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Driving Green Port Implementation: The Role of Engineering Infrastructure and Dual Performance in Indonesian Container Terminals

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Abstract: The transition toward sustainable port management has intensified interest in how institutional pressures and organizational capabilities shape environmental and operational outcomes. This study investigates how environmental regulation, stakeholder pressure, employee training, and managerial commitment influence green engineering infrastructure and innovation and, in turn, green port implementation. The model specifies a serial mediation in which green engineering infrastructure and innovation and green port implementation connect institutional drivers to environmental performance and operational efficiency. Survey data from 221 respondents in two Indonesian container terminals were analyzed using partial least squares modeling. Results show that environmental regulation is the most influential driver, while stakeholder pressure, training, and managerial commitment reinforce capability building and adoption of low emission technologies. Green engineering infrastructure and innovation facilitates green port implementation, which significantly improves environmental performance and operational efficiency. Theoretically, the study extends institutional and resource based perspectives by clarifying how two stage mediation translates institutional pressures into dual sustainability outcomes in port settings. Practically, the findings show that sustainable port transformation in emerging economies depends on aligning regulation with investments in human capital and green technologies, guiding policymakers and port authorities.

Keywords: Green port development; Environmental regulation; Managerial commitment; Employee training; Green engineering infrastructure; Green port innovation; Serial mediation; Sustainability performance

1 Introduction

Sustainability mandates increasingly shape the strategic direction of contemporary organisations, particularly in the maritime port sector, where high operational intensity generates substantial local environmental impacts [1, 2]. Ports function as critical nodes in global supply chains and are expected to demonstrate that operational efficiency can progress in parallel with environmental responsibility. The growing importance of Environmental, Social, and Governance (ESG) criteria in regulatory assessments and investment decisions reinforces this shift, positioning sustainability as a core structural requirement within port operations rather than a supplementary initiative [3–5].

Translating sustainability commitments into consistent operational practice remains a significant challenge for container terminals. Capital-intensive infrastructure, reliance on energy-intensive equipment, and involvement of multiple stakeholder groups constrain the pace and uniformity of environmentally responsible practices [6–8]. Existing studies acknowledge these constraints but often examine individual drivers or outcomes in isolation, which limits understanding of how sustainability transformation unfolds through interconnected organisational mechanisms [9]. A more integrated perspective is therefore required, one that conceptualises sustainability not as a set of discrete interventions but as a sequential transformation process.

A key gap concerns how external pressures, internal commitments, and technological capacities interact to generate measurable sustainability outcomes. Prior research has examined drivers such as managerial commitment, stakeholder pressure, and regulatory requirements; however, the pathways by which these antecedents translate into operational capabilities and performance improvements remain insufficiently explained. In particular, few studies conceptualise green engineering infrastructure and innovation and green port implementation as consecutive stages within a broader transformation pathway. This limitation highlights the need for an analytical framework that explicitly links institutional drivers, intermediate capabilities, and dual environmental and operational performance.

The present study conceptualises green port transformation as a sequential process shaped by four organisational and institutional forces: managerial commitment, stakeholder pressure, environmental regulation, and employee training and awareness [2, 10]. These forces create an organisational climate that supports two mediating mechanisms. Green engineering infrastructure and innovation capture the technological and infrastructural readiness that enables environmental improvements [11]. Green port implementation reflects the extent to which these capabilities are embedded in operational routines and decision-making processes [12, 13]. By integrating institutional theory, the resource-based view, and implementation perspectives, the framework specifies a serial mediation pathway in which institutional and organisational drivers operate through green engineering capabilities and implementation practices to enhance environmental and operational performance [14, 15].

The Indonesian port sector provides an appropriate empirical setting to examine this model. Regulatory complexity, diverse stakeholder expectations, and uneven organisational capabilities characterise the operational environment of many emerging economies. This study focuses on two primary container terminals, New Makassar Container Terminal 1 and Terminal Petikemas Surabaya, which play central roles in the national logistics network. New Makassar Container Terminal 1 supports distribution in eastern Indonesia, whereas Terminal Petikemas Surabaya functions as a main hub for western and central regions. Both terminals operate under international management standards, including ISO 9001:2015, ISO 14001:2015, and ISO 45001:2018, and exhibit multilayered organisational structures that illustrate the practical challenges of implementing sustainability initiatives in developing country contexts [16, 17]. This study offers several contributions. Theoretically, it proposes and tests a serial mediation model that clarifies the pathways linking sustainability drivers, green engineering infrastructure and innovation, green port implementation, and dual environmental and operational outcomes [18]. Empirically, it provides evidence on the mediating mechanisms that help open the black box between sustainability initiatives and performance in container terminal operations [19]. Methodologically, it applies structural Equation modelling to capture the interconnected stages of sustainability transformation within a multi-terminal setting. In practice, the findings inform policymakers and port managers about the combinations of institutional pressure, managerial commitment, training, and technological investment that strengthen the effectiveness of sustainability implementation and support long-term competitiveness in emerging port systems.

2 Literature Review

2.1 Management Commitment as the Foundation of Green Engineering Infrastructure and Innovation

Managerial commitment is a fundamental factor that directs port organizations toward integrated sustainability practices. Within the resource-based view, leadership support is considered a strategic resource that strengthens an organization's capability to pursue long-term sustainable advantage [20]. In port operations, this commitment is reflected in managerial willingness to invest in eco-friendly technologies, energy-efficient systems, and innovation-oriented waste management, all of which form the basis of Green Engineering Infrastructure and Innovation support green engineering infrastructure and innovation [21, 22]. Such commitment shapes strategic orientation and provides clarity for sustainability-driven decisions.

Empirical studies consistently demonstrate that managerial involvement enhances the adoption of green practices. Leadership involvement directly affects an organization's readiness and encourages employees to support sustainability efforts [23]. Managerial support also strengthens a company's ability to develop sustainable processes adaptable to evolving environmental challenges [24]. Organizations that exhibit strong sustainability commitment tend to integrate green innovation into routine operational activities more effectively, thereby reinforcing the strategic relevance of managerial commitment in advancing [25]. Taken together, these findings indicate that managerial commitment is not merely an internal policy statement but a strategic driver that enables the development of green infrastructure and technical innovation.

2.2 Management Commitment and Its Influence on Green Port Implementation

Managerial commitment also plays a crucial role in the successful implementation of green port initiatives. Upper Echelon Theory argues that organizational decisions mirror the values, visions, and preferences of its leaders [10]. In the port sector, consistent leadership commitment ensures that sustainability principles extend beyond formal policy documents and become embedded within operational procedures.

