integrated

accounting approaches. Furthermore, the literature emphasizes that rigorous methodology is essential because variations in assumptions could lead to significant effects on emissions estimates and comparability (Fei et al., 2025; González-Laxe et al., 2024). Despite several challenges being presented, it is extensively accepted that these indicators are strategically superior compared to earlier pollution metrics because they directly provide sustainability planning, infrastructure investment, and policy alignment (Ye et al., 2025).

3.2.2 Energy use and transition indicators

In the 2022 - 2026 period, the energy-related indicators have become one of the significant green port evaluation metrics, focusing on energy transition and electrification through technological readiness, infrastructure deployment, and system integration. For instance, several studies reveal an increase in electric cargo handling equipment, electrified terminal operations, and port energy consumption structure transformations, which are evidence of ports' shifting toward sustainability of the global green initiatives (Alfian et al., 2022; Alfian et al., 2025; Di Micco et al., 2025; Sogut & Erdoğan, 2022; Bartosiewicz & Kucharski, 2023; Baldaconi da Silva Bispo et al., 2025). However, these indicators only highlight the transformation of technology structure toward decarbonization operations rather than incremental optimization (Fei et al., 2025), unlike pre-2021 related indicators, which were weighted on performance outcomes.

However, some literature, for instance, Alfian et al. (2022) and Di Micco et al. (2025), highlight that electrification indicators directly connect environmental performance with capital investment and long-term planning, leading to highly strategic decision-making. In addition, Wang et al. (2023) and Ye et al. (2025) demonstrate that the use of electricity might shift emissions upstream by not eliminating them, if the generating sources come from carbon-intensive origins. Moreover, this concern is particularly significant in major port economies, where coal remains the primary energy source. For instance, China uses coal for electricity generation at approximately 60 % and over 70 % in India, respectively.

As a result, port electrification in this context may not reach net-zero GHG reduction without concurrent grid decarbonization (Fei et al., 2025; Wang et al., 2023). This raises fundamental questions regarding the environmental validity of electrification indicators in the case of applying without grid carbon intensity accounting and underscores that using only infrastructure deployment metrics is insufficient as a proxy for actual emissions reduction. Therefore, recent research exposes new dependencies for evaluation frameworks design, including electricity supply reliability, grid carbon intensity, and port stakeholder coordination, avoiding misleading conclusions (Fei et al., 2025; Housni et al., 2022; Kizielewicz, 2022; Xu et al., 2023; Bayraktar et al., 2025; Baldaconi da Silva Bispo et al., 2025).

3.2.3 Composite and strategic performance indicators

One of the important indices for contemporary green port assessments is the strategic assessment that has been transformed into a more system-level approach. These indicators have been integrated with environmental metrics, economic competitiveness, intermodal connectivity, and regional sustainability objectives (González-Laxe et al., 2022; Khalifeh & Caliskan, 2023; González-Laxe et al., 2024; Wang et al., 2025). They present the reflection that port sustainability could not be assessed in isolation from broader logistics and socio-economic systems. However, the complexities in the methodology of these indicators were found by Stein & Acciaro (2020), which include unclear and inconsistent data collection, even though they enhance conceptual completeness. Moreover, the integration of the three pillars, environmental, operational, and economic, requires data harmonization and weighting decisions, which may lead to a compromise on transparency and reproducibility (Fei et al., 2025; Gningue et al., 2023; Taljaard et al., 2024).

Furthermore, these indicators typically rely on aggregated data, which leads to a reduction in sensitivity to specific port-level interventions and limits operational decision-making usefulness. In

addition, Ye et al. (2025) demonstrated that the indicators may contribute to the distinction between port performance and contextual conditions, such as regional economic structure or policy environment, which remain unclear. Consequently, external conditions could affect port performance, even proactive environmental efforts, which raises concerns about fairness and interpretability in comparative assessments (Chen et al., 2024; Wang et al., 2025). Therefore, in order to balance the evaluation of system-level and strategic performance indicators, it is necessary to complement it with disaggregated and action-oriented metrics (Fei et al., 2025; González-Laxe et al., 2024; Taljaard et al., 2024).

