# Sustainability Analysis of Loading and Discharging Process Supervision in the Era of Green Port

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***Abstract***
*This research examines the sustainability of monitoring loading and discharging processes in ports adopting Green Port principles. Using a mixed-methods approach combining qualitative and quantitative descriptive methods, this study analyzes the effectiveness of green technology implementation, environmental impacts, and economic efficiency in port operations. The findings reveal that green technologies, including electric-powered cranes and automated energy-efficient systems, successfully reduced carbon emissions by 20-30% and decreased fossil fuel consumption by 15%. Life Cycle Assessment (LCA) results demonstrated a 25% reduction in $CO_2$ emissions and a 40% decrease in operational waste. Cost-Benefit Analysis (CBA) indicated that despite initial investment costs being 15-20% higher than conventional options, long-term operational savings of 10-15% annually were achieved, with operational time reduced by 8%. Key challenges identified include the lack of technical skills among operators, high initial investment costs, particularly for small and medium-sized ports, and regulatory constraints. Survey results showed that 75% of operational staff supported green port initiatives, while 65% reported improved workplace safety due to reduced exposure to pollution. This research provides strategic recommendations for enhancing sustainability in loading and discharging monitoring, including continuous workforce training, public-private collaboration to finance green technology, and the development of supportive regulatory policies. The findings serve as a practical guide for port operators and policymakers in implementing environmentally friendly monitoring practices aligned with global sustainability targets.*

***Keywords:*** *Green port, loading and discharging monitoring, sustainability, green technology, port operations*

**Abstrak**
*Penelitian ini mengkaji keberlanjutan pengawasan proses loading dan discharging di pelabuhan yang mengadopsi prinsip Pelabuhan Hijau (Green Port). Menggunakan pendekatan metode campuran yang menggabungkan metode deskriptif kualitatif dan kuantitatif, penelitian ini menganalisis efektivitas implementasi teknologi hijau, dampak lingkungan, dan efisiensi ekonomi dalam operasional pelabuhan. Temuan menunjukkan bahwa teknologi hijau, termasuk crane bertenaga listrik dan sistem otomatis hemat energi, berhasil mengurangi emisi karbon sebesar 20-30% dan menurunkan konsumsi bahan bakar fosil sebesar 15%. Hasil Life Cycle Assessment (LCA) menunjukkan penurunan emisi $CO_2$ sebesar 25% dan pengurangan limbah operasional hingga 40%. Cost-Benefit Analysis (CBA) mengindikasikan bahwa meskipun biaya investasi awal 15-20% lebih tinggi dibandingkan opsi konvensional, penghematan operasional jangka panjang mencapai 10-15% per tahun dengan pengurangan waktu operasional sebesar 8%. Tantangan utama yang teridentifikasi meliputi kurangnya keterampilan teknis operator, biaya investasi awal yang tinggi terutama bagi pelabuhan kecil dan menengah, serta kendala regulasi. Hasil survei menunjukkan 75% staf operasional mendukung inisiatif pelabuhan hijau, sementara 65% melaporkan peningkatan keselamatan kerja akibat berkurangnya paparan polusi. Penelitian ini memberikan rekomendasi strategis untuk meningkatkan keberlanjutan dalam pengawasan loading dan discharging, meliputi pelatihan berkelanjutan tenaga kerja, kolaborasi pemerintah-swasta untuk pembiayaan teknologi hijau, dan pengembangan kebijakan regulasi yang*

*mendukung. Temuan ini menjadi panduan praktis bagi operator pelabuhan dan pembuat kebijakan dalam menerapkan praktik pengawasan ramah lingkungan yang selaras dengan target keberlanjutan global.*

**Kata Kunci**: *Pelabuhan hijau, pengawasan loading dan discharging, keberlanjutan, teknologi hijau, operasional pelabuhan*

## INTRODUCTION

The maritime and port sector faces significant environmental challenges due to intensive energy consumption and carbon emissions, particularly during loading and discharging operations. Traditional port operations contribute substantially to greenhouse gas emissions, air pollution, and water contamination, threatening both local ecosystems and global climate stability. Despite increasing awareness of environmental sustainability, many ports continue to rely on conventional technologies and practices that prioritize operational efficiency over environmental protection. The transition toward Green Port principles has emerged as a critical solution, yet the implementation of sustainable monitoring practices in loading and discharging processes remains understudied. This gap is particularly evident in understanding how green technologies can be effectively integrated into operational monitoring while maintaining efficiency and economic viability.

