Volume 14-Issue 5 (2025)

Journal of Transportation Science and Technology

Journal homepage: https://tapchicongnghegtvt.vn

Emission Calculation Methods for Handling Equipment in Inland Container Depots: A Systematic Review and Research Directions

Doan Thi Hoang Thao[1], Pham Nguyen Dang Khoa[1,*], Quach Thi Ha[2], Duong Linh Chi[1], Nguyen Minh Hieu[1]

[1]*University of Transport Ho Chi Minh City*

[2]*Vietnam Maritime University*

Keywords:

ICD
Emissions
Handling equipment
Green logistics
Systematic review

ABSTRACT

Emission calculation from handling equipment in inland container depots is crucial for environmental management in logistics operations. This systematic review analyzes 47 high-quality papers selected from 942 initial studies to examine current emission calculation methodologies. Results identify four main approaches: activity-based, simulation-based, direct measurement, and integrated optimization methods. Terminal tractors, RTG/RMG cranes, and reach stackers emerge as primary emission sources. Three significant trends are identified: equipment electrification, integration of emission calculations into terminal planning, and development of standardized toolkits. Key challenges include data quality issues, lack of unified standards, and limited research on pollutants beyond CO_2. The study proposes three future research directions: developing harmonized calculation frameworks that balance universal applicability with local factors, comprehensive characterization of multi-pollutant emission profiles under real-world conditions, and integration of real-time analytics and machine learning for dynamic emission management. These advancements are essential for achieving sustainable terminal operations while maintaining operational efficiency.

1. Introduction

The accurate calculation of emissions from handling equipment in inland container depots (ICDs) represents a critical component in understanding and mitigating the environmental impact of logistics operations [1]. Contemporary research demonstrates a diverse array of methodological approaches, each offering distinct advantages in terms of complexity, accuracy, and practical application [2-3].

The methodological landscape encompasses several key approaches, ranging from activity-based and bottom-up methods to advanced simulation models and real-world measurement systems. Among these, activity-based methods have gained widespread adoption due to their effective balance between accuracy and practical implementation [1-2]. These methods leverage detailed operational data combined with emission factors to estimate carbon dioxide (CO_2) and other

---

* Pham Nguyen Dang Khoa. University of Transport Ho Chi Minh City
Email: khoapnd@ut.edu.vn

https://www.doi.org/10.55228/JTST140503
Recieved: August 02, 2025; Recieved in revised: August 15, 2025; Accepted: August 21, 2025
Available online: Septemper 15, 2025
pISSN: 1859-4263; eISSN: 3030-4261

pollutant emissions, while accounting for equipment types, operational cycles, and terminal layout configurations [2-6].

Recent developments in the field have increasingly emphasized simulation-based models and real-time measurement systems [7-9]. These advanced tools capture the dynamic nature of terminal operations more effectively and provide valuable validation for emission inventories. The selection of appropriate methodology typically depends on several factors, including data availability, specific pollutants of interest such as CO_2, nitrogen oxides (NO_x), particulate matter (PM), and sulfur oxides (SO_x), and the unique operational context of each ICD.

A particularly significant trend in current research involves the integration of emission calculations into comprehensive terminal planning and optimization frameworks [10-12]. This integration serves dual purposes: ensuring regulatory compliance and advancing sustainability initiatives within the logistics sector. Such holistic approaches recognize that emission management cannot be treated in isolation but must be considered as an integral part of terminal operations and strategic planning.

Despite considerable progress in this field, the industry continues to face substantial challenges. The standardization of methodologies across different contexts remains elusive, and ensuring the accuracy of emission factors for diverse equipment types and operational settings presents ongoing difficulties [13-16]. These challenges underscore the need for continued research and collaboration among stakeholders to develop more robust and universally applicable frameworks.

This comprehensive review synthesizes the latest research on emission calculation methodologies for handling equipment in ICDs, examining methodological developments, highlighting key findings, and exploring practical implications for sustainable terminal management. The insights presented here provide valuable guidance for practitioners and researchers working toward more environmentally responsible logistics operations.

2. Systematic screening methodology

The systematic literature review followed a rigorous multi-stage selection process to identify relevant research on emission calculations for handling equipment in ICDs. This comprehensive literature review employed a rigorous four-stage systematic review methodology to identify and evaluate research on emission calculation methods for ICD handling equipment. The initial search strategy yielded 942 potentially relevant papers from multiple academic databases, including Web of Science, Scopus, IEEE Xplore, and ScienceDirect.

2.1. Stage 1: Initial screening and duplicate removal

The first stage involved comprehensive duplicate detection using both automated tools and manual verification. During this phase, 358 duplicate entries were systematically removed through cross-referencing DOI numbers, author names, publication years, and title similarities. An additional 41 papers were excluded due to missing abstracts or incomplete bibliographic information, reducing the dataset to 584 unique papers for detailed evaluation.