3.2.4 Renewable energy and alternative fuel readiness indicators

The renewable energy and alternative fuel readiness indicators have emerged as key components of green port assessment frameworks from 2022 to 2026. In this context, renewable energy means energy generated from naturally replenishing sources. This includes solar photovoltaic (PV) systems, wind turbines (onshore and offshore), tidal and wave energy systems, and green hydrogen produced from renewable-powered electrolysis (Wang et al., 2023; Alfian et al., 2025; Fei et al., 2025).

Renewable energy indicators normally measure on-site generation capacity, renewable electricity shares, and energy storage deployment, while alternative fuel indicators approach the preparation of infrastructure, safety systems, and bunkering capability for emerging fuels (Wang et al., 2023; Alfian et al., 2025; Lafta & Aletaiby, 2025). Many studies show readiness assessment based on planning documents, pilot projects, or announced investments rather than operational performance and rigorous evaluation useful limitation (Fei et al., 2025), as well as highlighting their largely qualitative and aspirational nature. Hence, these indicators do not generally measure performance outcomes but often function as signals of intent.

The uncertainty and path dependency also limit the usefulness of these indicators; the study revealed that ports usually face significant uncertainty regarding future fuel pathways, which complicates indicator design and evaluation (Ye et al., 2025). As can be seen, the indicators that prioritize only one renewable energy or technology may unintentionally limit ports into suboptimal transition pathways. Consequently, the effective indicators commonly require flexible and adaptive indicators that can accommodate multiple transition scenarios rather than fixed technological benchmarking (Fei et al., 2025).

Furthermore, the crucial gap in the 2022 - 2026 indicator developments is the absence of lifecycle environmental considerations for renewable technologies themselves. For instance, the lifetime of solar PV panels and wind turbine components includes manufacturing, installation, and end-of-life disposal of materials, which impact environmental burdens that are not measured by operational performance indicators (Fei et al., 2025). Thus, this gap introduces a limitation for future indicator frameworks that should be addressed by incorporating lifecycle assessment (LCA) dimensions alongside operational deployment metrics.

In conclusion, the literature review shows that the indicators from 2022 - 2026 provide a significant advancement in scope and ambition. **Table 2** clarifies the priorities of maritime environmental monitoring that transition toward carbon intensity benchmarking after 2021. However, some previous studies, such as Fei et al. (2025), Wang et al. (2023), and Ye et al. (2025), highlight that inconsistent system boundaries, attribution, heterogeneous methodology, and overreliance on proxy indicators rather than verified environmental outcomes are still unresolved challenges for indicators' expansion. Furthermore, the indicators' evaluation heavily depends on transparent assumptions and integrated interpretation, even though the carbon and energy transition provides strategic relevance. In conclusion, future studies should focus not only on indicator coverage expansion but also on improving the rigorous methodology, harmonization, and causal inference in green port performance assessments.

Table 2 Pre-2021 and 2022 - 2026 indicators comparison.