Research findings highlight that managerial commitment is a prerequisite for the effective implementation of sustainable practices [26, 27]. Leaders who prioritize sustainability provide the necessary resources, set operational expectations, and reinforce environmental accountability across departments. This leadership consistency is essential to balancing environmental responsibility with operational efficiency and to ensuring that green policies are translated into measurable actions [28]. Additional studies in the port context confirm that active managerial involvement is required to allocate resources, guide strategic direction, and nurture a work culture that supports green initiatives [29]. Leadership disposition also determines the success of port decarbonization programs, which represent a core component of green port development [30]. These insights emphasize that managerial commitment functions as the institutional backbone that enables comprehensive and effective green port implementation.

2.3 Stakeholder Pressure, Employee Training and Awareness, and Environmental Regulation as Drivers of Green Engineering Infrastructure and Innovation

Employee training and environmental awareness are central components that strengthen ports' capacity to develop support green engineering infrastructure and innovation. Human capital theory holds that investing in employee skills improves organisational productivity and competitiveness [31]. In the context of port operations, environmental training enhances employees' technical understanding of low-emission equipment, energy-efficient systems, and green operational procedures, thereby supporting the development of innovation capabilities [32]. Empirical evidence shows that environmental awareness training significantly increases green innovation by encouraging proactive, sustainability-oriented work behaviour [33].

Continuous training also helps establish a sustainability-oriented work culture. Green training increases employee involvement in green innovation and promotes more efficient resource use [32]. In developing countries, where technical limitations frequently hinder modernisation efforts, training becomes a strategic mechanism that bridges capability gaps and strengthens readiness for technological adoption [21]. Research indicates that sustainability training enhances ecological awareness and managerial innovation, shifting organisations from basic compliance toward more adaptive green strategies [34]. When training is supported by strong managerial commitment, the effectiveness of green technology adoption increases significantly [35].

Environmental regulation further strengthens these internal processes. Institutional theory explains that regulatory and normative pressures shape organisational strategies toward compliance and innovation [36]. A clean, predictable regulatory environment encourages ports to invest in low-carbon technologies and align their operations with sustainability requirements [28]. The natural resource-based view also suggests that pollution prevention and energy efficiency support sustainable competitive advantage [20]. Empirical findings show that stringent environmental policies stimulate green innovation in various industries [37]. Empirical findings show that stringent environmental policies stimulate green innovation in various industries [38].

In developing countries, effective regulation has been shown to accelerate the transition toward renewable energy adoption, equipment electrification, and logistical efficiency [38]. Evidence from Vietnam shows that government pressure and environmental standards increase the likelihood that businesses will adopt greener production methods [39]. In the global port sector, international frameworks such as MARPOL Annex VI and IMO policies have driven the adoption of low-emission technologies and improved energy efficiency [28, 40]. Consequently, environmental regulation, combined with training and awareness, forms a synergistic mechanism that drives the advancement of support green engineering infrastructure and innovation.

2.4 Green Engineering Infrastructure and Innovation, Green Port Implementation, Environmental Performance, and Operational Efficiency

Green Engineering Infrastructure and Innovation serves as A central mechanism that links internal capabilities with successful Green Port Implementation. Within the Natural Resource-Based View, green infrastructure and environmental innovation are regarded as strategic resources that enable sustainable competitive advantage [11]. In port operations, support green engineering infrastructure and innovation includes technical modernisation, low-emission equipment, digital systems, and energy-efficient technologies that facilitate the practical realisation of green port implementation [41]. Successful innovation adoption depends on internal factors such as managerial support, technological readiness, and financial capacity, and is also shaped by external regulatory expectations and stakeholder involvement [8].

Implementing green port implementation results in significant improvements in environmental performance. Studies indicate that ports that adopt green strategies are better able to reduce emissions, improve energy efficiency, and manage operational externalities [29, 42, 43]. Evidence from global ports demonstrates that green initiatives significantly enhance environmental conditions, including reductions in air pollution and improvements in local ecosystems [44]. The adoption of shore-side power systems has further reduced fuel consumption and emissions, which strengthens the environmental benefits of green port implementation [45].

Green port implementation also generates tangible improvements in operational performance. Ports that integrate green technologies and digital innovation can reduce operational expenses, accelerate cargo flows, and enhance asset reliability [46]. Smart ports that leverage digital tools, the Internet of Things, and automation achieve higher operational efficiency while minimising environmental impact [47]. Electrified terminal equipment is generally more efficient and less costly to operate than fossil-fuel machinery. Electrified terminal equipment is generally more efficient and less costly to operate than fossil-fuel machinery [48]. Empirical evidence substantiates that green operations enhance economic performance and overall port competitiveness [29].

Environmental regulation is a primary catalyst that motivates ports to adopt support green engineering infrastructure and innovation and pursue green port implementation. The Natural Resource-Based View argues that effective environmental management produces long-term competitive advantages [49]. Empirical evidence substantiates that green operations enhance economic performance and overall port competitiveness [50]. Regulatory pressure encourages the adoption of clean technologies that support support green engineering infrastructure and innovation and subsequently enhance both operational and environmental performance [51–53]. Regulatory pressure encourages the adoption of clean technologies that support green engineering infrastructure and innovation and subsequently enhance both operational and environmental performance [54, 55]. Regulatory pressure encourages the adoption of clean technologies that support green engineering infrastructure and innovation and subsequently enhance both operational and environmental performance.

2.5 Serial Mediation in Sustainability, Green Management, and Dual Performance

Serial mediation models have been widely applied in sustainability and green management research to explain how organizational practices influence performance through multiple interrelated mediators [56]. One study found that green supply chain management (GSCM) practices do not directly affect environmental performance but operate indirectly via proactive environmental strategy and green product innovation. In contrast, green organizational culture demonstrated both direct and indirect effects on performance, underscoring the importance of internal strategic orientation and innovation as mechanisms that translate environmental policies into measurable outcomes [56]. Similarly, another study revealed that ambidextrous leadership significantly enhances sustainability performance through the sequential mediation of employee green creativity and green product innovation, although these findings were limited to a single industry and country context [57].