2.2. Stage 2: Relevance assessment criteria

The second stage implemented a structured relevance assessment protocol examining each paper's direct applicability to ICD operations and emission calculation methodologies. The evaluation criteria included methodological rigor, empirical validation, and practical applicability to container handling equipment. This systematic assessment eliminated 296 papers based on specific exclusion criteria.

The excluded papers fell into four primary categories. First, 127 papers focused exclusively on road transportation vehicles without addressing container handling equipment at ICDs. Second, 89 studies examined emission calculation methods but lacked application to logistics operations. Third, 52 papers presented purely theoretical frameworks without empirical data or practical implementation examples. Fourth, 28 studies demonstrated geographical scope limitations that prevented generalization to broader ICD operations.

2.3. Stage 3: Quality assessment framework

The third stage applied stringent quality assessment criteria to the remaining 343 papers. Each study underwent evaluation for methodological soundness, data validation procedures, publication venue credibility, and practical applicability. Papers were required to demonstrate clear research methodology, validated data sources, publication in journals with minimum impact factors of 1.5, and high applicability to real-world ICD operations.

2.4. Stage 4: Final selection protocol

The final selection stage identified 47 high-quality papers that provided substantive contributions to understanding emission calculation methods for ICD handling equipment. These selected studies demonstrated comprehensive coverage of different equipment types including cranes, forklifts, and container movement equipment, validated calculation methodologies, and practical implementation frameworks suitable for diverse ICD operational contexts.

3. Results

3.1. Methodological approaches

The literature reveals four primary methodological approaches for calculating emissions in inland container depots, each offering distinct advantages for different operational contexts and research objectives. Comparison of key studies on emission calculation methods for ICD handling equipment is shown in Table 1.

3.1.1. Activity-based approaches

Activity-based methods, also known as bottom-up approaches, represent the most widely adopted framework in current practice. These methods leverage detailed operational data including equipment operating hours, fuel consumption rates, and movement cycles, combining them with established emission factors to generate estimates for each equipment type [1-3, 6-8]. The granularity of this approach allows for highly adaptable calculations that can accommodate the specific characteristics of individual terminals while maintaining consistency with standardized emission factor databases. The widespread adoption of activity-based methods stems from their ability to balance data requirements with practical implementation considerations, making them particularly suitable for routine emission monitoring and reporting.

3.1.2. Simulation-based approaches

Simulation-based models have emerged as powerful tools for understanding the complex dynamics of terminal operations and their environmental implications. Researchers increasingly employ discrete-event and agent-based simulations to model terminal activities and estimate emissions under diverse operational scenarios. These models prove particularly valuable when evaluating potential changes to terminal operations, such as equipment allocation strategies or transitions to electrified handling equipment [9-15]. The ability to test multiple scenarios without disrupting actual operations makes simulation an essential tool for strategic planning and investment decision-making.

3.1.3. Direct measurement approaches

Direct measurement approaches utilizing portable emission measurement systems (PEMS) and real-time monitoring technologies provide the most accurate representation of actual emissions from handling equipment. These methods capture real-world operational conditions and equipment performance variations that may not be fully reflected in standardized emission factors. Beyond providing immediate emission data, direct measurement serves a crucial validation function, enabling researchers to refine emission factors and verify the accuracy of emission inventories developed through other methods [16, 17].

3.1.4. Hybrid and optimization approaches

The evolution toward hybrid and optimization models represents a significant advancement in

integrating environmental considerations into terminal management. These sophisticated frameworks combine emission calculation capabilities with optimization algorithms to address multiple objectives simultaneously. Applications include terminal layout planning, equipment scheduling optimization, and investment analysis for emission reduction projects [18-32]. By embedding emission calculations within broader decision-support systems, these models facilitate the development of strategies that balance operational efficiency with environmental performance.

Table 1. Comparison of key studies on emission calculation methods for ICD handling equipment.

Methodology	Equipment	Key results	Validation/Accuracy
Activity-based	Terminal tractors, CHE	0.011335 tCO_2e/TEU; tractors dominant source	Case study, scenario analysis
Activity-based	Terminal tractors, trucks	42.39% CO_2 from tractors; 0.01259 tCO_2/TEU	Performance indicator for MobES
Activity-based, OFFROAD model	CHE	PM10, PM2.5, NO_x, SO_x, CO, HC emissions quantified	Compared to previous fuel-based estimates
Three-stage model, design-based	RTGs, RMGs, AGVs	Energy consumption per cycle and total; 2200–13,470 kWh/day	Performance indicator for MobES
Activity-based, movement theory	Cranes, RTGs, trucks, stackers	CO_2 emissions by equipment; cranes 56%, RTGs 27%, trucks 14%, stackers 3%	<1% deviation from actual data

3.2. Key Findings on Emission Sources and Factors

3.2.1. Dominant emission sources

The research consistently identifies specific equipment types as the dominant contributors to emissions within inland container depots and container terminals. Terminal tractors, various crane configurations including rubber-tired gantry cranes and rail-mounted gantry cranes, and reach stackers emerge as the primary sources of both CO_2 and other pollutant emissions [1-3, 5, 23]. This finding remains remarkably consistent across different geographical locations and terminal configurations, suggesting that emission reduction strategies should prioritize these equipment categories. The concentration of emissions among these key equipment types also indicates that targeted interventions focusing on these assets could yield disproportionately significant environmental benefits.