Indicator Groups	Period		Key Transition
	Pre-2021	2022 - Present	
Air and Climate Emission Indicators	- Focus on conventional air pollutants, such as NOx, SOx, and particulate matter, from ship to shore operations, which uses fuel consumption and emission coefficients to estimate and evaluate against thresholds and trends (Lun, 2011; Lee & Wu, 2014; Winkel et al., 2016).	- Emphasis on GHG accounting (CO2e), emissions intensity, and source attribution across port system, such as ships at berth, cargo handling, and energy use (Wang et al., 2025; Pradana et al., 2023; Lafta & Aletaiby, 2025). - Developing to align with the global climate target (IMO, 2023; ESPO, 2022).	- Shifting from local pollutant compliance monitoring to climate-oriented carbon accounting and decarbonization pathways.
Energy Use and Transition Indicators	- Total energy consumption and energy intensity per throughput, which was used for benchmarking efficiency and cost-effectiveness, energy efficiency, treated as proxy for environmental performance (Lirn et al., 2013; Munim et al., 2020).	- Transition-oriented focus, including energy restructuring, electrification, and integration with decarbonization targets, linked more strongly to emissions impacts (Fei et al., 2025). - Environmental performance directly connects to capital investment and long-term planning, influencing decision-making (Alfian et al., 2025; Di Micco et al., 2025).	- Shifting from operational efficiency optimization to structural energy transition and electrification performance.
Composite and Strategic Performance Indicators	- Composite indicators combining environmental, operational, and economic factors by using DEA, MCDM, and sustainability index frameworks tools to develop indicators (Cullinane & Wang, 2010; Puig et al., 2014; Lim et al., 2019). - Performance outcomes and policy interpretation depend on indicator selection, weighting structure, and normalization method (Arof et al., 2021; Castellano et al., 2020; Lim et al., 2019).	- Expanding toward system-level sustainability integrating competitiveness, intermodal connectivity, and regional development objectives (González-Laxe et al., 2022; Khalifeh & Caliskan, 2023; González-Laxe et al., 2024; Wang et al., 2025).	- Shifting from port-level benchmarking tools to holistic sustainability governance frameworks.

Table 2 (continued) Pre-2021 and 2022 - 2026 indicators comparison.

Indicator Groups	Period		Key Transition
	Pre-2021	2022 - Present	
Governance and Environmental Management Indicators	- EMS adoption, environmental policies, reporting, voluntary programs, stakeholder engagement, which are easy to observe and compare, to assess institutional readiness (Lee & Wu, 2014; Walker, 2016; Teslya & Gutman, 2020). - Used to assess organizational capacity, institutional commitment, and managerial readiness to address environmental challenges (Lun, 2011; Lee & Wu, 2014; Lam & Notteboom, 2014).	- More enabling rather than directing outcome indicators, and that have been criticized when disconnected from real performance outcomes (Arof et al., 2021; Ye et al., 2025). - Supporting carbon and transition governance rather than standalone performance indicators (Fei et al., 2025).	- Shifting from process-based compliance legitimacy to supportive governance for decarbonization strategy.
Renewable Energy and Alternative Fuel Readiness Indicators	- Indirectly discussed as general green initiatives due to rarely being formalized (Arof et al., 2021).	- Measures renewable generation share, storage deployment, and alternative fuel infrastructure readiness, which reflect long-term transition preparedness (Wang et al., 2023; Alfian et al., 2025; Lafta & Aletaiby, 2025). - The readiness assessment depends on planning documents preparation, pilot projects, and announced investments (Fei et al., 2025).	- Absence and limited focus on forward-looking readiness indicators to align with decarbonization pathways.

Note: Created by Authors. Acronyms: DEA = Data Envelopment Analysis; MCDM = Multi-Criteria Decision-Making; EMS = Environmental Management System; GHG = Greenhouse Gas; CO_{2e} = Carbon Dioxide Equivalent

4. Findings

4.1 Evolution of green port indicators

The reviewed literature clearly presents a green port indicator evolution, which is shifting from localized, compliance-driven environmental metrics toward strategic and transition-oriented sustainability performance measurement. In the past decade, the indicator frameworks have been shaped by regulatory pressure and institutional alignment, particularly concerning port city

environments, which contribute to air, noise, and waste pollution within the social community (Lun, 2011; Lee & Wu, 2014; Winkel et al., 2016). As a result, the indicator dynamics were designed to support incremental environmental control and reporting rather than long-term transformation guidance and investment decision-making (as shown in **Figure 3**).

On the other hand, climate governance and renewable energy have been significantly influencing and shaping the green port indicators since 2022. For instance, Wang et al. (2023) and Fei et al. (2025) revealed that modern port development is embedded with GHG emissions accounting, low-carbon technology deployment, and strategic sustainability performance. Importantly, the indicators' evolution introduces ports transition toward the global decarbonization systems from pollution control areas, particularly in energy and infrastructure aspects, which focus on measuring infrastructure planning and competitiveness under transition pressures (Ye et al., 2025; Wang et al., 2025). This reflects that the purpose of the indicators has moved beyond compliance reporting toward enabling decision-making on long-term investment and the restructuring of operations, as well as aligning with the global ambitious target (IMO, 2023).