This research needs to be conducted for several urgent reasons: first, the lack of empirical data on the effectiveness of green technologies in the context of loading and discharging monitoring creates uncertainty for port operators in making investment decisions; second, the absence of comprehensive practical guidelines regarding implementation challenges, including economic, technical, and human resource aspects, hinders the widespread adoption of Green Ports; third, with increasing international regulatory pressure and global commitments to carbon emission reduction, ports require evidence-based strategies to transform their operations without sacrificing productivity; fourth, the research gap concerning workforce perception and readiness in adopting green technologies needs to be bridged to ensure long-term implementation success. The lack of comprehensive research on practical challenges, economic implications, and workforce adaptation required for sustainable port operations impedes the widespread adoption of Green Port initiatives globally. Therefore, this research is crucial for filling these knowledge gaps and providing strategic recommendations that can be implemented by ports of varying scales and geographic contexts.

Recent literature highlights various strategies for implementing Green Port concepts, including the adoption of renewable energy sources such as solar and wind power for port operations (Dwipayana & Darmayanti, 2024), integration of energy-efficient technologies to reduce consumption and operational costs, and comprehensive waste management practices to minimize pollution and promote recycling (Anwar & Prawiraatmadja, 2024). Studies demonstrate that implementing green logistics can lead to significant reductions in carbon emissions intensity, particularly through optimizing energy systems in the transportation industry. Green Port Management Practices (GPMP) are essential for balancing economic growth with ecological concerns, as evidenced by studies of 12 Asian ports that highlight pollution control as a significant driver (Mahmud et al., 2023). Automation and digitalization play crucial roles in enhancing GPMP by facilitating efficient operations while minimizing environmental impacts. The deployment of green technologies, such as electric-powered cranes and renewable energy systems, significantly reduces ports' environmental footprint (Elnabawi & Elsalam, 2023; Parhamfar et al., 2023). Case studies, such as the Port of Rotterdam, demonstrate the effectiveness of these technologies in achieving operational efficiency and environmental improvements. However, challenges such as regulatory complexity and high initial investment costs hinder the widespread adoption of green technologies (Rudzki et al., 2023).

This research argues that the successful implementation of sustainable monitoring in loading and discharging processes within Green Ports requires a holistic approach that integrates technological innovation, workforce development, and supportive policy frameworks. It is hypothesized that green technologies, when combined with adequate infrastructure readiness and comprehensive staff training, can significantly reduce carbon emissions and operational costs while improving overall port efficiency. Furthermore, the research posits that the effectiveness of green technology adoption varies depending on port size, available resources, and regulatory support, with larger ports demonstrating greater success due to better access to capital and advanced infrastructure. The study also hypothesizes that workforce perception and technical competency are critical determinants of successful green technology implementation, and that continuous training programs can accelerate adaptation periods and enhance operational outcomes. Economic analysis is expected to reveal that while initial investment costs are substantially higher for green technologies, long-term operational savings and environmental benefits justify the transition, particularly when supported by government incentives and public-private partnerships.

This research aims to comprehensively analyze the sustainability of monitoring loading and discharging processes in ports that adopt Green Port principles. Specifically, the study seeks to: (1) evaluate the effectiveness of green technologies, including electric-powered cranes and automated energy-efficient systems, in reducing carbon emissions and fossil fuel consumption during port operations; (2) assess the environmental impacts through Life Cycle Assessment (LCA) and quantify improvements in waste management and water quality; (3) conduct a Cost-Benefit Analysis (CBA) to determine the economic viability of green technology investments and identify the return on investment timeline; (4) identify key challenges and barriers to implementing sustainability measures, including technical skill gaps, high initial costs, and regulatory constraints; (5) examine workforce perceptions and attitudes toward Green Port initiatives and their willingness to adapt to new technologies; and (6) develop strategic recommendations for enhancing sustainability in loading and discharging monitoring that can serve as practical guidelines for port operators, policymakers, and stakeholders globally in implementing environmentally friendly practices aligned with international sustainability targets.

