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An Innovation of Geo-Logistics toward Sustainable Strategies for Small and Medium-Sized Ports in Thailand

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ABSTRACT

This study investigates the integration of geo-logistics as a strategic framework for enhancing sustainability within Small and Medium-sized Ports (SMPs) in Thailand, focusing on improving environmental, innovation and economic performance. The geo-logistics framework in this study considers the spatial aspects of logistics activities around the port areas to achieve sustainability goals. This research employs a mixed-methods approach statistical analysis (ANOVA), combined with semi-structured interviews and an intensive literature review to assess both internal and external management criteria across three key regional ports—Songkhla, Map Ta Phut, and Ranong. Findings reveal significant variations of internal factors to assess digitalization, waste management, green procurement, and energy-efficient operations. Beside that externally explores ecosystem protection, stakeholder collaboration, and regulatory compliance. The results showed that Map Ta Phut port demonstrated the most comprehensive sustainability initiatives within its geo-logistics framework, while Songkhla port and Ranong port showed moderate progress. These variations highlight the differing levels of preparedness and commitment to sustainability across the selected ports. Successful implementation of geo-logistics in this research requires strong governmental support, financial incentives, and capacity building to empower Thai SMPs toward long-term sustainability and enhanced competitiveness in the global maritime sector. Lastly, this framework offers a practical roadmap for transforming regional ports into resilient, green, and smart logistics hubs.

Keywords: Small and Medium-sized Ports (SMPs); Sustainable Port Development; Geo-logistics; Port Supply Chain; Maritime Innovation

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1. Introduction

Ports are indispensable components for maritime logistics. Every sea-connected nation must have ports to enhance its national economy [1]. According to Alamoush et al. [2] mentioned that Worldwide, there are 8,292 ports in 222 nations, with 835 being the most active seaports that manage 99% of maritime traffic and trade. Ports are not only vital infrastructures and maritime connectivity [3] but also key drivers of competitive performance in global trade and efficiency of port operation [4].

The International Maritime Organization (IMO) has highlighted a significant trend towards sustainability and decarbonization goals in maritime transport. This trend shed light the specific action to make a green port initiatives should be adoption of digital technologies and operation processes to promote sustainability transportation [5]. Including, the main idea for sustainable ports is gaining attention by reducing carbon emissions, renewable energy and reduce a negative environmental impacts without endangering economic expansion. It is characterized as a long-term strategy for the sustainable and modern port development of port infrastructure [6]. Lastly, each port must plan and manage their operations sustainably to address space limitations environment, increased trade connectivity and digitalization [7].

Geo-logistics is one of comprehensive concepts in logistics and supply chain management that reflects an evolution in the field. It represents the complexity of logistics evolved into the planning, implementation, innovation, goods movement and information system which can support into flow of chain through various transportation modes. From another perspective, this concept incorporates technological advancements to address the complexities of modern supply chains and innovation to maximize the benefit of the world's resources. Then geo-logistics can empower more smarter and greener logic with sustainability into port for by operate the energy-efficient, operational efficiency, waste reduction, emissions monitoring and optimize cargo flow [8]. This logical can support global sustainability by promoting environmental protection in regional areas and fostering both economic development and ecological responsibility.

The small and medium-sized ports (SMPs) are regional maritime facilities that handle a lower volume of cargo and vessel traffic compared to major international hub ports. This size of ports are important in the growth of trade in regional economics facilitating the movement of goods, enhancing connectivity, and supporting regional marketing [9]. However, several of ports face with structural limitations such as a budgets, capacity, and technology bring less influence over global supply chains, which hinder their ability to achieve sustainability outcomes. Currently, SMPs in Thailand have become an important part in maritime strategy to enhance connectivity and serve in maritime logistics & supply chain in regional trade in South East Asia [10]. The regional port from the perspective of sustainability led to a renewed interest not only reduces emissions but also enhances operational efficiency, trade in green commodities and cost savings [11]. By addressing these challenges regional ports are ensure their long-term competitiveness and contribute to global.