In the domain of human resource management, green HRM has been shown to improve environmental performance via the sequential mediators of green work engagement and green innovation [58]. Related research confirmed a serial mediation path in which environmentally specific servant leadership (ESSL) influences pro-environmental behavior (PEB) through green psychological empowerment and green creativity [59]. These findings suggest that sustainability outcomes are not solely dependent on formal policy interventions but are also shaped by internal mechanisms such as employee empowerment, organizational culture, and innovative capacity [8, 11, 12]. However, many of these studies are constrained by cross-sectional designs and geographically limited samples, reducing their potential for broader causal inference and generalization [60].

In the service sector, green banking practices were found to enhance sustainable performance through the dual mediation of green HRM and corporate green image [61]. Collectively, these studies confirm that serial mediation models offer valuable insight into how green practices influence organizational outcomes. Yet, to date, no research has specifically examined the interconnected influence of management commitment, environmental regulation, employee training, and stakeholder pressure on green engineering and innovation, and how these in turn affect port sustainability performance in developing countries. Therefore, this study aims to address that gap by investigating a serial mediation framework within the context of green ports, thereby contributing new empirical evidence to the literature on sustainability transformation in the maritime sector. Based on the theoretical foundations and empirical evidence reviewed in this section, the following hypotheses are formulated to guide the proposed research model.

H1: Management Commitment has a positive effect on Green Engineering Infrastructure and Innovation.

H2: Stakeholder Pressure has a positive effect on Green Engineering Infrastructure and Innovation.

H3: Employee Training and Awareness has a positive effect on Green Engineering Infrastructure and Innovation.

H4: Environmental Regulation has a positive effect on Green Engineering Infrastructure and Innovation.

H5: Green Engineering Infrastructure and Innovation has a positive effect on Green Port Implementation.

H6: Green Port Implementation has a positive effect on Environmental Performance.

H7: Green Port Implementation has a positive effect on Operational Efficiency.

H8: Green Engineering Infrastructure and Innovation mediates the relationships between the sustainability drivers (Management Commitment, Stakeholder Pressure, Employee Training and Awareness, and Environmental Regulation) and Green Port Implementation.

H9: Green Port Implementation mediates the relationship between Green Engineering Infrastructure and Innovation and Environmental Performance.

H10: Green Port Implementation mediates the relationship between Green Engineering Infrastructure and Innovation and Operational Efficiency.

H11: Green Engineering Infrastructure and Innovation and Green Port Implementation jointly mediate the relationships between the sustainability drivers and Environmental Performance.

H12: Green Engineering Infrastructure and Innovation and Green Port Implementation jointly mediate the relationships between the sustainability drivers and Operational Efficiency.

3 Methodology

3.1 Research Design and Sample

This study employed a cross-sectional survey design with a quantitative approach to examine the relationships between institutional drivers, organisational capabilities, and dual performance outcomes in green port implementation. The target population comprised 617 port employees, including 392 personnel from Terminal Petikemas Surabaya and 225 from Terminal Petikemas New Makassar 1, who were directly involved in port operations, engineering, safety, or environmental management.

The required sample size was determined using Slovin's formula with a 5% margin of error and a 95% confidence level, yielding a minimum of 243 respondents. The sample was proportionally allocated across the two terminals, resulting in 154 targeted respondents from Terminal Petikemas Surabaya and 89 from Terminal Petikemas New Makassar 1. A purposive sampling strategy was applied, with eligibility criteria requiring at least one year of work experience in the terminal and sufficient familiarity with operational processes or environmental programmes.

Questionnaires were distributed during working hours with the support of terminal management. After initial screening for completeness and basic response quality, 221 usable questionnaires were retained for analysis. The final sample provided broad organisational representation across hierarchical levels, including managers, assistant managers, supervisors, operational and engineering staff, health and safety officers, and outsourced workers, thereby supporting the robustness and internal validity of the empirical results.

3.2 Data Collection and Research Instrument

Primary data were collected through a structured questionnaire based on established literature to ensure content validity. All items were measured using a five-point Likert scale (1 = strongly disagree to 5 = strongly agree). The instrument covered eight constructs. Management Commitment (MC) was assessed using four items that reflect leadership support, resource allocation, strategic integration, and the promotion of sustainable practices [62]. Stakeholder Pressure (ST) included two items on external stakeholder influence and customer demands [63]. Employee Training and Awareness (ET) comprised four items capturing training adequacy, awareness programs, and preparedness for sustainability initiatives [64]. Environmental Regulation (ER) was measured with four items focusing on clarity, monitoring, enforcement, and policy support [65].

The mediating construct Green Engineering Infrastructure and Innovation (GEII) was measured with four items covering investment in green technologies, infrastructure adequacy, system effectiveness, and innovation [22]. Green port implementation included five items on monitoring systems, performance metrics, decision-making, continuous improvement, and sustainability progress [28]. The outcome constructs comprised Environmental Performance (EP) with four items covering air quality, water quality, waste reduction, and energy efficiency, Green port dues—the case of hinterland transport [4], and Operational Efficiency (OE) with four items reflecting cost savings, process improvements, competitive advantage, and profitability [66, 67]. A pilot test with ten respondents was conducted to refine clarity and contextual fit prior to full-scale distribution.

To ensure applicability in the Indonesian context, the measurement items were adapted to reflect the local operational environment and terminology commonly used in Indonesian port settings. A pilot test involving thirty respondents was conducted to assess item clarity, contextual relevance, and preliminary reliability. Reliability scores from the pilot test indicated that all constructs reached acceptable internal consistency, with Cronbach's Alpha values ranging from 0.72 to 0.84. These results confirmed that the adapted instrument was clearly understood and consistently interpreted by respondents, requiring no substantial revision. The finalised questionnaire was subsequently distributed to the full sample.

3.3 Questionnaire Development and Localisation

The questionnaire was developed and localised through a multi-stage process to ensure conceptual, linguistic, and cultural suitability for the Indonesian port context. First, an initial pool of items was compiled from prior empirical and theoretical studies on institutional pressures, green engineering, green port implementation, environmental performance, and operational outcomes. Overlapping or ambiguous items were removed, and the remaining items were assigned to the eight constructs based on theoretical definitions.

Second, the English questionnaire was translated into Indonesian by a professional translator who is familiar with technical and business terminology. A separate bilingual expert then conducted a back translation from Indonesian into English. The research team compared the original and back-translated English versions to identify discrepancies in meaning. Any inconsistencies were resolved through iterative refinement until the Indonesian wording accurately reflected the original scales' intended conceptual content.