3.2.2. Emission factors and variability

A critical insight from the literature concerns the substantial variability in emission factors across different operational contexts. While standardized emission factors provide a useful baseline for calculations, real-world measurements frequently reveal significant deviations from these theoretical values. Factors contributing to this variability include equipment type specifications, fuel quality, duty cycle characteristics, and specific operational patterns unique to each terminal. Perhaps most significantly, actual emissions often exceed certification standards, sometimes by considerable margins. This discrepancy underscores the limitations of relying solely on manufacturer specifications or regulatory standards for emission calculations. The findings strongly advocate for routine emission surveillance programs and the development of locally calibrated emission factors that reflect the actual operating conditions of specific terminals [16, 17, 19, 33].

3.2.3. Impact of terminal layout and operations

The influence of terminal design and operational practices on emission profiles represents another crucial finding [5, 14, 28]. Research demonstrates that terminal layout configurations, whether employing parallel or perpendicular arrangements, can materially impact total emissions through their effects on equipment travel distances and operational efficiency. Equipment allocation strategies similarly influence emission patterns, with optimized deployment potentially reducing unnecessary movements and idle time. Yard congestion emerges as a particularly important factor, as it leads to increased equipment idle time, longer travel distances, and reduced operational efficiency, all of which contribute to higher emissions. While some layout modifications offer only marginal improvements in energy efficiency and emission reduction, the cumulative effect of multiple design and operational optimizations can be substantial. These findings emphasize the importance of considering environmental impacts during the terminal planning phase and continuously optimizing operations to minimize emissions.

3.3. Innovations and Trends

3.3.1. Electrification and alternative fuels

The transition toward electrification and alternative fuels represents one of the most significant technological shifts in reducing emissions from handling equipment in inland container depots. Research demonstrates substantial emission reduction potential through the systematic electrification of terminal equipment, with particular emphasis on converting diesel-powered assets to battery-electric or hybrid alternatives. Simulation studies and well-to-wheel analyses provide quantitative evidence of these benefits, accounting not only for operational emissions but also for the upstream impacts of electricity generation and fuel production. Beyond electrification, alternative fuels such as liquefied natural gas and hydrogen are gaining attention as transitional or long-term solutions for equipment that may be challenging to electrify due to operational requirements or technological constraints. The literature reveals that while the emission reduction benefits vary depending on the local electricity grid composition and fuel supply chains, the overall trajectory points toward significant improvements in environmental performance. These technological transitions, however, require careful analysis of total cost of ownership, infrastructure requirements, and operational implications to ensure successful implementation [9, 34, 35].

3.3.2. Integration with terminal planning

The integration of emission calculations into comprehensive terminal planning and management systems marks a fundamental shift from treating environmental considerations as an afterthought to embedding them as core decision criteria. Modern terminal design increasingly incorporates emission modelling at the conceptual stage, allowing planners to evaluate the environmental implications of different layout options, equipment configurations, and operational strategies before construction begins. This proactive approach extends to operational decision-making, where emission considerations are integrated into equipment scheduling algorithms, maintenance planning, and capacity allocation decisions. Investment frameworks now routinely include emission reduction potential as a key evaluation criterion alongside traditional financial metrics, reflecting the growing recognition that environmental performance directly impacts long-term competitiveness and regulatory compliance. This holistic integration supports the dual objectives of operational efficiency and sustainability, demonstrating that environmental stewardship and business performance can be mutually reinforcing rather than conflicting goals [4, 20, 25, 28].

3.3.3. Standardization and toolkits

The development of standardized methodologies and comprehensive toolkits addresses a critical need for consistency and comparability in emission reporting across the logistics sector. International standards such as ISO 14064-1 provide overarching frameworks for greenhouse gas accounting, while sector-specific initiatives like the GLEC Framework offer detailed guidance tailored to logistics operations [6, 18, 36]. These standardization efforts facilitate benchmarking across terminals and enable meaningful comparisons of environmental performance. Methodological toolkits increasingly incorporate software tools and databases that streamline the calculation process while ensuring consistency with accepted standards. The adoption of these standardized approaches benefits multiple stakeholders: terminal operators gain access to validated methodologies and simplified reporting processes, regulators receive comparable data for policy development and compliance monitoring, and customers obtain reliable information for their supply chain emission assessments. As these frameworks mature and gain wider adoption, they are expected to accelerate the industry's transition toward more transparent and accountable emission management practices.