## METHOD

### 1. Research Design.

This study employs a mixed-methods research design that combines qualitative descriptive and quantitative approaches to comprehensively analyze sustainable monitoring practices in loading and discharging processes at green ports. The mixed-methods approach provides a holistic understanding of sustainability practices by integrating diverse data sources and perspectives, enhancing the depth and validity of the analysis. This approach is particularly effective for maritime research as it allows for both in-depth exploration of contextual factors and statistical validation of findings.

### 2. Research Location and Context.

This research was conducted at three major seaports in Indonesia that have implemented or are in the process of implementing Green Port initiatives: Tanjung Priok Port (Jakarta), Tanjung Perak Port (Surabaya), and Belawan Port (Medan). These ports were selected based on purposive sampling criteria, including: (1) active implementation of green technology initiatives, (2) significant cargo handling volume, (3) availability of both conventional and green technology systems for comparison, and (4) willingness of port management to participate in the research. The study was conducted over a six-month period from January to June 2024.

**3. Population and Sample.**

The research population consists of port operational staff, supervisors, managers, and stakeholders directly involved in loading and discharging operations at the selected ports. Using purposive sampling technique, a total of 150 respondents were selected, comprising: 80 operational staff (crane operators, cargo handlers, technical personnel), 40 supervisors and middle managers, 20 senior managers and port authorities, and 10 external stakeholders (shipping company representatives, environmental consultants, and regulatory officials). The sample size was determined based on the principle of data saturation for qualitative data and statistical adequacy for quantitative analysis.

**4. Data Collection Methods**

***Qualitative Data Collection,*** Semi-structured in-depth interviews were conducted with 45 key informants, including port managers, operational supervisors, and technical staff, to gather detailed insights into implementation challenges, workforce adaptation, and operational experiences with green technologies. Interview sessions lasted 45-60 minutes and were audio-recorded with participant consent. Direct observation was carried out at loading and discharging sites to document actual operational practices, technology utilization patterns, and environmental management procedures. Observations were conducted during both peak and off-peak operational hours across a total of 120 hours. Document analysis was performed on port operational records, environmental impact reports, energy consumption data, maintenance logs, and policy documents to triangulate findings from interviews and observations.

***Quantitative Data Collection,*** Structured questionnaires were administered to 150 respondents to collect data on workforce perceptions, attitudes toward sustainability, technical competency levels, and safety perceptions. The questionnaire used a 5-point Likert scale and was validated through expert review and pilot testing with 20 respondents prior to full deployment. Technical measurements included collection of quantitative data on carbon emissions ($CO_2$), energy consumption, operational time, waste generation, and water quality indicators. Data were obtained from port monitoring systems, equipment sensors, and environmental monitoring reports covering the period 2022-2024. Life Cycle Assessment (LCA) data were collected to evaluate the environmental impacts of loading and discharging operations, comparing conventional and green technology approaches across the entire operational lifecycle. Cost-Benefit Analysis (CBA) data were gathered from financial reports, operational budgets, investment records, and maintenance cost documentation to assess the economic viability of green technology investments.

***Research Instruments.*** Interview guides with open-ended questions covering technology effectiveness, implementation challenges, workforce adaptation, and policy support; Structured observation checklists for documenting operational practices, technology usage, safety procedures, and environmental management activities; Validated questionnaires containing demographic information, technical competency assessment, perception scales, and attitude measurements regarding green port initiatives; Data extraction forms for systematically collecting quantitative data from monitoring systems, reports, and documents.

**5. Data Analysis Procedures**

***Qualitative Data Analysis*****.** Interview transcripts and observation notes were analyzed using thematic analysis following these steps: (1) data familiarization through repeated reading of transcripts, (2) initial coding to identify meaningful segments, (3) theme development by grouping related codes, (4) theme review and refinement, and (5) defining and naming final themes. NVivo 12 software was used to facilitate the coding process and ensure systematic analysis. Triangulation was performed by comparing findings from interviews, observations, and document analysis to enhance credibility and validity.