Up to date only a limited number of studies have examined sustainability in the context of regional ports, and the integration of Geo-logistics idea with sustainability in these settings remains largely unexplored. In this gap bring a research highlights approach focusing on sustainability management and Geo-logistics idea to build up the new concept foundation. Strengthening Thailand's regional ports—such as Songkhla Port, Map Ta Phut Port, and Ranong Port—is essential to enhancing the country's maritime economy. This study set out to clarify several aspects in each regional port of Thailand as: (1) Conducted both internal and external reviews to assess their sustainability combine with Geo-logistics concept. (2) A mixed-methods approach, incorporating compare mean in one-way ANOVA, is employed to comprehensively evaluate each port's performance in terms of sustainability and geo-logistics, with the aim of assessing their contributions to environmental objectives and regional development goals. (3) Building on the strategic importance of strengthening these ports as a components of maritime innovation, the study provides recommendations that integrate new concepts, including green operations, smart port, and geo-logistics solutions. These efforts are essential steps toward sustainable port development and supporting the long-term growth industry standards and logistics ecosystem to national and global sustainability targets.

2. Literature Reviews

2.1. The Sustainability in Port

The sustainability development goal clearly states that development needs to be environmentally and socially friendly. Currently, port performance is inevitably related to environmental protection. Ports cannot perform well if continuous environmental problems keep occurring [12]. The environmental impacts happen during both the construction and operation phases. The environmental aspect of port

sustainability is largely influenced by the demands of governments and port authorities, requiring port operators to adhere to environmental laws, policies, and guidelines. It can ensure that the port can adopt sustainable practices and fit environmental requirements [13]. In addition, another study identifies key domains of smart port operations, including pollution control, waste management, environmental protection, water management, energy, safety, and security, as significant components of the port sustainability system [14] and impacts on the unmanned surface vehicle for long run sustainability [15]. In addition, Environmental management in ports involves implementing international standards water consumption management plans, and smart technologies for water quality monitoring. Sustainable waste management, automation for air quality assessment, and tracking greenhouse gas (GHG) emissions are essential for minimizing environmental impacts [5,14]. The growing interest of stakeholders in the shipping industry highlights on social, environmental, and developing performance, reflecting an increasing demand for sustainability which impacts shipping networks [16]. Besides that, Port supply chain integration (PSCI) enhances economic performance while advancing environmental sustainability through pollution management, energy efficiency, and green port practices. It helps ports minimize their environmental footprint while maintaining competitiveness [17]. Several studies have explored the relationship between environmental and economic investment aspects in ports [18]. One study assessed the environmental performance of major Korean ports using factor analysis including alternative fuels, pollution reduction incentives, and renewable energy [19]. Another study applied a fuzzy-integrated approach to analyze the environmental performances of ten major ports in Türkiye [20]. Additional research has highlighted ship speed reduction and the use of onshore power supply as effective strategies for improving port sustainability [21]. The spatial expansion of ports has also been examined in relation to environmental, economic, and social impacts [22]. Moreover, it has been shown that the performance of companies involved in port operations- including port authority, terminal operators and stevedores, and integrated carriers- might be impact by the release of environmental, social, and governance (ESG) policies [23]. Environmental sustainability is becoming a crucial factor in determining the competitiveness of port operations [24]. Finally, recent study emphasized the importance of integrating smart technologies such as AI and IoT within geo-logistics frameworks to enhance spatial planning, real-time monitoring, and adaptive decision-making in distribution systems, thereby minimizing environmental impacts through more efficient resource utilization and coordinated stakeholder collaboration [25].

The concept of sustainable development in port operations by focusing environmental quality, efficient resource utilization, and the adoption of circular economic models, while an operation-centric approach is concerned with operational efficiency to meet these sustainability goals. Green ports aim to minimize negative ecological impacts through innovations such as renewable energy usage, eco-friendly infrastructure, reduced emissions, and effective waste management. The operational dimension enhances these efforts through digitalization, automation, and streamlined logistics processes that minimize idle time, fuel consumption, and environmental footprints. Besides that, the green practice and operation centric have mention the electricity and power supply for emission saving for green ports including alternative fuels such as hybrid or electric vehicles, for terminal and vessel [26]. Including with the concept of synergistic model where environmental stewardship is embedded in core port activities, promoting long-term sustainability without compromising economic performance. On the other hand, the elements of green port technologies and operational optimization could support green operational models. This strategy can raise the target of IMO for decarbonization and emissions reduction targets. Therefore, the green port and operation-centric can present the future transformation and innovation of maritime logistics combined with ecological responsibility with operational efficiency.

Environmental management is increasingly recognized as a core component of strategic business planning, particularly in efforts aimed at achieving sustainability and operational efficiency. Executing environmental initiatives and green marketing strategies contributes to enhanced environmental performance by implementing standard management for improved environmental performance. Apart from the environmental impact previous research adoption of diverse digital initiatives at the port has significantly optimized its operations which is linked to its sustainable development [27]. Additionally, marketing strategies to green ports have been explored to highlight how major ports can effectively integrate economic, social, and environmental sustainability [28].