However, even though indicators evolve adaptively with the global climate situation, they do not improve validity or transparency automatically, and several challenges remain, such as weak consistency and methodological comparability (Arof et al., 2021; Fei et al., 2025). Hence, the evolution of indicators still requires ambition, as well as a stronger stabilization methodology, in order to support robust evaluation and benchmarking.

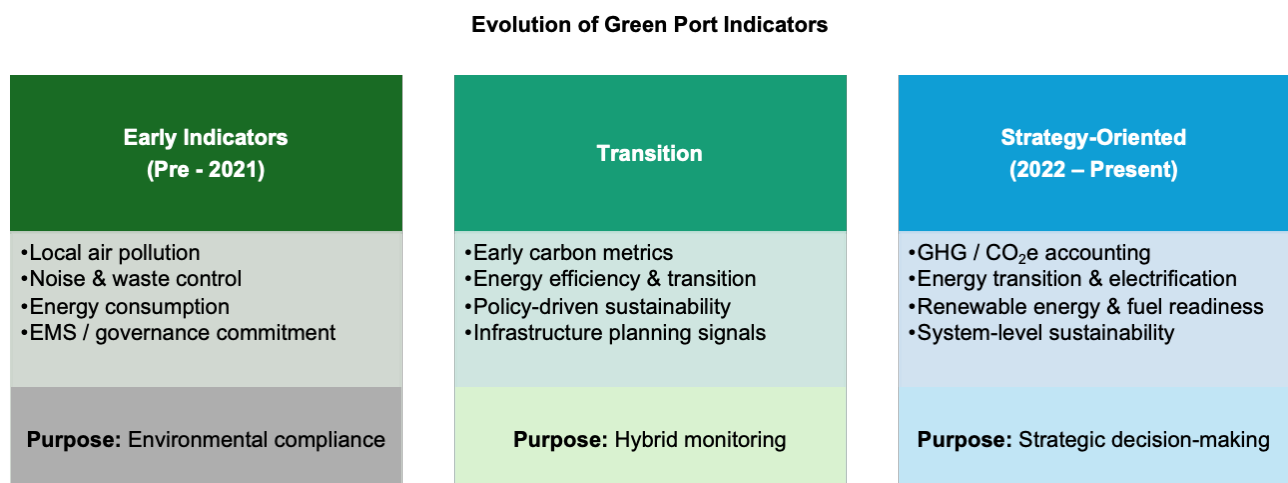


Figure 3 Evolution of green port indicators from compliance-oriented environmental monitoring toward sustainability performance assessment.

Note: Created by Authors

4.2 Dominant indicator groups used across studies

The findings across the literature found the repeatedly prioritized indicator groups due to measurability, institutional familiarity, and decision relevance. Early dominance patterns of indicators have been widely used for measurement because of their maturity, quantifiability, and significant political relevance with the port-city environmental context (Arof et al., 2021). Thus, these indicators demonstrate ports' environmental engagement without requiring complex data integration or the whole accounting system.

Moreover, energy-related indicators were strongly committed to operational optimization and productivity-driven evaluations, which were easily adapted into benchmarking models and performance analysis frameworks (Lirn et al., 2013; Munim et al., 2020). However, the literature

demonstrates that these indicators were often used to identify generic green proxies because they did not explicitly represent environmental outcomes or carbon impacts, particularly when energy source composition was not incorporated (Castellano et al., 2020). For this reason, it is undeniable that dominant indicator selection did not always equate to conceptual adequacy.

Similarly, Walker (2016) and Teslya and Gutman (2020) revealed that environmental responsibility evidence and managerial capability were frequently proven by environmental policy adoption, reporting systems, voluntary programs, and stakeholder engagement indicators. However, these indicators not only provide the verification of environmental shifts but also substitute missing outcome data and reinforce an emphasis on procedural legitimacy (Arof et al., 2021).