**Quantitative Data Analysis.** Descriptive statistics (mean, standard deviation, frequency distribution, percentage) were calculated to summarize respondent characteristics, perception scores, and technical measurements. Comparative analysis was conducted using independent t-tests and ANOVA to compare emission levels, energy consumption, and operational efficiency between conventional and green technology operations. Cost-Benefit Analysis (CBA) was performed by calculating initial investment costs, operational savings, payback periods, and return on investment (ROI) over a 10-year projection period. Life Cycle Assessment (LCA) was conducted following ISO 14040 standards to quantify environmental impacts across operational stages, including resource extraction, energy production, equipment operation, and waste management. Statistical analysis was performed using SPSS version 26, with significance levels set at $p < 0.05$.

**Data Integration.** The mixed-methods integration followed a convergent parallel design where qualitative and quantitative data were collected simultaneously, analyzed independently, and then merged during interpretation. Integration occurred through: (1) comparing statistical findings with qualitative themes to identify convergence or divergence, (2) using qualitative data to explain quantitative patterns, and (3) using quantitative data to validate qualitative findings. Joint displays were created to visually present integrated findings and facilitate comprehensive interpretation.

**Ethical Considerations.** This research obtained ethical approval from the institutional research ethics committee. All participants provided informed consent after receiving detailed information about the research purpose, procedures, and their rights. Confidentiality and anonymity were maintained by assigning codes to participants and securely storing data. Participants were informed of their right to withdraw from the study at any time without penalty. Port operations were not disrupted during data collection, and all safety protocols were strictly followed during site observations.

**Research Limitations.** This study acknowledges several limitations: (1) the focus on three Indonesian ports may limit generalizability to other geographical contexts with different regulatory environments and infrastructure capabilities, (2) the six-month data collection period may not capture long-term trends or seasonal variations in port operations, (3) self-reported data from questionnaires may be subject to social desirability bias, and (4) limited access to proprietary financial data from some port operators may affect the comprehensiveness of economic analysis. These limitations are addressed through triangulation of multiple data sources and transparent reporting of findings.

## DISCUSSION

This study reveals significant findings regarding the implementation of green technologies in the supervision of loading and discharging at ports adopting Green Port principles. The discussion below synthesizes empirical results with theoretical frameworks and existing literature to provide comprehensive insights into sustainability practices in port operations.

### Effectiveness of Green Technologies in Reducing Environmental Impact

The empirical findings demonstrate that green technologies, particularly electric-powered cranes and automated energy-efficient systems, achieved substantial reductions in carbon emissions (20-30%) and fossil fuel consumption (15%). These results align with previous research emphasizing the critical role of technological innovation in maritime sustainability. However, the variation in reduction rates across the three studied ports—Tanjung Priok, Tanjung Perak, and Belawan—reveals that effectiveness is not uniform but contingent upon several moderating factors.

Infrastructure readiness emerged as a primary determinant of technology effectiveness. Ports with advanced infrastructure systems demonstrated faster adaptation and higher efficiency gains compared to those with limited technical capacity. This finding corroborates theoretical frameworks suggesting that technological adoption requires complementary organizational capabilities and physical infrastructure. The 8% reduction in operational time further validates that green technologies can enhance both environmental and operational performance simultaneously, challenging the traditional assumption that sustainability initiatives necessarily compromise efficiency.

Workforce training intensity also significantly influenced outcomes. Ports that implemented comprehensive and continuous training programs for operators achieved more consistent emission reductions. This underscores the socio-technical nature of sustainability transitions, where human capital development is as crucial as technological investment. The qualitative data revealed that operators who received extensive training demonstrated greater confidence and competency in utilizing green equipment, resulting in optimized operational patterns that maximized environmental benefits.

**Environmental Sustainability: Life Cycle Assessment Insights**

The Life Cycle Assessment (LCA) results provide robust evidence of environmental improvements across multiple indicators. The 25% reduction in $CO_2$ emissions and 40% decrease in operational waste represent substantial progress toward environmental sustainability goals. These findings are particularly significant when contextualized within Indonesia's maritime sector, where traditional port operations have historically contributed heavily to regional pollution.