2.2. The Sustainability in Small and Medium Size Port

Port sustainability is influenced by various factors, with port size being a critical determinant. Larger ports tend to exert greater environmental pressures, necessitating comprehensive environmental design and stricter standards addressing air quality, noise, dust,

and infrastructure development [13]. To address sustainability challenges in smaller ports, a Digitalization Readiness Index has been proposed as a customizable tool to enhance environmental performance and support regional economic development [29]. Subsequent studies further presented the integration of environmental responsibility and digital efficiency within the framework of a green and digital economy in small and medium-sized ports [30]. The transformation of environmental and digital systems in smaller port ecosystems has been shown to significantly affect operational efficiency, sustainability practices, and the adoption of digital technologies for improved management and environmental monitoring [31]. Additionally, environmental initiatives have been found to significantly enhance regional energy performance through technological advancements, a crucial factor in promoting sustainability within port operations [32]. Green ports are those that actively work on developing, implementing, and overseeing practices aimed at minimizing environmental impacts, going beyond mere regulatory compliance based on the size of ports [33]. Furthermore, small ports are increasingly confronted with legal liabilities and responsibilities related to environmental impacts. To address these challenges, it should actively implement an Environmental Management System (EMS) to monitor and report their environmental performance [34].

Several studies have explored sustainable port development in Thailand, focusing on various environmental, economic, and operational aspects. One study introduced the concept of a sustainable port by incorporating environmental indicators to assess factors such as climate change, energy consumption, and market dynamics [11]. Another study examined the Eastern Economic Corridor (EEC) initiative, which focuses on the infrastructure development in the seaports of Rayong, Chonburi, and Chachoengsao. This research integrated smart and sustainable port management using 21 key performance indicators covering environmental, social, and economic aspects to enhance port operations. This framework improves sustainability, corporate efficiency, and renewable energy while also enhancing health, safety, and emissions management. Therefore, this port can move toward international standards in smart and sustainable management [35]. Further findings suggest that cost efficiency, implementation of environmental policies, and enforcing occupational health and safety management systems are the key factors influencing the sustainability of ports and terminals in Thailand [36]. Additionally, research has considers ecosystems and green port policy for achieving sustainability goals in the city port [37]. In doing so, coastal zones and protected areas are critical in preserving marine biodiversity, promoting sustainable use of coastal resources [38]. Ports in Thailand are increasingly adopting innovation and digitalization to enhance sustainability, incorporating advanced information systems, innovative and green port initiatives, and electronic energy solutions.

2.3. The Concept of GEO-logistics

Geo-logistics, as introduced in earlier studies, refers to the assessment planning of the Earth's resources and inventory [8]. It involves the integration of global natural resources into the logistics flow encompassing all components of the logistics process [39]. Previous research has examined the role of geo-logistics within the maritime supply chain, highlighting its relevance in optimizing resource use and transportation efficiency [9]. Other reports have mentioned geo-logistics with in the context of sustainable development through environmentally which promotes decarbonization, economization, and humanization of logistics activities under the lean concept [40]. Additional studies have framed geo-logistics as a means of leveraging global resources to enhance human welfare [41]. For instance, the case of Port of Koper demonstrated the application of green infrastructure solutions that reduce environmental impacts while boosting logistical competitiveness [42]. Similarly, another study explored the "green port" strategy as a long-term environmental approach, identifying key performance indicators such as air quality, noise pollution, and waste management to guide sustainable port practices. Broader perspectives on green logistics, emphasizing the importance of minimizing external costs such as emissions, noise, and accidents while promoting hinterland logistics solutions for ports [43]. Including, The logistics systems within sustainable ports are primarily focused on Sustainable Procurement (SP), Green Warehousing (GW), Logistics Optimization (LO), and Social Values (SV) [44]. This conceptual gap explains why geo-logistics has not been broadly adopted, especially among maritime nations and port environments. Therefore, geo-logistics in this context are defined as the strategy of logistics combined with sustainability ports in small and medium size ports.