Third, content validity and contextual fit were evaluated through an expert panel review. The panel comprised academics in transport, logistics, and environmental management, as well as senior practitioners from Indonesian container terminals. Experts rated each item on relevance, clarity, and appropriateness for Indonesian port operations. Their qualitative comments led to simplifying the wording, removing jargon, and aligning terminology with expressions commonly used by port personnel. The content validity index indicated satisfactory agreement on the relevance of all items retained in the final instrument.

Fourth, cognitive interviews and pilot testing were conducted prior to the primary survey. In the cognitive interview phase, a small group of port employees completed the draft questionnaire and commented on how they interpreted the questions and response options. This exercise resulted in minor adjustments to item wording and question order to improve clarity and response flow. A subsequent pilot test with 30 respondents from the two terminals was carried out to examine response distributions and preliminary reliability. All constructs showed acceptable internal consistency, with Cronbach's alphas ranging from 0.72 to 0.84. These results indicated that the items were clearly understood and consistently interpreted, and no major revisions were required before launching the primary survey.

3.4 Data Analysis

Before estimating the PLS SEM model, the dataset was subjected to systematic screening. Questionnaires were checked for missing values and incomplete responses, and cases with extensive missing data were removed. Response patterns were examined to identify straight-line answering, defined as respondents selecting the same response category across most items. Cases that exhibited such patterns were excluded from further analysis.

At the indicator level, item statistics and inter-item correlations were inspected to detect redundancy. Within the OE construct, one indicator (OE4) showed a very high loading and substantial conceptual overlap with other items that capture financial and competitive benefits of green initiatives. To avoid redundancy and artificial inflation of reliability and validity estimates, OE4 was removed from the final measurement model. Operational efficiency was therefore treated as a three-item construct (OE1–OE3) in the primary analysis, while OE4 is documented in Appendix for transparency. After all screening procedures, 221 observations remained and were used in the PLS SEM analysis.

Standard method bias was addressed through procedural and statistical remedies. Procedurally, respondents were assured of anonymity and confidentiality, items from different constructs were intermingled in the questionnaire, and neutral wording was used to reduce evaluation apprehension and social desirability. Statistically, full collinearity variance inflation factors were computed for all latent constructs. All full collinearity (VIF) values were below the recommended cut-off of 3.3, indicating that common method bias is unlikely to pose a serious threat to the validity of the findings [68].

Data were analysed using Partial Least Squares Structural Equation Modelling (PLS-SEM) with SmartPLS 4.0, following the two-step approach for measurement and structural model assessment [69]. PLS-SEM was considered appropriate given the model's complexity, the exploratory context, and the moderate sample size standard in studies of developing countries [68]. Measurement model evaluation confirmed convergent validity, with factor loadings above 0.70 and average variance extracted (AVE) values exceeding 0.50 [69]. Internal consistency was established through Cronbach's alpha and composite reliability values above 0.70 [70]. Discriminant validity was verified using the Fornell-Larcker criterion and the heterotrait monotrait ratio (HTMT) ratios below 0.90 [68]. Descriptive statistics indicated positive perceptions across constructs, with mean values above the scale midpoint and adequate response variance, confirming the dataset's reliability for hypothesis testing.

Second, the structural model was assessed by estimating path coefficients and testing their significance using bootstrapping. Explanatory power was evaluated using R-squared values for the endogenous constructs, and effect sizes were interpreted using f-squared. Predictive relevance was examined using Q-square statistics and additional predictive diagnostics. Since the data were collected from two terminals, measurement invariance was investigated using the measurement invariance of composite models (MICOM) procedure to test whether the constructs were measured equivalently across groups [68]. The results supported partial measurement invariance, which is sufficient to justify pooling the data and conducting multi-group analysis to explore potential differences in structural relationships between the Surabaya and New Makassar 1 terminals.

4 Results

4.1 Descriptive Statistics

Descriptive statistics were used to examine the central tendency and distributional properties of the constructs. All items were measured on a five-point Likert scale, so higher values indicate more favourable perceptions of the respective concept. Table 1 reports the descriptive statistics that have been aggregated at the construct level from their corresponding indicators.

The mean values of the constructs range from 3.20 (ET) to 3.72 (GEII). This pattern shows that respondents tend to agree with statements related to employee training (ET), environmental regulation (ER), environmental performance (EP), green port implementation (GPI), managerial commitment (MC), stakeholder pressure (ST), environmental orientation (EO), and green engineering infrastructure and innovation (GEII). Median values are mostly equal to 3 or 4, which confirms that the responses are concentrated around the “neutral” and “agree” categories. GEII and MC obtain the highest mean scores, which suggests that, in this sample, respondents perceive green engineering infrastructure and managerial commitment to sustainability as relatively strong. The standard deviations range from 0.69 to 0.78, which indicates a moderate spread of responses around the mean for all constructs. Skewness values lie between -0.219 and 0.522, which indicates only mild asymmetry in the distributions. Excess kurtosis varies between -0.646 and 1.208. ET shows the highest positive kurtosis, which points to a more peaked distribution, whereas MC presents the most negative kurtosis, which indicates a flatter distribution. Overall, the magnitudes of skewness and kurtosis do not suggest severe departures from normality, so the data are suitable for subsequent PLS-SEM estimation and bootstrapping procedures.

Table 1. Descriptive statistics

Construct	Mean	Median	Standard Deviation	Excess Kurtosis	Skewness
ET	3.202	3.0	0.712	1.208	-0.219
ER	3.314	3.0	0.774	0.595	0.124
EP	3.428	3.0	0.686	0.226	-0.056
GPI	3.477	3.0	0.698	0.121	0.180
MC	3.628	3.5	0.713	-0.646	0.522
ST	3.586	4.0	0.774	0.018	0.079
EO	3.599	4.0	0.766	-0.206	0.062
GEII	3.716	4.0	0.758	-0.020	-0.181

Table 2. Factor loadings, reliability, and validity of constructs

Constructs	Code	FD	α	CR	AVE
ER	ER1	0.902	0.921	0.921	0.808
	ER2	0.898			
	ER3	0.890			
	ER4	0.905			
ET	ET1	0.895	0.899	0.900	0.767
	ET2	0.865			
	ET3	0.864			
	ET4	0.879			
MC	MC1	0.897	0.899	0.902	0.767
	MC2	0.885			
	MC3	0.854			
	MC4	0.868			
ST	ST1	0.948	0.880	0.882	0.893
	ST2	0.941			
GEII	GEII1	0.895	0.909	0.909	0.785
	GEII2	0.875			
	GEII3	0.880			
	GEII4	0.894			
GPI	GPI1	0.866	0.900	0.902	0.715
	GPI2	0.807			
	GPI3	0.827			
	GPI4	0.862			
	GPI5	0.862			
EP	EP1	0.859	0.856	0.861	0.699
	EP2	0.803			
	EP3	0.828			
	EP4	0.852			
EO	EO1	0.895	0.868	0.869	0.791
	EO2	0.883			
	EO3	0.890			

4.2 Reliability and Aalidity Tests

Reliability and validity were evaluated to ensure that the measurement model met the required psychometric standards before estimating the structural relationships. Table 2 reports the factor loadings (FD), Cronbach's alpha, composite reliability (CR), and AVE for all constructs. The factor loadings range from 0.803 to 0.948 across all indicators, which is higher than the commonly recommended threshold of 0.70. This result indicates that each item loads strongly on its intended construct and supports indicator reliability [64].