Water quality improvements, with an 18% reduction in pollution levels, demonstrate that green port initiatives extend beyond atmospheric emissions to encompass broader ecological health. The implementation of advanced Port Waste Management Systems (PWMS) proved effective in minimizing operational waste generation and improving waste treatment processes. This holistic environmental improvement suggests that green port strategies should adopt integrated approaches addressing multiple environmental dimensions simultaneously rather than focusing narrowly on carbon emissions alone.

However, the study also identified variability in environmental outcomes across different port sizes and operational scales. Larger ports with greater resource availability consistently achieved more substantial environmental improvements compared to smaller ports. This disparity highlights potential environmental justice concerns, where smaller ports and their surrounding communities may continue experiencing disproportionate environmental burdens due to resource constraints limiting green technology adoption. Addressing this inequity requires targeted policy interventions and financial support mechanisms specifically designed for smaller port facilities.

**Economic Viability and Cost-Benefit Analysis**

The Cost-Benefit Analysis reveals a complex economic picture that challenges simplistic assessments of green technology investments. While initial investment costs were 15-20% higher than conventional alternatives, the long-term operational savings of 10-15% annually demonstrate clear economic advantages over extended timeframes. The payback period analysis indicates that most green technology investments achieve positive returns within 5-8 years, making them economically viable from a lifecycle perspective.

Energy efficiency gains proved particularly significant in driving economic benefits. Reduced energy consumption translated directly into lower operational costs, while decreased maintenance requirements for newer green equipment further enhanced cost savings. The 8% reduction in operational time also generated indirect economic benefits through increased throughput capacity and improved service delivery to shipping companies.

Nevertheless, the economic analysis exposed significant barriers for small and medium-sized ports. The high upfront capital requirements create substantial financial hurdles for ports with limited budgets or restricted access to financing. This finding suggests that market mechanisms alone may be insufficient to drive widespread green port adoption, necessitating public sector intervention through subsidies, low-interest financing programs, or public-private partnership models to enable smaller ports to participate in sustainability transitions.

**Workforce Perceptions and Organizational Change**

Survey results revealing that 75% of operational staff support green port initiatives indicate generally positive workforce attitudes toward sustainability. However, this support coexists with concerns about technical competency requirements and adaptation challenges. The qualitative interviews revealed that while workers intellectually endorse environmental goals, they simultaneously express anxiety about their ability to master new technologies and worry about potential job implications.

The reported improvement in workplace safety perceptions (65% of respondents) represents an important but often overlooked benefit of green port transitions. Reduced exposure to pollutants and hazardous materials directly enhances worker health and safety, creating intrinsic motivation for sustainability beyond environmental concerns. This finding suggests that framing green port initiatives in terms of worker welfare alongside environmental benefits may enhance acceptance and engagement.

The adaptation period required for workforce proficiency with green technologies exceeded initial expectations in all three studied ports. This temporal dimension of organizational change highlights the importance of realistic implementation timelines and sustained training investments. Rapid technology deployment without adequate workforce preparation risks operational disruptions and suboptimal utilization of green equipment capabilities.

**Regulatory and Policy Challenges**

Regulatory constraints emerged as significant impediments to green port implementation across all research sites. Inconsistent environmental standards across different jurisdictions, bureaucratic complexities in obtaining permits for new technologies, and absence of clear green port certification frameworks create uncertainty and increase transaction costs for port operators considering sustainability investments.

The research identified a critical policy gap: while national governments have established broad environmental goals, specific operational guidelines and technical standards for green port implementation remain underdeveloped. This regulatory vacuum forces individual ports to develop ad-hoc approaches, resulting in inefficient resource allocation and missed opportunities for standardization and knowledge sharing across the sector.

Conversely, where supportive policies existed—such as tax incentives for renewable energy investments or streamlined approval processes for green technology installations—adoption rates and implementation success increased markedly. This pattern strongly suggests that comprehensive policy frameworks combining regulatory requirements, financial incentives, and technical support mechanisms are essential for accelerating green port transitions at scale.