3.4. Limitations and Challenges

The implementation of accurate emission calculation methodologies faces several persistent challenges that limit their effectiveness and widespread adoption across inland container depots. These limitations stem from both technical constraints and institutional factors, creating barriers to comprehensive environmental assessment and management.

3.4.1. Data quality and availability

Data quality and availability emerge as fundamental obstacles to precise emission calculations. High-resolution operational data, essential for accurate activity-based calculations, often remains inaccessible due to inadequate data collection systems or concerns about commercial sensitivity [16, 18, 19]. Many terminals lack the sophisticated monitoring infrastructure necessary to capture detailed equipment usage patterns, fuel consumption rates, and operational cycles. Furthermore, the absence of locally calibrated emission factors compounds these data challenges. While generic emission factors provide a starting point, they may not accurately reflect the specific operating conditions, equipment age profiles, and maintenance practices characteristic of individual terminals. This data scarcity forces researchers and practitioners to rely on assumptions and approximations that potentially compromise the accuracy and reliability of emission estimates.

3.4.2. Lack of standardization

The absence of universally accepted methodological standards represents another critical challenge impeding progress in emission management. Despite various initiatives to develop standardized frameworks, the industry continues to grapple with multiple competing approaches, each with different assumptions, boundaries, and calculation procedures. This methodological fragmentation creates significant difficulties for stakeholders attempting to benchmark performance across terminals or integrate emission data into broader supply chain assessments. The lack of standardization also complicates regulatory compliance and voluntary reporting initiatives, as different jurisdictions and certification schemes may require incompatible calculation methods. This inconsistency undermines efforts to establish industry-wide emission reduction targets and track progress toward environmental goals [6, 18].

3.4.3. Under-researched pollutants

The research literature reveals a concerning imbalance in the pollutants addressed by current emission calculation efforts. While CO_2 receives extensive attention due to its climate change implications, other significant pollutants remain substantially under-researched despite their severe environmental and public health impacts. NO_x, PM, and SO_x from diesel-powered handling equipment contribute to local air quality degradation and respiratory health problems, particularly affecting communities adjacent to logistics facilities [3, 19, 37, 38]. The limited focus on these pollutants represents a significant gap in understanding the full environmental footprint of ICD operations. This narrow focus may lead to emission reduction strategies that successfully address climate impacts while inadvertently neglecting or even exacerbating local air quality concerns. Addressing this limitation requires expanding research efforts and calculation methodologies to encompass a more comprehensive range of pollutants, enabling truly holistic environmental management strategies.

4. Discussion

The body of research examining emission calculations for handling equipment in inland container depots has reached a mature stage, characterized by continuous methodological refinement and increasing operational sophistication. Contemporary approaches demonstrate a clear evolution toward more granular, data-driven methodologies that better capture the complexity of terminal operations. Activity-based and simulation models have established themselves as industry standards, providing the necessary balance between computational accuracy and practical flexibility to accommodate diverse terminal contexts and operational requirements [1-7].

A particularly encouraging development involves the growing adoption of real-world measurement and validation techniques, which have substantially enhanced the reliability and credibility of emission inventories [16-18, 39]. These empirical approaches provide crucial feedback for refining theoretical models and ensuring that calculated emissions reflect actual operational conditions. Nevertheless, persistent challenges in data collection infrastructure and the absence of standardized protocols continue to constrain the full potential of these validation efforts [40].

The strategic integration of emission calculations into comprehensive terminal planning and optimization frameworks represents a paradigm shift in how the industry approaches environmental management [20, 25, 28, 41-45]. This integration enables decision-makers to evaluate emission implications alongside operational and financial considerations, leading to more effective emission reduction strategies and better-informed investment decisions. The ability to model environmental impacts during the planning phase, rather than as a post-hoc assessment, fundamentally transforms the potential for achieving meaningful emission reductions.

Despite these advances, significant gaps persist in the current research landscape. The absence of universally accepted methodological standards continues to impede cross-terminal comparisons and industry-wide benchmarking efforts. Additionally, the research community's predominant focus on CO_2 emissions, while understandable given climate change concerns, has resulted in the relative neglect of other environmentally significant pollutants and specific operational scenarios that may have disproportionate local impacts.

The quality and depth of available evidence varies considerably across different aspects of emission calculation. Research addressing CO_2 emissions and energy consumption demonstrates high methodological rigor and comprehensive coverage. However, investigations into other pollutants such as nitrogen oxides, particulate matter, and sulfur oxides remain comparatively underdeveloped. Moving forward, the field requires concerted efforts to harmonize methodologies across geographical regions and equipment types while expanding the scope of analysis to encompass the full spectrum of environmental impacts associated with ICD operations. Only through such comprehensive approaches can the industry develop truly effective strategies for minimizing its environmental footprint while maintaining operational efficiency. Matrix of research topics and methods, highlighting area with limited coverage in the literature is shown in Table 2.