Furthermore, the recent indicator groups are in line with the global GHG emissions reduction and decarbonization targets, moving toward electrification, renewable energy readiness, and broader system-level sustainability evaluation (Wang et al., 2023; Alfian et al., 2025). These movements show that indicator usage has shifted from local pollution control to climate-aligned performance measurement, which is in line with the IMO's ambitious target in GHG emissions reduction (IMO, 2023). However, quality is not guaranteed by the dominant paradigm; in particular, fast-growing indicator sets can intensify comparability problems and evaluation ambiguity (Fei et al., 2025).

4.3 Indicator evaluation approaches

The literature presents the evaluation approach through monitoring and reporting, benchmarking and efficiency comparison, and composite multi-criteria performance assessment. Earlier studies found that performance evaluation was usually focused on monitoring and reporting to support regulatory compliance and progression monitoring but also providing performance governance and strategic effectiveness limitation (Lee & Wu, 2014). However, this approach is still limited when the target shifts from reporting to performance governance, even though it is useful for identifying environmental hotspots and tracking progress. Furthermore, the benchmarking and efficiency evaluation approach is also often used for intensity (per TEU or per ton) indicators and comparative performance techniques. As can be seen, environmental performance evaluation is generally integrated into port efficiency assessment through productivity, cost-effectiveness, and operational optimization (Lirn et al., 2013; Munim et al., 2020). However, Castellano et al. (2020) present a fragile assumption because high efficiency does not mean low environmental impact when excluding external impacts or inconsistent boundaries.

Additionally, a composite and multi-criteria modelling approach is used, in which indicators are combined into index scores through weighting and ranking methods. These frameworks support structured decision-making and multiple dimension comparison across ports in terms of environmental, economic, and operational metrics (Munim et al., 2020). However, Arof et al. (2021) reveal several weaknesses in this approach regarding sensitive methodological design options, particularly in weighting structures, indicator selection, and normalization assumptions. It could reduce interpretability because high scores can obscure the underlying performance driver changes and reduce the diagnostic value of the evaluation.

Therefore, the recent decarbonization indicators and energy-related metrics are strongly sensitive to data and boundary assumptions, which require a transparent methodology in evaluation (Fei et al., 2025; Wang et al., 2023). While evaluation is complex, methodological variation still undermines reproducibility and comparability. Therefore, the literature reveals that the indicators may become only reporting, rather than practical, instruments for environmental decision-making without balancing complexity and clarity in evaluation frameworks.

4.4 Key methodological problems identified

The literature review found critical findings that the expansion of green port indicators has introduced persistent methodological weaknesses that remain unresolved. First, the inconsistency

boundary, particularly for carbon and system-level indicators. The different perspectives of several studies argue whether indicators should include ship at berth emission, tenant emissions within port-owned assets only, or count the wider hinterland transport impacts as well, because ports typically operate across many stakeholders (Fei et al., 2025; Wang et al., 2023). As a result, this might lead to unreliable benchmarking in reporting on port emissions intensity from different fundamental calculations.

The attribution and causal inference remain unresolved and do not determine the reason for performance improvement, while offering trend measurement. Ye et al. (2025) reveal that emission reduction not only reflects the investment aspect, but also external conditions driven by market fluctuations, such as reduced traffic, fleet modernization, and operational restructuring. Thus, port-level effectiveness may overstate the evaluation if there are no separate intervention effect designs (Fei et al., 2025). Additionally, methodological heterogeneity presents challenges across indicator definitions, calculation units, data sources, and normalization practices. Several studies applied different variables to similar indicators, including emission factors, throughput denominators, and estimation approaches, which led to weak comparability (Fei et al., 2025; Wang et al., 2023). It is a crucial problem for carbon indicators due to changes in assumptions, producing large variations in results.

Lastly, the literature identifies overreliance on proxy indicators, particularly in transition readiness domains. The studies demonstrate the attractive and easily measurable indicators, including governance indicators, infrastructure availability measures, and policy-based readiness metrics (Walker 2016; Teslya & Gutman 2020). However, without operational utilization indicators and environmental outcome measures, it may lead to narratively inflated sustainability performance (Arof et al., 2021; Fei et al., 2025). Therefore, the unresolved methodological problems represent unreliable indicators for benchmarking and policy evaluation at the current stage.