**Strategic Recommendations for Enhanced Sustainability**

Based on the integrated findings, several strategic recommendations emerge for improving sustainability in loading and discharging supervision:

***Capacity Building and Training*****:** Establish mandatory continuous professional development programs specifically focused on green technology operation and maintenance. These programs should combine theoretical instruction with hands-on practical training and include regular competency assessments to ensure workforce readiness.

***Financial Mechanisms:*** Develop diversified financing options including government subsidies, green bonds, concessional loans, and public-private partnerships tailored to different port sizes and financial capacities. Priority should be given to supporting small and medium-sized ports that face the greatest financial barriers.

***Regulatory Harmonization:*** Create unified national standards for green port operations that provide clear technical specifications, performance benchmarks, and certification criteria. Regulatory frameworks should include both mandatory requirements and voluntary excellence standards to drive continuous improvement.

***Technology Transfer and Knowledge Sharing*****:** Establish formal mechanisms for sharing best practices, technical knowledge, and lessons learned among ports. This could include industry consortia, technology demonstration projects, and peer-learning networks that facilitate knowledge diffusion across the maritime sector.

**I*ntegrated Monitoring Systems:*** Implement comprehensive environmental monitoring systems that track multiple sustainability indicators in real-time, enabling data-driven decision-making and continuous performance optimization.

**Research Implications and Future Directions**

This research contributes to both theoretical understanding and practical implementation of green port initiatives. Theoretically, it demonstrates that sustainability transitions in complex socio-technical systems like ports require simultaneous attention to technological, economic, human, and institutional dimensions. Practical implications include actionable guidance for port operators, policymakers, and maritime industry stakeholders seeking to implement effective sustainability strategies.

Future research should examine longitudinal outcomes of green technology implementations to assess long-term sustainability and identify potential rebound effects. Comparative studies across different geographical contexts would enhance understanding of how regional factors influence green port success. Additionally, investigation of emerging technologies such as hydrogen fuel cells, shore power systems, and artificial intelligence applications in port operations could provide insights into next-generation sustainability solutions.

The findings underscore that while technological solutions are necessary for environmental sustainability, they are insufficient without complementary organizational capabilities, supportive policies, adequate financing, and committed workforce engagement. Successful green port implementation requires holistic strategies that address this multidimensional challenge comprehensively rather than pursuing technological fixes in isolation.

## CONCLUSION

This research provides comprehensive empirical evidence on the sustainability of supervision of loading and discharging processes in ports adopting Green Port principles. Based on the mixed-methods analysis conducted at three major Indonesian ports—Tanjung Priok, Tanjung Perak, and Belawan—several significant conclusions can be drawn regarding the implementation and effectiveness of green technologies in port operations.

First, green technologies demonstrate substantial environmental benefits when properly implemented. The study confirms that electric-powered cranes and automated energy-efficient systems successfully reduce carbon emissions by 20-30% and decrease fossil fuel consumption by 15%. Life Cycle Assessment (LCA) results further validate these findings, showing a 25% reduction in $CO_2$ emissions and a 40% decrease in operational waste. Water quality improvements, reflected in an 18% reduction in pollution levels, indicate that green port initiatives extend beyond atmospheric emissions to encompass broader ecological sustainability. These environmental improvements confirm that technological innovation plays a critical role in mitigating the maritime sector's environmental footprint and contributing to global climate goals.

Second, economic analysis shows that green technology investments are financially viable over the long term despite higher initial costs. While upfront investment costs are 15-20% higher than conventional alternatives, ports achieve long-term operational savings of 10-15% annually through reduced energy consumption, lower maintenance requirements, and improved operational efficiency. The 8% reduction in operational time generates additional economic benefits through increased throughput capacity and enhanced service delivery. The payback period for green technology investments typically ranges from 5 to 8 years, demonstrating the economic rationality of sustainability transitions. However, the economic analysis also exposes significant disparities, with small and medium-sized ports facing substantial financial barriers due to limited access to capital and financing mechanisms.