Internal consistency reliability is supported by Cronbach's alpha and composite reliability. Cronbach's alpha values range from 0.856 (EP) to 0.921 (ER), and CR values range from 0.861 (EP) to 0.921 (ER). All coefficients exceed the minimum recommended value of 0.70, so the constructs can be considered internally consistent [65]. Convergent validity is confirmed by the AVE values, which lie between 0.699 (EP) and 0.893 (ST). Since all AVE values are greater than 0.50, each construct explains more than half of the variance in its indicators, in line with the criterion proposed by Fornell and Larcker [65].

Table 3. HTMT

	EO	EP	ER	ET	GEII	GPI	MC	ST
EP	0.641							
ER	0.616	0.765						
ET	0.575	0.718	0.792					
GEII	0.754	0.773	0.740	0.789				
GPI	0.864	0.820	0.699	0.660	0.838			
MC	0.685	0.586	0.580	0.509	0.704	0.788		
ST	0.727	0.641	0.626	0.638	0.787	0.792	0.742	

Table 4. Fornell–Larcker criterion

	EO	EP	ER	ET	GEII	GPI	MC	ST
EO	0.890							
EP	0.559	0.836						
ER	0.551	0.678	0.899					
ET	0.509	0.632	0.722	0.876				
GEII	0.669	0.684	0.677	0.714	0.886			
GPI	0.767	0.724	0.637	0.597	0.758	0.845		
MC	0.608	0.517	0.527	0.459	0.638	0.710	0.876	
ST	0.636	0.561	0.564	0.569	0.704	0.706	0.665	0.945

Table 5. Collinearity statistics (VIF) at the indicator level

Indicator	VIF	Indicator	VIF
EO1	2.382	GEII1	2.891
EO2	2.121	GEII2	2.507
EO3	2.359	GEII3	2.612
EP1	2.114	GEII4	2.892
EP2	1.819	GPI1	2.589
EP3	1.875	GPI2	1.997
EP4	2.162	GPI3	2.154
ER1	3.228	GPI4	2.502
ER2	3.070	GPI5	2.512
ER3	2.858	MC1	3.274
ER4	3.251	MC2	3.153
ET1	2.884	MC3	2.475
ET2	2.460	MC4	2.629
ET3	2.419	ST1	2.611
ET4	2.636	ST2	2.611

Table 6. Collinearity statistics (VIF) for structural paths

Path	VIF
ER → GEII	2.357
ET → GEII	2.271
MC → GEII	1.909
ST → GEII	2.157
GEII → GPI	1.000
GPI → EO	1.000
GPI → EP	1.000

Discriminant validity was assessed using the HTMT and the Fornell–Larcker criterion. Table 3 presents the HTMT values, which range from 0.509 to 0.864 and remain below the conservative threshold of 0.90. This indicates that the constructs are empirically distinct while still related in a theoretically meaningful way. Table 4 shows the Fornell–Larcker matrix. For each construct, the square root of the AVE on the diagonal is higher than the correlations with other constructs in the same row and column. This pattern confirms that each construct shares more variance with its own indicators than with other constructs, which supports discriminant validity.

In addition, the potential for common method bias was assessed using the full collinearity VIF approach. All VIF values for the predictor constructs in the structural model range from 1.000 to 2.357 (Table 5 and Table 6), which is below the recommended cut-off value of 3.3. This result indicates that common method variance is unlikely to pose a substantial threat to the validity of the estimated relationships among the variables.

Several procedural remedies were also implemented during data collection. The questionnaire was administered anonymously, items measuring predictor variables and outcome variables were placed in separate sections of the instrument, and the order of items within each section was randomised. These design choices were intended to reduce respondents' evaluation apprehension, limit systematic response patterns, and minimise the potential bias arising from common method bias.

4.3 Model Fitness

Model fitness was evaluated to determine the overall adequacy of the structural model and to assess whether the empirical data supported the proposed theoretical framework. The assessment incorporated several global fit indices typically recommended in PLS-SEM analysis. In Table 7, the SRMR value of 0.025 indicated an excellent level of absolute model fit because it was well below the recommended threshold of 0.08. This value reflects a minimal discrepancy between the empirical correlation matrix and the model-implied correlations, demonstrating that the model accurately represents the observed data structure.

Table 7. Model fit indices

Test	Result
SRMR	0.025
d_ULS	0.298
d_G	4.265
Chi-square	4207.683
NFI	0.801

The d_ULS and d_G values were 0.298 and 4.265, respectively, both falling within acceptable ranges and indicating that the model showed no substantial misspecification. The chi-square statistic of 4207.683 further provided support for the model's internal consistency, although this index is often sensitive to sample size. The Normed Fit Index (NFI) value of 0.801 met the commonly accepted cutoff of 0.80, showing that the proposed structural model demonstrated a substantially better fit than the null model.

4.4 Structural Model Assessment and Hypothesis Testing

The explanatory power and predictive relevance of the structural model were assessed using the R^2 and Q^2 statistics for the endogenous constructs (Table 8). GEII is explained to a substantial extent by its predictors (R^2 = 0.684), and GPI also shows a relatively high level of explained variance (R^2 = 0.575). EO and EP have moderate levels of explained variance, with R^2 values of 0.588 and 0.524, which indicates that the institutional and organisational drivers in the model account for a meaningful proportion of variance in both intermediate capabilities and sustainability outcomes.