The notable absence of studies from developing regions represents a critical gap in understanding ICD operations where logistics activities are rapidly expanding. ICDs in Southeast Asia, South Asia, and Africa operate under fundamentally different conditions including aging equipment fleets, tropical climatic conditions affecting fuel consumption, lower operational density but extended operating hours, and limited infrastructure. These factors can cause significant deviations from emission factors developed using temperate climate data, with preliminary studies indicating 8-15% higher fuel consumption in high-temperature, high-humidity environments.

To address these challenges, we propose a three-tier framework for adapting existing calculation methods to local conditions:

Tier 1 - Basic factor adjustment: Develop climate correction factors for local temperature, humidity, and fuel quality conditions. Initial research suggests temperature-humidity indices can systematically adjust baseline emission factors for tropical operations.

Tier 2 - Operational model adaptation: Modify operational parameters reflecting regional work density patterns, cycle characteristics, and equipment utilization profiles. Many developing region ICDs exhibit lower throughput intensity but longer operational periods, affecting idle-time ratios and total emissions.

Tier 3 - Socio-economic integration: Incorporate technology accessibility, local environmental policies, and investment capacity to ensure emission reduction solutions remain feasible within regional constraints.

This framework enhances calculation accuracy while providing foundations for developing region-appropriate emission reduction strategies that balance global sustainability goals with local implementation realities.

Table 2. Matrix of research topics and methods, highlighting area with limited coverage in the literature.

Topic/Method	Activity-based	Simulation	Direct Measurement	Optimization/ Planning	Standardization/ Toolkit
CO2/energy emissions	12	7	3	5	4
NOx/PM/SOx emissions	4	2	2	1	1
Equipment-specific analysis	8	4	2	3	2
Terminal layout/operations	5	3	1	2	1
Alternative fuels/electrification	3	3	1	2	1

5. Conclusion

The comprehensive analysis of emission calculation methodologies for handling equipment in inland container depots reveals a field that has achieved considerable maturity while simultaneously facing significant challenges. The evolution from rudimentary estimation techniques to sophisticated activity-based models, advanced simulations, and real-world measurement systems represents substantial progress in environmental assessment capabilities. These methodological advances have transformed emission data from abstract estimates [46] into practical tools that inform operational decisions and strategic planning. The particular strength in carbon dioxide and energy consumption research provides a robust foundation for climate impact assessment, supported by extensive validation studies and operational implementation across diverse terminal contexts.

5.1. Research gaps

Critical gaps in the current research landscape continue to limit the comprehensive understanding and management of emissions from ICD operations [47, 48]. The most pressing gap concerns the persistent lack of methodological standardization, which creates barriers to performance benchmarking and impedes the development of industry-wide emission reduction strategies. This standardization challenge extends beyond mere technical specifications to encompass fundamental questions about system boundaries, allocation methods, and reporting framework. The limited attention to non-CO_2 pollutants represents another significant research gap with serious implications for public health and local environmental quality. While climate change considerations justify the focus on greenhouse gases, the relative neglect of nitrogen oxides, particulate matter, and sulfur oxides leaves communities adjacent to logistics facilities potentially exposed to unquantified health risks. This gap becomes particularly concerning as terminals pursue decarbonization strategies that may inadvertently affect local air quality in unforeseen ways.

Furthermore, the application of existing methodologies across diverse ICD contexts reveals limitations in their adaptability and transferability. Research has predominantly focused on large-scale facilities in developed economies, leaving smaller terminals and those in developing regions underrepresented. The unique operational characteristics, equipment profiles, and regulatory environments of these facilities require tailored approaches that current methodologies may not adequately address.

5.2. Further studies

To address the limitations identified in current research and meet the practical needs of the logistics industry, future research directions must be specified with clear objectives, feasible timelines, and directly applicable deliverables. Rather than general orientations, the following seven priority research objectives are designed to address specific knowledge gaps and create practical tools for ICD managers.

5.2.1. Standardized emission calculation frameworks for Vietnam contexts

Specific Research Priority 1: Develop climate-adjusted emission factors for CHEs operating in tropical conditions (temperature >30°C, humidity >80%), targeting accuracy within ±5% of direct measurements. This study should produce validated correction factors applicable across Southeast Asian region or Vietnam.

Specific Research Priority 2: Create simplified calculation protocols for small-scale ICDs (throughput <50,000 TEU/year, <10 equipment units) that require minimal data inputs while maintaining regulatory compliance standards.

Specific Research Priority 3: Establish integrated yard planning algorithms that simultaneously optimize container stacking patterns and equipment routing while achieving emission reduction targets of 10-15%. Focus on developing decision support tools for medium-scale terminals (50,000-200,000 TEU/year).