4.5 Emerging trends and indicator priorities (2022 - present)

The literature review demonstrates several emerging priorities shaping green port indicators from 2022 to 2026. GHG and carbon emissions accounting have become a mandatory performance evaluation, according to several studies that have found increasingly quantifying emission baselines, intensity metrics, and major ports' emission sources (Wang et al., 2025; Pradana et al., 2023; Lafta & Aletaiby, 2025). This trend reflects a movement of green port evaluation that has shifted from local environmental actors toward the global decarbonization target (Wang et al., 2025; Ye et al., 2025). Moreover, the increasing adoption of renewable technology and infrastructure investment, such as electrified cargo handling and low-carbon operational restructuring (Alfian et al., 2022; Alfian et al., 2025; Bartosiewicz & Kucharski, 2023; Baldaconi da Silva Bispo et al., 2025; Di Micco et al., 2025; Sogut & Erdoğan, 2022), increases the electrification and energy transition indicators more significantly. However, Wang et al. (2023) and Fei et al. (2025) highlight that these measures require careful interpretation because grid carbon intensity and operational utilization generally influence emission reduction results (**Table 3**).

Furthermore, renewable energy and alternative fuel readiness indicators have been playing an increasing role as strategic signals of transition preparedness, which reflects ongoing development of future marine fuel pathways and the need for flexible port infrastructure planning (Wang et al., 2023; Alfian et al., 2025; Lafta & Aletaiby, 2025). However, Fei et al. (2025) review that several readiness indicators often measure plans rather than performance. In addition, environmental performance integration with port competitiveness, intermodal connectivity, and regional sustainability dynamics requires system-level indicators, reflecting the transition toward holistic port sustainability governance. On the other hand, there are several limitations due to methodological complexity and conflated risks, such as transparency in data collection and external conditions (Ye et al., 2025; Fei et al., 2025).

Table 3 Key approaches and limitations of green port indicators by groups.

Indicator Groups	Approach Method	Evaluation Method	Key Limitations
Air and Climate Emission Indicators	- Pre-2021, focused on localized pollutants control (e.g., NO_x, SO_x, PM) by fuel-based emission estimation. - 2022 - 2026, more emphasis on GHG accounting (CO₂e) emission intensity, and decarbonization pathways.	- Emission inventories - Fuel consumption and emission-factor calculation - Threshold compliance monitoring - Carbon intensity benchmarking - Baseline-trajectory analysis	- Inconsistent system boundaries, such as ship-at-berth inclusion - Variability in emission factors - Attribution challenges - High sensitivity to accounting assumptions - Limited cross-port comparability
Energy Use and Transition Indicators	- Pre-2021, focused on energy use and intensity as efficiency proxies. - 2022 - 2026, focusing on electrification, infrastructure deployment, and energy system restructuring toward low-carbon transition.	- Energy consumption per throughput benchmarking - Electrification rate tracking - Infrastructure readiness assessment - Transition progress monitoring	- Efficiency does not equal environmental effectiveness - Upstream emissions risk (grid carbon intensity) - Infrastructure availability may not reflect utilization - Limited lifecycle consideration
Composite and Strategic Performance Indicators	- Pre-2021, integration of environmental, operational, and economic factors through multi-criteria models. - 2022 - 2026, expending toward system-level sustainability governance and competitiveness alignment.	- Weighted scoring models - Multi-criteria decision analysis (MCDA) - Composite indices - Efficiency frontier models - System-level aggregation	- Subjective weighting and normalization - Methodological opacity - Reduced transparency - Risk of conflating contextual factors with port performance - Diminished diagnostic precision
Governance and Environmental Management Indicators	- Measures institutional readiness through EMS adoption, environmental policies, reporting systems, and stakeholder engagement. - Emphasizes procedural legitimacy.	- Presence and absence scoring - Qualitative benchmarking - Compliance auditing - Governance maturity assessment	- Proxy-based measurement - Weak causal link to measurable environmental outcomes - Potential symbolic compliance - Overestimation of environmental effectiveness
Renewable Energy and Alternative Fuel Readiness Indicators	- Assesses renewable generation share, storage deployment, and infrastructure readiness for alternative fuels. - Forward-looking transition preparedness logic.	- Infrastructure deployment tracking - Renewable share calculation - Readiness scoring - Planning and investment-based assessment	- Often aspirational (plans vs. performance) - Uncertainty in fuel pathways - Technology lock-in risk - Limited operational outcome verification - Inconsistent measurement standards