Table 8. Explanatory power and predictive relevance

Construct	R^2	R^2 **Adjusted**	Q^2**_Predict**
EO	0.588	0.586	0.422
EP	0.524	0.522	0.438
GEII	0.684	0.678	0.672
GPI	0.575	0.573	0.592

Table 9. Effect sizes

Relationship	f^2
ER-GEII	0.036
ET-GEII	0.162
MC-GEII	0.074
ST-GEII	0.114
GEII-GPI	1.353
GPI-EO	1.426
GPI-EP	1.100

Table 10. MICOM

Step 2		
Construct	**Original Correlation**	p**-value**
EO	1.000	0.482
EP	0.999	0.299
ER	1.000	0.605
ET	0.999	0.190
GEII	0.999	0.063
GPI	0.999	0.068
MC	1.000	0.713
ST	1.000	0.193
Step 3 (Mean)		
Construct	**Original Difference**	p**-value**
EO	0.058	0.645
EP	0.015	0.901
ER	-0.040	0.778
ET	-0.069	0.620
GEII	-0.176	0.207
GPI	-0.165	0.224
MC	-0.109	0.391
ST	-0.202	0.129
Step 3b (Variance)		
Construct	**Original Difference**	p**-value**
EO	-0.117	0.556
EP	-0.511	0.033
ER	-0.670	0.007
ET	-0.571	0.051
GEII	-0.581	0.008
GPI	-0.602	0.010
MC	-0.370	0.038
ST	-0.410	0.029

The Q^2 statistics further confirm the predictive relevance of the model. All endogenous constructs record Q^2 values greater than zero, ranging from 0.422 for EO and 0.438 for EP to 0.672 for GEII and 0.592 for GPI. These values show that the model achieves adequate predictive accuracy for the endogenous constructs rather than merely reproducing the observed data.

Table 11. Results model hypothesis

Relationship	Path Coefficient (O)	P-Value
	Direct Effect	
ER → GEII	0.163	0.010
ET → GEII	0.341	0.000
MC → GEII	0.211	0.000
ST → GEII	0.278	0.000
GEII → GPI	0.758	0.000
GPI → EO	0.767	0.000
GPI → EP	0.724	0.000
	Indirect Effect	
ER → GEII → GPI	0.123	0.010
ET → GEII → GPI	0.259	0.000
MC → GEII → GPI	0.160	0.000
ST → GEII → GPI	0.211	0.000
ST → GEII → GPI → EO	0.162	0.000
MC → GEII → GPI → EO	0.122	0.000
MC → GEII → GPI → EP	0.116	0.000
ST → GEII → GPI → EP	0.153	0.000
ER → GEII → GPI → EP	0.089	0.012
ER → GEII → GPI → EO	0.095	0.011
ET → GEII → GPI → EP	0.187	0.000
ET → GEII → GPI → EO	0.198	0.000
GEII → GPI → EO	0.581	0.000
GEII → GPI → EP	0.549	0.000
	Total Effect	
ER → EO	0.095	0.011
ER → EP	0.089	0.012
ER → GEII	0.163	0.010
ER → GPI	0.123	0.010
ET → EO	0.198	0.000
ET → EP	0.187	0.000
ET → GEII	0.341	0.000
ET → GPI	0.259	0.000
GEII → EO	0.581	0.000
GEII → EP	0.549	0.000
GEII → GPI	0.758	0.000
GPI → EO	0.767	0.000
GPI → EP	0.724	0.000
MC → EO	0.122	0.000
MC → EP	0.116	0.000
MC → GEII	0.211	0.000
MC → GPI	0.160	0.000
ST → EO	0.162	0.000
ST → EP	0.153	0.000
ST → GEII	0.278	0.000
ST → GPI	0.211	0.000

The f^2 results in Table 9 indicate that the effects of ER, MC, and ST on GEII fall within the small effect size range, while ET shows a medium effect size on GEII. In contrast, the effects of GEII on GPI and of GPI on EO and EP clearly exceed the conventional benchmark for a large effect size and can be classified as very large.

Measurement invariance between the Surabaya and New Makassar 1 groups was examined using the MICOM procedure, and the results are summarised in Table 10. The Step 2 results show that the original correlations between the composites and their permuted counterparts are close to one and that all permutation p values are above 0.05. This pattern indicates compositional invariance and suggests that the composites for EO, EP, ER, ET, GEII, GPI, MC, and ST have a comparable meaning in both groups. The Step 3 results further show that the differences in composite means are small and not statistically significant, which implies that the latent means do not differ meaningfully between the two terminals.

For the composite variances, several constructs display significant differences, as indicated by permutation p values below 0.05 in Table 10. These findings indicate that the model attains partial rather than full measurement invariance. Partial invariance is generally regarded as sufficient to compare structural relationships across groups and to pool the data in the main PLS SEM analysis. The combined sample can therefore be used to estimate and interpret the structural model, while acknowledging that some constructs exhibit different levels of dispersion between the two terminals.

The structural model results in Table 11 show that all direct relationships are positive and statistically significant ($p < 0.05$, with most paths at $p < 0.001$). ER, ET, MC, and ST each have significant effects on GEII, indicating that regulatory pressure, training, managerial commitment, and stakeholder expectations jointly reinforce green engineering infrastructure and innovation. GEII has a strong positive effect on GPI, and GPI in turn exerts substantial positive effects on EO and EP. These results indicate that GEII and GPI act as central mechanisms that translate institutional and organisational drivers into dual sustainability outcomes at the port level.

The indirect and total effects reported in Table 10 further confirm a consistent serial mediation pattern. ER, ET, MC, and ST influence GPI, EO, and EP through GEII and GPI, with all indirect effects reaching statistical significance. The serial pathways show that institutional and organisational factors first shape technological capabilities and implementation practices, which then improve environmental orientation and environmental performance. The magnitude and significance of the total effects for ET, MC, and ST on EO and EP highlight the combined contribution of direct capability building and mediated channels. Overall, the pattern of direct, indirect, and total effects supports the proposed structural model and underlines the role of integrated institutional and resource based processes in driving green port transformation (Figure 1).