5.2.2. Equipment-specific multi-pollutant characterization

Specific Research Priority 4: Conduct comprehensive emission profiling for NO_x, PM_{10}, $PM_{2.5}$, and SO_x from RTG/RMG cranes under varying load conditions and maintenance states. Target: establish emission factors for equipment age categories (0-5, 5-10, >10 years) with statistical confidence >95%.

Specific Research Priority 5: Develop emission profiles for electrified equipment combinations, including hybrid systems and battery-electric alternatives, incorporating well-to-wheel analysis for different electricity grid compositions.

5.2.3. Technology-enabled emission monitoring and management

Specific Research Priority 6: Design cost-effective real-time monitoring systems using IoT sensors and PEMS integration for continuous emission tracking. Target implementation cost <$50,000 per terminal with payback period under 3 years through operational optimization.

Specific Research Priority 7: Create machine learning models for predictive emission forecasting based on operational schedules, weather conditions, and equipment performance data. Focus on 24-48 hour prediction accuracy >85% to enable proactive emission management decisions.

These seven priority research objectives form a comprehensive program transforming emission management from static assessment to dynamic, adaptive systems. Success requires close collaboration between research institutions, terminal operators, and equipment manufacturers, supported by an international data sharing platform incorporating standardized data structures, tiered access controls for commercial sensitivity, and secure APIs. This platform aligns with digital transformation trends in logistics, leveraging cloud computing, IoT integration, and machine learning to evolve from static repositories into intelligent systems providing real-time emission insights and automated compliance reporting.

These initiatives will contribute to global emission reduction goals while creating sustainable competitive advantages for ICDs through operational optimization and compliance with stringent environmental standards. The methodologies and insights presented provide essential foundations for achieving sustainable terminal operations in an era of increasing environmental accountability and supply chain transparency requirements.

Contributions of authors in this article

Doan Thi Hoang Thao: Methodology, Data management, Formal analysis, Validation, Feedback on peer review, Writing – original manuscript. **Pham Nguyen Dang Khoa**: Methodology, Supervision, Manuscript Editing. **Quach Thi Ha**: Methodology, Supervision, Feedback on peer review. **Duong Linh Chi:** Data compilation, Data analysis, Writing – original manuscript. **Nguyen Minh Hieu:** Data compilation, Data analysis, Writing – original manuscript.

Declaration of competing interest and dedication to copyright

The authors declare the absence of any potential conflicts of interest from this study and affirm that the paper has not been previously published.

Data available

Data will provided upon request.

References

[1] O. Okşaş, "Carbon emission strategies for container handling equipment using the activity-based method: A case study of Ambarlı container port in Turkiye," *Marine Policy*, vol. 149, 2023, Art. no. 105480, doi: 10.1016/j.marpol.2023.105480.

[2] G. Kara et al., "Estimation of land-based emissions during container terminal operations in the Ambarlı Port, Turkey," *Proc. Inst. Mech. Eng., Part M: J. Eng. Maritime Environ.*, vol. 235, no. 4, pp. 872-886, 2021, doi: 10.1177/14750902211052223.

[3] Y. Zhang et al., "Air emission inventory of container ports' cargo handling equipment with activity-based 'bottom-up' method," *Adv. Mech. Eng.*, vol. 9, no. 6, 2017, doi: 10.1177/1687814017711389.

[4] M. Brzeziński et al., "Method of Estimating Energy Consumption for Intermodal Terminal Loading System Design," *Energies*, vol. 17, no. 24, 2024, Art. no. 6409, doi: 10.3390/en17246409.

[5] M. A. Budiyanto et al., "Modest Method for Estimating CO2 Emissions from Container Handling Equipment at Ports," *Sustainability*, vol. 16, no. 23, 2024, Art. no. 10293, doi: 10.3390/su162310293.

[6] Z. Miodrag et al., "Assessment of Emissions Caused by Logistics Handling Operations in Multimodal-terminals," *Transp. Res. Procedia*, vol. 14, pp. 2754-2761, 2016, doi: 10.1016/J.TRPRO.2016.05.483.

[7] O. Olanrewaju et al., "Estimating on-site emissions during ready mixed concrete (RMC) delivery: A methodology," *Case Stud. Constr. Mater.*, vol. 13, 2020, Art. no. e00439, doi: 10.1016/J.CSCM.2020.E00439.

[8] A. Ziółkowski et al., "Analysis of Emissions and Fuel Consumption in Freight Transport," *Energies*, vol. 15, no. 13, 2022, Art. no. 4706, doi: 10.3390/en15134706.

[9] C. Fiori et al., "A discrete-event multi-agent simulation framework supporting well-to-wheel analysis for greening commercial maritime ports," *Simul. Model. Pract. Theory*, vol. 138, 2024, Art. no. 103061, doi: 10.1016/j.simpat.2024.103061.

[10] B. Liu and Y. Wang, "Simulation-based emission calculation method for container terminal production operation system," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 638, 2021, Art. no. 012028, doi: 10.1088/1755-1315/638/1/012028.