Note: Created by Authors

5. Discussion and recommendations

5.1 Discussion

The evolution of green port indicators is not only a change in measurement scope but also reflects a fundamental reconceptualization of what port environmental performance means. Before 2021, environmental performance frameworks were treated as operational efficiency, meaning that ports that consumed less energy or adopted EMS were considered green ports without evolving actual emission outcomes (Lun, 2011; Lirn et al., 2013; Lee & Wu, 2014). However, the transition of post-2021 indicators has forced a more demanding standard, as the indicators must demonstrate measurable progress toward climate targets, rather than merely institutional compliance (IMO, 2023; ESPO, 2022; González-Laxe et al., 2024). This transition provides significant challenges to the port sector, particularly in emerging economies, as the new frameworks demand outcome verification due to a lack of infrastructure, data systems, and regulatory mandate (Fei et al., 2025; Arof et al., 2021).

Moreover, the methodological weaknesses, including inconsistent boundaries, attribution gaps, heterogeneous calculation methods, and proxy reliance, are not isolated technical problems (Wang et al., 2023; Fei et al., 2025). These reflect structural tension, because indicator frameworks are expanding faster than the methodological consensus needed to make them comparable and reliable (Arof et al., 2021; Lim et al., 2019). As a result, the indicators from 2022 - 2026 may become performative rather than evaluative, which means that post-2021 indicators measure ambition and readiness rather than verified environmental outcomes (Taljaard et al., 2024; Gningue et al., 2023). Thus, without harmonized boundary definitions and causal inference frameworks, benchmarking across ports remains unreliable; also, policy decisions based on indicator rankings may misattribute performance improvements to port-led interventions when they, in fact, reflect external market or fleet conditions (Ye et al., 2025; Wang et al., 2025).

Furthermore, ports are not the same; they differ in terms of size, location, governance systems, regulatory pressures, and technological capacity (Silva et al., 2025). For instance, large ports in Europe often operate under stricter environmental regulations, such as the EU ETS and FuelEU Maritime, and usually have more financial and technical resources to implement electrification and carbon accounting systems (Sage-Fuller, 2017). In contrast, small and medium-sized ports, particularly in emerging countries, probably have limited financial resources, weaker regulatory frameworks, and different operational priorities, which are significant barriers to green port transition. The applicability and relevance of green port indicators can vary depending on the characteristics of each port; thus, the indicator development should prioritize port typology and development context rather than assuming a single standard for universal applicability (Taljaard et al., 2024; Fei et al., 2025).

As of 2026, the green port indicator frameworks remain lacking in embodied carbon accounting for emissions from the construction of port infrastructure, whether concrete foundations, quay walls, or steel-intensive equipment (Notteboom et al., 2021). Additionally, the post-2021 indicator frameworks are still missing the environmental risks from hazardous cargo handling, including storage procedures, leading to environmental impacts beyond routine operational emissions from such toxic and explosive risks, like the explosion of the Beirut Port in 2020 (Ali et al., 2022). Therefore, future development of green port indicators should address these gaps in order to provide a more comprehensive and risk-inclusive assessment of port environmental performance.

5.2 Recommendations

This study focused on a literature review of pre-2021 and post-2021 green port indicators (2022 - 2026) only; therefore, future research should prioritize methodological improvement and strategic applicability. In particular, a more consistent framework for defining system boundaries for carbon accounting and ship emissions is needed to strengthen comparability across ports and improve benchmarking validity (Wang et al., 2023; Fei et al., 2025). The inconsistencies in emissions reporting

could be reduced by standardized boundary logic, as well as by providing a more credible foundation for performance comparison.