The Sustainability Port and Geo-Logistics framework, as illustrated in **Figure 1**. At its core, the diagram presents how geo-logistics integrates six key domains—transportation, supply chain, domestic and international trades, social, technology, and economics—each contributing to sustainability through targeted strategies. These interconnected elements collectively enhance logistics and supply chain performance while minimizing environmental impact, thereby supporting long-term economic growth aligned with global sustainability objectives. The framework provides a clear roadmap for transforming SMPs into

more sustainable, efficient, and competitive hubs in the global maritime sectors. Finally, this study addresses gaps by incorporating both internal and external management aspects across the core dimensions of sustainability, innovation and geologists. Nevertheless, there remains a significant gap in the sustainability of small and medium-sized ports in Thailand where unique challenges and opportunities for sustainable development are not yet to be fully explored. Including combining the discussion with the new trends of geologistics.

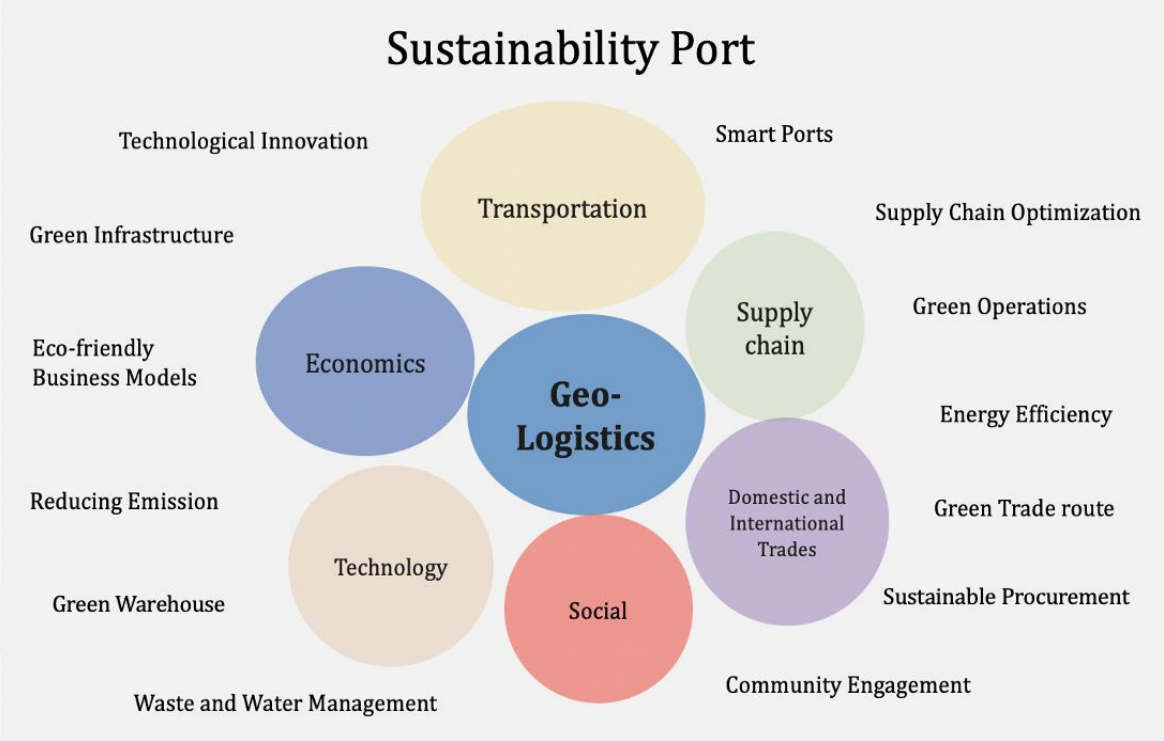

Figure 1. Sustainability port and geo-logistics framework (Source: Authors).

3. Methodology

This research aims to validate an innovation of geo-logsitics into sustainable development framework specifically designed for SMPs in Thailand's. Adopting a mixed-methods approach with integrated semi-structured interviews and comprehensive literature reviews shed light on how these ports are practically implementing sustainability measures. This method not only highlights critical sustainability standards but also assesses their relevance to the distinct environmental, operational challenges, innovation and geo-logistics concept of Thailand's port sector. The findings contribute to the creation of a robust framework aimed at promoting innovation of geo-logistics to environmental responsibility in regional ports. This study examined a key of small and medium-sized ports in Thailand which serve the regional maritime transport. Both internal and external factors were analyzed to assess their performance effectively.