[11] W. Yang and S. Takakuwa, "A simulation model for estimating the carbon footprint of vehicles in the terminal operating processes," in *Proc. Winter Simul. Conf.*, 2017, pp. 3062-3073.

[12] H. Hu et al., "Improved Benders decomposition for stochastic yard template planning in container terminals," *Transp. Res. Part C: Emerg. Technol.*, vol. 132, 2021, Art. no. 103365, doi: 10.1016/j.trc.2021.103365.

[13] P. Yun et al., "A simulation-based research on carbon emission mitigation strategies for green container terminals," *Ocean Eng.*, vol. 163, pp. 288-298, 2018, doi: 10.1016/J.OCEANENG.2018.05.054.

[14] K. Liu et al., "Simulation-based Research on the Allocation of Low-carbon Container Terminal Handling Equipment," *DEStech Trans. Comput. Sci. Eng.*, 2018, doi: 10.12783/DTCSE/MMSTA2017/19631.

[15] J. Yang et al., "Carbon emissions performance in logistics at the city level," *J. Cleaner Prod.*, vol. 231, pp. 1258-1266, 2019, doi: 10.1016/J.JCLEPRO.2019.05.330.

[16] K. Pang et al., "Characterization of Pollutant Emissions from Typical Material Handling Equipment Using a Portable Emission

Measurement System," *Atmosphere*, vol. 12, no. 5, 2021, Art. no. 598, doi: 10.3390/ATMOS12050598.

[17] M. Pirhadi et al., "Criteria pollutant and greenhouse gas emissions from cargo handling equipment operating at the Ports of Los Angeles and Long Beach," *Sci. Total Environ.*, vol. 926, 2024, Art. no. 172084, doi: 10.1016/j.scitotenv.2024.172084.

[18] E. Varese et al., "Assessing Dry Ports' Environmental Sustainability," *Environments*, vol. 9, no. 9, 2022, Art. no. 117, doi: 10.3390/environments9090117.

[19] Z. Li et al., "Air Pollution and Control of Cargo Handling Equipments in Ports," *E3S Web Conf.*, vol. 93, 2019, Art. no. 02001, doi: 10.1051/E3SCONF/20199302001.

[20] Y.-C. Yang, "Operating strategies of CO2 reduction for a container terminal based on carbon footprint perspective," *J. Cleaner Prod.*, vol. 141, pp. 472-480, 2017, doi: 10.1016/J.JCLEPRO.2016.09.132.

[21] M. Dulebenets et al., "Minimizing Carbon Dioxide Emissions Due to Container Handling at Marine Container Terminals via Hybrid Evolutionary Algorithms," *IEEE Access*, vol. 5, pp. 8131-8147, 2017, doi: 10.1109/ACCESS.2017.2693030.

[22] D. Prayogo, "Carbon emission modelling in container terminal operations planning using a system dynamics approach," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 703, 2019, Art. no. 012014, doi: 10.1088/1757-899X/703/1/012014.

[23] D. Tang et al., "Energy consumption and emissions analysis of large container seaports considering the impact of COVID-19: A case study of Ningbo Zhoushan Port," *Ocean Coast. Manage.*, vol. 230, 2023, Art. no. 106781, doi: 10.1016/j.ocecoaman.2023.106781.

[24] M. A. Budiyanto et al., "Evaluation of CO2 emissions and energy use with different container terminal layouts," *Sci. Rep.*, vol. 11, 2021, Art. no. 5476, doi: 10.1038/s41598-021-84958-4.

[25] R. Zhao et al., "Bi-Objective Combinatorial Optimization Model for Emission Reduction Projects at Container Terminals Considering Investment Amount and Reduction Efficiency," *Transp. Res. Rec.*, vol. 2678, no. 11, pp. 584-596, 2024, doi: 10.1177/03611981241255364.

[26] S. Khorram, "A novel approach for ports' container terminals' risk management based on formal safety assessment: FAHP-entropy measure—VIKOR model," *Nat. Hazards*, vol. 103, pp. 1671-1707, 2020, doi: 10.1007/s11069-020-03976-z.

[27] E. Budiyanto et al., "The Application of Business Impact Analysis Due to Electricity Disruption in a Container Terminal," *Sustainability*, vol. 13, no. 21, 2021, Art. no. 12038, doi: 10.3390/su132112038.

[28] X. Hu et al., "Container storage space assignment problem in two terminals with the consideration of yard sharing," *Adv. Eng. Informatics*, vol. 47, 2021, Art. no. 101224, doi: 10.1016/j.aei.2020.101224.

[29] X. Jiang et al., "Optimization of integrated scheduling of restricted channels, berths, and yards in bulk cargo ports considering carbon emissions," *Expert Syst. Appl.*, vol. 255, 2024, Art. no. 124604, doi: 10.1016/j.eswa.2024.124604.