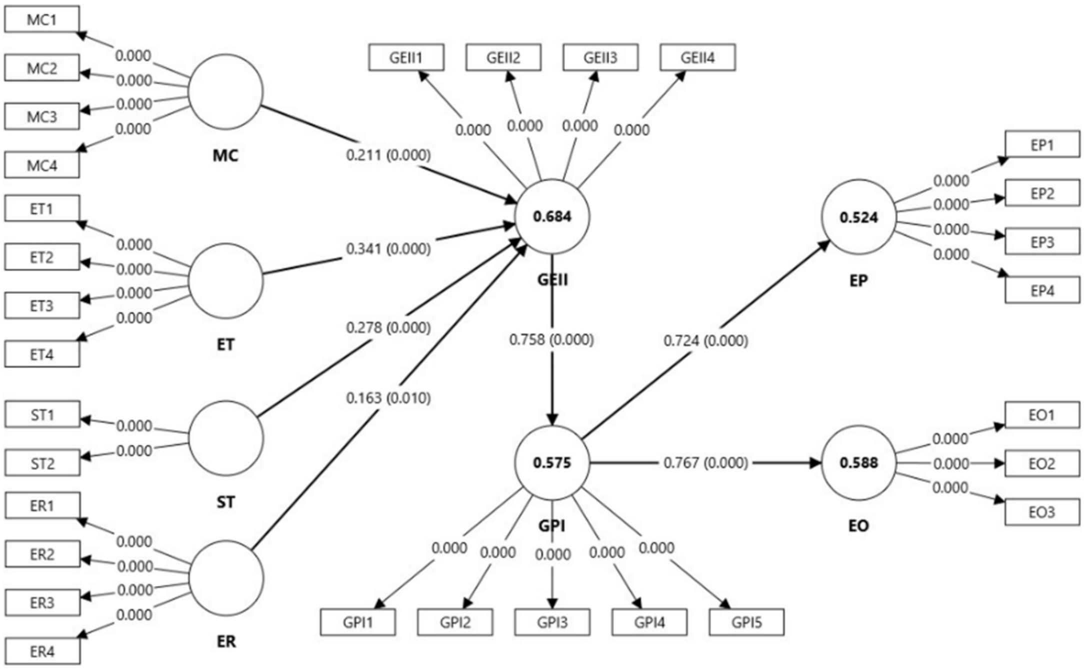

Figure 1. Assessment of structural model

Note: The model was estimated using PLS-SEM with N = 221 and a bootstrap procedure with 5,000 resamples (two-tailed test).

5 Discussion

The results indicate that environmental regulation plays the most decisive role in shaping green engineering infrastructure and innovation. Regulatory mandates function as the dominant institutional mechanism that compels ports to invest in cleaner technologies and improve environmental standards. This pattern aligns with the core argument of institutional theory, which identifies coercive pressure as the strongest driver of organizational change [36]. A similar trend is observed in global maritime settings, where international frameworks such as MARPOL Annex VI and IMO decarbonization policies have accelerated the adoption of energy-efficient technologies in major ports [28, 40]. Regulation in Indonesia compensates for limitations in technological readiness and capital resources, thereby reinforcing observations that environmental regulation often stimulates innovation in resource-constrained environments [20].

This finding becomes more comprehensible when juxtaposed with European ports, including Rotterdam, Antwerp, and Hamburg. These ports function in highly institutionalized regulatory environments, where advanced innovation platforms consistently enforce environmental policy. Studies in these regions indicate that strict environmental rules mandate compliance and accelerate the development of cleaner technologies by reinforcing long-term investment certainty [28]. The findings of this study align with this pattern; however, the Indonesian context exhibits a heightened reliance on regulation due to the ongoing development of organizational resources and technological ecosystems.

We also conclude that stakeholder pressure positively influences the development of green infrastructure and environmental innovation. Customers, communities, and logistics partners appear to be increasingly aware of environmental responsibilities, shaping expectations for cleaner operations. This supports the logic of stakeholder theory, which links organizational legitimacy to responsiveness toward stakeholder expectations [70]. Although stakeholder influence in Indonesia remains less institutionalized than in European ports, the emerging pattern resembles findings from Asian contexts where normative expectations are rising gradually as awareness increases [41]. Ports in East Asia offer relevant comparisons because stakeholder expectations there are strengthened by urban port city dynamics and high public scrutiny. These regions demonstrate how stakeholder influence can progressively shape technology adoption, reflecting a future trajectory that Indonesian ports may follow as institutional maturity increases.

Employee training contributes significantly to the development of green engineering innovation. This is in line with human capital theory, which says that the skills and abilities of the workforce are important for changing an organization [31]. Environmental training increases employees' technical understanding of energy-saving technologies, digital tools, and low-emission operational procedures, consistent with studies showing that training enhances green innovation behaviors [32]. Training also reinforces ecological awareness and managerial innovation, enabling organizations to transition from basic compliance toward more adaptive strategies [33, 34]. Singapore's and Busan's ports show how highly structured training systems can help people quickly learn new technologies. Indonesian ports, on the other hand, use training to fill in skill gaps and build the basic skills needed for GEII development [21].

Managerial commitment also plays a crucial role. Leadership involvement ensures that sustainability goals are embedded in strategy, resource allocation, and daily operational decision-making. This aligns with the resource-based view, which emphasizes that intangible assets such as leadership commitment and organizational culture contribute to long-term competitive advantage [71]. Studies in port settings similarly highlight that committed leadership strengthens organizational readiness for environmental transformation [23–25]. Upper Echelon Theory elucidates that strategic decisions frequently mirror the values and perspectives of senior leaders, underscoring the necessity for unwavering leadership commitment in sustainability initiatives [10].

Research demonstrates that the implementation of green port practices directly benefits from green engineering infrastructure. This supports the natural resource-based view, which views green innovation and technical modernization as strategic assets that enable sustainable performance improvements [11]. Evidence from port studies shows that infrastructure modernization, such as the adoption of shore-side power or digital monitoring systems, naturally evolves into more structured green port practices [41].Comparing this with East Asian ports reveals that ports with advanced GEII transition more quickly to operational green practices because of higher levels of automation and digital maturity. Indonesian ports follow the same pattern but require ongoing investment to strengthen their technological base.

Green port implementation contributes significantly to both environmental and operational performance. Ports that adopt structured green practices achieve reductions in emissions and improvements in environmental quality, confirming observations from ports in China, Europe, and Southeast Asia [42–44]. Green operations also enhance efficiency, reduce fuel use, and minimize downtime, consistent with evidence that digital optimization and equipment electrification improve operational reliability [45–48]. While environmental and operational outcomes are influenced by multiple structural and market factors, the results confirm that green operational practices form a significant component of performance improvement.