Third, workforce perceptions and adaptation emerge as critical determinants of implementation success. Survey results showing that 75% of operational staff support green port initiatives indicate generally positive attitudes toward sustainability. The reported improvement in workplace safety perceptions among 65% of respondents, attributed to reduced exposure to pollutants and hazardous materials, represents an important co-benefit that enhances worker motivation beyond environmental concerns. However, the research identifies significant challenges related to technical competency gaps and extended adaptation periods. Despite intensive training programs, operators required more time than initially anticipated to achieve proficiency with green technologies, highlighting the socio-technical complexity of sustainability transitions and the necessity of continuous professional development.

Fourth, infrastructure readiness and institutional support significantly influence implementation effectiveness. Ports with advanced infrastructure systems and comprehensive training programs consistently achieved better environmental and operational outcomes compared to those with limited technical capacity. This finding underscores that the effectiveness of green technology is contingent upon complementary organizational capabilities, adequate physical infrastructure, and sustained human capital investment. The variation in outcomes across the three studied ports demonstrates that technological solutions alone are insufficient—successful green port implementation requires holistic strategies integrating technology, infrastructure, workforce development, and supportive management practices.

Fifth, regulatory and policy frameworks remain critical yet underdeveloped enablers of green port transitions. The research identifies significant policy gaps, including inconsistent environmental standards across jurisdictions, bureaucratic complexities in permit acquisition, and the absence of clear certification frameworks for green port operations. Where supportive policies existed—such as tax incentives for renewable energy investments or streamlined approval processes—adoption rates and implementation success increased markedly. This pattern indicates that comprehensive policy frameworks combining regulatory requirements, financial incentives, and technical support mechanisms are essential for accelerating widespread green port adoption.

The strategic recommendations emerging from this research emphasize the need for integrated approaches. Mandatory continuous professional development programs should be established to ensure workforce readiness for green technology operations. Diversified financing mechanisms, including government subsidies, green bonds, and public-private partnerships, must be developed to support ports of different sizes and financial capacities, with priority given to small and medium-sized facilities facing the greatest barriers. Unified national standards for green port operations should specify clear technical requirements, establish performance benchmarks, and define certification criteria. Formal knowledge-sharing mechanisms, including industry consortia and peer-learning networks, should facilitate the diffusion of best practices across the maritime sector. Comprehensive environmental monitoring systems enabling real-time data collection and performance tracking should support continuous improvement and evidence-based decision-making.

This research contributes significantly to both theoretical understanding and practical implementation of green port initiatives. Theoretically, it demonstrates that sustainability transitions in complex socio-technical systems require simultaneous attention to technological, economic, human, and institutional dimensions. The findings challenge simplistic assumptions that technological adoption alone drives sustainability outcomes, revealing the critical importance of complementary organizational capabilities and supportive institutional frameworks. Practically, the research provides actionable guidance for port operators, policymakers, and maritime stakeholders seeking to implement effective sustainability strategies aligned with international climate commitments.

The study's limitations—including its geographical focus on Indonesian ports, a six-month data-collection period, and potential social desirability bias in self-reported data—suggest important directions for future research. Longitudinal studies examining long-term outcomes and potential rebound effects would enhance understanding of sustainability durability. Comparative analyses across different geographical contexts would illuminate how regional factors influence the success of green ports. Investigating emerging technologies such as hydrogen fuel cells, shore power systems, and artificial intelligence applications could yield insights into next-generation sustainability solutions.

In conclusion, this research establishes that sustainable loading and discharging supervision in green ports is both environmentally beneficial and economically viable when implemented through holistic strategies integrating technological innovation, workforce development, infrastructure enhancement, and supportive policy frameworks. While green technologies are necessary for environmental sustainability, they are insufficient without complementary organizational capabilities, adequate financing, supportive policies, and committed workforce engagement. The successful transformation of port operations toward sustainability requires comprehensive approaches that address this multidimensional challenge rather than pursuing isolated technological solutions. As global pressure to reduce carbon emissions intensifies, the findings of this research provide practical guidance for ports worldwide seeking to balance operational efficiency with environmental responsibility, thereby contributing to the maritime sector's critical role in achieving global sustainability targets.

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