Moreover, future studies should strengthen causal inference and attribution analysis, because the indicators should be related to specific interventions, rather than port-led progress assumptions. This improvement may require long-term research designs, intervention-based evaluation frameworks, and analytical approaches, which separate internal port actions and external contextual drivers (Ye et al., 2025; Fei et al., 2025). Thus, it requires these approaches to prevent overstatement of performance assessment regarding the effectiveness of transition policies and infrastructure investment.

Furthermore, research about energy transition indicators development should integrate electrification metrics, as well as electricity carbon intensity, utilization effectiveness, and operational performance outcomes. As can be seen, the electrification indicators should not be interpreted through infrastructure deployment only but must also be considered in terms of measurable emissions reductions to avoid proxy-based inflation of green performance claims (Di Micco et al., 2025; Wang et al., 2023). Also, renewable energy and alternative fuel readiness indicators should be reflected in operational effectiveness and performance impacts through measurable progress indicators (Alfian et al., 2025; Fei et al., 2025).

Additionally, multi-level evaluation designs are required for future indicator study, including operational indicators, transition indicators, and strategic indicators. Ye et al. (2025) and Wang et al. (2025) highlighted that impartiality and interpretability in comparative studies can be ensured during system-level indicators design through avoiding conflating internal port performance and external regional conditions. Therefore, future research should prioritize transparency in indicator selection, weighting, and normalization to enhance reproducibility, particularly in the expansion of composite and multi-criteria evaluation frameworks in green port research (Munim et al., 2020; Fei et al., 2025).

6. Conclusions

The literature review presents the evaluation of green port indicators, which have shifted from localized pollutant control, energy consumption, and governance commitment toward carbon accounting, energy transition readiness, and strategic sustainability performance prioritization. Pre-2021 indicators offered practical and institutionally accessible methods for environmental monitoring and policy compliance through air pollution and operational efficiency metrics. However, these indicators were often limited by indirect reliable governance measures and the possibility of interpreting efficiency as sustainability without aligning with environmental outcomes. On the other hand, the indicators from 2022 have become stronger and prioritize global climate mitigation and decarbonization, as well as GHG emissions, electrification measures, renewable energy indicators, and transition readiness assessment.

The findings identified unresolved problems in methodological challenges that limited the performance of post-2021 green port indicators. Moreover, the factors that undermine comparability and decision-making are typically impacted by inconsistent boundaries, uncertain attribution, heterogeneous calculation methods, and readiness indicators' persistence. Overall, the study emphasizes ambitious and strategically oriented approaches among the green port indicator developing pathway; however, the evaluative strength depends heavily on improved methodological harmonization and outcome verification. Additionally, port characteristics also require consideration in indicator adoption, which typically depend on port size, location, governance systems, and compliance with regional regulations, as well as financial resource concerns.

Declaration of generative AI in scientific writing

The authors declare that during the preparation of this work, generative AI and AI-assisted technologies, including ChatGPT 5.2 (openai.com) and Grammarly, were applied in order to improve the readability and language of the manuscript. With or without AI applications, the authors are fully

accountable for every process of the work and manuscript writing. All final edits, interpretations, and conclusions are the sole responsibility of the authors. The authors have academically and ethically confirmed that the stated AI statements are true, and the authors are ultimately responsible and accountable for the contents of the published work, including the correctness of the references in the reference list.

CRediT contribution statement

Boodsayapan Thitanon: Conceptualization; Methodology; Investigation; Formal Analysis; Visualization; Writing – Original Draft; Writing – Review & Editing; Project Administration. **Jihong Kim:** Conceptualization; Methodology; Data Curation; Formal Analysis; Visualization; Writing – Review & Editing; Supervision. **Thi Thuy Linh Pham:** Conceptualization; Validation; Investigation; Resources; Writing – Review & Editing. **Thi Kim Tin Nguyen:** Conceptualization; Supervision; Writing – Review & Editing.

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