[30] Y. Song and Y. Zhang, "A Branch-and-Price-and-Cut Algorithm for the Inland Container Transportation Problem with Limited Depot Capacity," *Appl. Sci.*, vol. 14, no. 24, 2024, Art. no. 11958, doi: 10.3390/app142411958.

[31] L. V. Hoang et al., "An assessment model of bio-efficiency for container terminals in the presence of air emissions," *PLOS One*, vol. 20, no. 1, 2025, Art. no. e0319423, doi: 10.1371/journal.pone.0319423.

[32] P. Bardoult et al., "Which carbon footprint for my ICU?Benchmark, hot spots and perspectives," *Ann. Intensive Care*, vol. 15, no. 1, 2025, Art. no. 8, doi: 10.1186/s13613-025-01445-z.

[33] M. Puig and R. Darbra, "Innovations and insights in environmental monitoring and assessment in port areas," *Curr. Opin. Environ. Sustainability*, vol. 71, 2024, Art. no. 101472, doi: 10.1016/j.cosust.2024.101472.

[34] S. Tsiulin and K. H. Reinau, "How to Reduce Emissions in Maritime Ports? An Overview of Cargo Handling Innovations and Port Services," in *Sustainable Logistics*, 2022, pp. 491-516, doi: 10.1007/978-3-031-16072-1_22.

[35] D. Testa et al., "Analysis of environmental benefits resulting from use of hydrogen technology in handling operations at airports," *Clean Technol. Environ. Policy*, vol. 16, pp. 1479-1494, 2014, doi: 10.1007/s10098-013-0678-3.

[36] B. Ashworth et al., "The Carbon Footprint of Pharmaceutical Logistics: Calculating Distribution Emissions," *Sustainability*, vol. 17, no. 2, 2025, Art. no. 760, doi: 10.3390/su17020760.

[37] Y. Zhou et al., "Port-Related Emissions, Environmental Impacts and Their Implication on Green Traffic Policy in Shanghai," *Sustainability*, vol. 12, no. 10, 2020, Art. no. 4162, doi: 10.3390/su12104162.

[38] M. Winther et al., "Emissions of NOx, particle mass and particle numbers from aircraft main engines, APU's and handling equipment at Copenhagen Airport," *Atmos. Environ.*, vol. 100, pp. 218-229, 2015, doi: 10.1016/J.ATMOSENV.2014.10.045.

[39] N. Tsolakis et al., "Towards AI driven environmental sustainability: an application of automated logistics in container port terminals," *Int. J. Prod. Res.*, vol. 60, no. 14, pp. 4508-4528, 2021, doi: 10.1080/00207543.2021.1914355.

[40] N. Tsolakis et al., "Towards AI driven environmental sustainability: an application of automated logistics in container port terminals," *Int. J. Prod. Res.*, vol. 60, no. 14, pp. 4508-4528, 2021, doi: 10.1080/00207543.2021.1914355.

[41] B. Lin and Y. Teng, "Industrial chain division and carbon emission intensity: The moderating effect of digitization," *Energy*, vol. 282, 2023, Art. no. 129573, doi: 10.1016/j.energy.2023.129573.

[42] S. Awad-Núñez et al., "How should the sustainability of the location of dry ports be measured? A proposed methodology using Bayesian networks and multi-criteria decision analysis," *Transport*, vol. 30, no. 3, pp. 312-319, 2015, doi: 10.3846/16484142.2015.1081618.

[43] J. Ries et al., "Environmental impact of warehousing: a scenario analysis for the United States," *Int. J. Prod. Res.*, vol. 55, no. 21, pp. 6485-6499, 2016, doi: 10.1080/00207543.2016.1211342.

[44] C. Quan et al., "Analysis on the influencing factors of carbon emission in China's logistics industry based on LMDI method," *Sci. Total Environ.*, vol. 734, 2020, Art. no. 138473, doi: 10.1016/j.scitotenv.2020.138473.

[45] F. Deng et al., "A big data approach to improving the vehicle emission inventory in China," *Nat. Commun.*, vol. 11, 2020, Art. no. 2801, doi: 10.1038/s41467-020-16579-w.

[46] A. Khaslavskaya and V. Roso, "Dry ports: research outcomes, trends, and future implications," *Maritime Econ. Logistics*, vol. 22, pp. 265-292, 2020, doi: 10.1057/s41278-020-00152-9.

[47] J. Jeevan et al., "The impact of dry port operations on container seaports competitiveness," *Maritime Policy Manage.*, vol. 46, no. 1, pp. 4-23, 2018, doi: 10.1080/03088839.2018.1505054.

[48] A. Khaslavskaya and V. Roso, "Outcome-Driven Supply Chain Perspectives on Dry Ports," *Sustainability*, vol. 11, no. 5, 2019, Art. no. 1492, doi: 10.3390/SU11051492.