Examining the sequential transformation pathway in this study provides a more profound understanding. Environmental regulation propels technological readiness via green engineering infrastructure. Technological readiness facilitates operational implementation via green port practices, which subsequently yield positive environmental and operational results. This multi-layered pathway reflects the findings of studies showing that green innovation and implementation capability act as consecutive mechanisms linking institutional pressure to sustainability performance [37, 38, 54, 55]. Comparisons with global ports confirm that this sequential model reflects the broader dynamics of sustainability transitions in the maritime sector: external pressures initiate change, internal capabilities enable it, and operational practices sustain it.

The patterns seen in this study show that the move toward greener port operations happens when regulatory direction, organizational capacity, and technological adaptation all work together. As these elements reinforce one another, green engineering systems begin to shape operational routines in ways that mirror developments in ports undergoing similar sustainability transitions. Evidence from maritime logistics research also highlights that such transitions typically unfold through cumulative adjustments in institutional pressure, technological readiness, and managerial support, illustrating a shared pathway across regions [51]. In the Indonesian context, these dynamics reveal how institutional strengthening, workforce capability, and leadership orientation gradually guide the evolution of sustainability practices, demonstrating that environmental upgrading is shaped through an ongoing and collective process within port organizations.

6 Conclusion

The study examined how environmental regulation, stakeholder pressure, employee training, and managerial commitment shape the development of green engineering infrastructure and the implementation of green port practices in two major Indonesian container terminals. The empirical evidence indicates that sustainability in port operations arises from the interaction between strong institutional forces and internal organizational capabilities. Environmental regulation emerged as the most influential driver, reflecting the importance of clear and enforceable policy standards in accelerating the adoption of low-emission technologies. Stakeholder expectations contributed positively, signaling growing public interest in environmental responsibility within the maritime sector. Employee training improved technical readiness and strengthened operational understanding, while managerial commitment ensured that sustainability priorities became embedded within strategic planning and routine operational decisions. The combined results expand theoretical perspectives by illustrating how institutional theory, human capital theory, the resource-based view, and the natural resource-based view collectively explain the layered progression of green transformation in port environments.

Policy and managerial implications arise from the empirical insights. Strengthened regulatory mechanisms and consistent enforcement can accelerate technological modernization at the terminal level. We need to expand human capital development programs to guarantee the technical competency of operational personnel in supporting low-carbon equipment and digital environmental systems. To strengthen long-term commitment to the organization, leadership structures should include sustainability indicators in evaluations of managers' performance. Investing in energy-efficient technologies, monitoring systems, and updated equipment can help make port operations more reliable and better for the environment.

Several limitations require attention. The analysis was confined to Terminal Petikemas Surabaya and Terminal Petikemas New Makassar 1, which restricts generalizability across ports with different institutional contexts, operational characteristics, or technological capabilities. The cross-sectional design constrains the capacity to monitor enduring shifts in organizational behavior and environmental innovation. Broader research that includes additional ports, longitudinal data, or mixed-method approaches may reveal more profound insights into the dynamics of sustainability adoption and the evolution of green operational systems. Comparative studies across various countries or maritime regions may elucidate contextual variations that influence global advancements toward sustainable port development.

Overall findings add to academic and applied discussions on maritime sustainability by showing that coordinated regulatory, organizational, and technological efforts can deliver meaningful improvements in environmental and operational outcomes. The study provides an empirical foundation for strengthening policy coherence, organizational capability, and technological investment to support long-term sustainable development within emerging port economies.

Author Contributions

Conceptualization: Z.Y.I. and G.S.; methodology: Z.Y.I. and G.S.; software: I.; validation: G.S. and I.; formal analysis: G.S., M.I., and I.; investigation: G.S., M.I., and I.; resources: Z.Y.I.; data curation: M.I. and I.; writing—original draft: Z.Y.I.; writing—review and editing: G.S., M.I., and I.; visualization: I. and M.I.; supervision: Z.Y.I.; project administration: Z.Y.I. and G.S. All authors have read and approved the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix

Table A1. Questionnaire items, outer loadings, and reliability

Construct	Code	Short Questionnaire Statement	Outer Loading	α	CR	AVE
ER	ER1	Environmental regulations in our operations are clear.	0.829	0.821	0.844	0.808
	ER2	Environmental regulations are regularly monitored by the authorities.	0.830			
	ER3	Environmental regulations are strictly enforced in our operations.	0.839			
	ER4	Environmental policies strongly support green port initiatives.	0.826			
ET	ET1	Employees receive adequate training on environmental issues.	0.902	0.899	0.829	0.817
	ET2	Awareness programmes explain the importance of green practices.	0.721			
	ET3	Employees are prepared to implement sustainability initiatives.	0.767			
	ET4	Regular training is provided on environmental management.	0.824			
MC	MC1	Top management clearly supports sustainability initiatives.	0.836	0.899	0.829	0.845
	MC2	Management provides sufficient resources for green programmes.	0.912			
	MC3	Environmental objectives are included in organisational strategic plans.	0.801			
	MC4	Management encourages employees to join sustainability efforts.	0.834			
ST	ST1	External stakeholders expect better environmental performance.	0.838	0.880	0.843	0.893
	ST2	Customers and partners pressure us to adopt greener practices.	0.834			
GEII	GEII1	We invest in infrastructure for environmentally friendly operations.	0.818	0.809	0.836	0.832
	GEII2	Existing infrastructure supports green engineering solutions.	0.811			
	GEII3	Technical systems reduce the environmental impact of operations.	0.815			

Table A1. Questionnaire items, outer loadings, and reliability

Construct	Code	Short Questionnaire Statement	Outer Loading	α	CR	AVE
GPI	GEII4	We develop and apply green engineering innovations.	0.821	0.800	0.826	0.815
	GPI1	Clear monitoring systems guide green port implementation.	0.890			
	GPI2	Green performance indicators are used in decision making.	0.890			
	GPI3	Management monitors progress in green port implementation.	0.825			
	GPI4	Continuous improvement activities support green practices.	0.821			
	GPI5	Green port initiatives are regularly reviewed and updated.	0.825			
EP	EP1	Air emissions from our operations have been reduced.	0.802	0.856	0.803	0.832
	EP2	Water quality around the port area has improved.	0.820			
	EP3	Waste from our activities has been reduced.	0.828			
	EP4	Energy efficiency in our operations has improved.	0.825			
EO	EO1	Green practices have reduced operating costs.	0.862	0.899	0.889	0.865
	EO2	Environmental initiatives have improved operational efficiency.	0.803			
	EO3	Green initiatives have improved our financial and market position.	0.840			
	EO4	Environmental initiatives have improved financial performance and profitability.	0.845			