3.1. Inside and Outside of Small and Medium Size Port in Thailand

Geographic locations of selected SMPs in Thailand: Ranong, Songkhla, and Map Tha Phut Ports are illustrate in **Figure 2**, are critical components of the nation's maritime infrastructure. Songkhla Port, located in the Southern part of Thailand, serves as an important gateway for regional trade and eco-friendly initiatives. Also, Map Tha Phut Port, situated on the Eastern coast, is known for its industrial and petrochemical activities, offering opportunities to enhance port efficiency through green technologies and digital tools. Ranong Port, located near the Thai-Myanmar border, is strategically positioned for maritime regional trade in Western size, particularly with Myanmar, and faces challenges related to coastal zone management and local community engagement. These ports are growing of Thailand's secondary port system, contributing to regional sustainability and geo-logistics by adopting green port services, eco-friendly technologies, and strengthening connectivity for sustainable development.

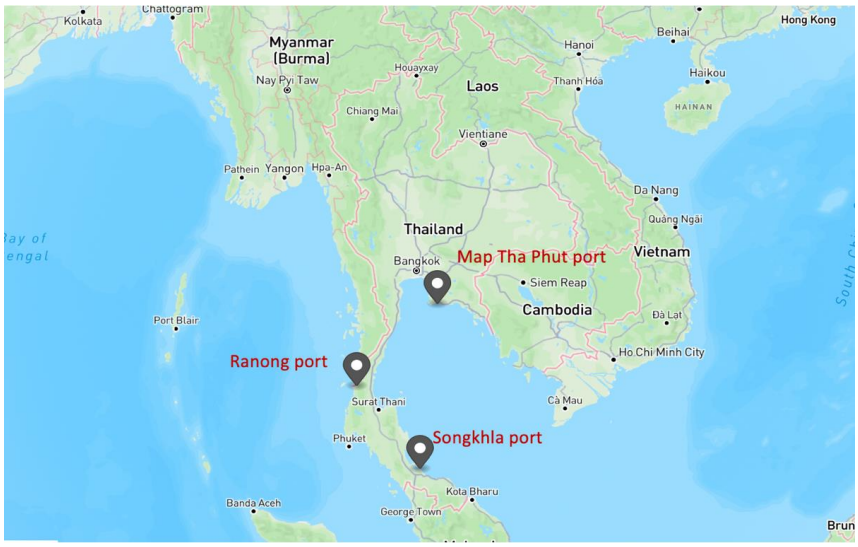

Figure 2. Geographic locations of selected small and medium-sized ports (SMPs) in Thailand: Ranong, Songkhla, and Map Tha Phut Ports (Source: Geojson).

3.1.1. Songkhla Port

Songkhla Port, located in southern Thailand, is a significant maritime hub that has evolved to meet the demands of contemporary trade and logistics. It facilitated the maritime transport between the East and West sides of Thailand, which contributed to regional markets. Currently, Songkhla port handles over 8 million TEUS annually and is improving modernisation efforts to enhance its operational efficiency and competitiveness through infrastructure upgrades and improved logistics services. In terms of sustainability, the port has adopted a comprehensive waste management system, incorporating a waste separation plant, recycling center, and composting facilities, reflecting its commitment to environmentally responsible operations. As a result of these efforts, Songkhla Port has emerged as a critical logistics hub and complex modern port that actively responds to the dynamics of global trade. Its strategic geographic position enables it to facilitate both domestic and international commerce, thereby boosting Thailand's trade capacity and regional integration [4,5].

3.1.2. Map Ta Phut

Map Ta Phut Port is a crucial industrial port located in Rayong Province in Thailand. It serves the Eastern Seaboard region, facilitating the import and export of liquid and bulk cargo that supports industrial sectors with global supply chains. Apart from that, Map Ta Phut port supports the Eastern Economic Corridor (EEC) for the development of logistical capabilities, including investments in infrastructure and advanced technologies in Thailand. In doing so, the industrial expansion led to the encroachment of industrial activities on the port's enhancement. This port faces critical environmental challenges, such as air and water pollution, which affect the maritime environment [45]. This port tries to promote responsible industrial practices and enhance community engagement in environmental oversight for a leader in sustainable maritime logistics. The Geographic Information System (GIS) and Remote Sensing (RS) tools have been employed to analyse environmental changes in the Map Ta Phut port to test the nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) concentrations. Nonetheless, the accumulation of pollution loads necessitates careful management to ensure that environmental standards are met and the ecosystem's carrying capacity is not exceeded. This includes plans for improved cargo storage solutions and the adoption of automated systems that incorporate Artificial Intelligence (AI) to streamline operations and reduce environmental impact.

3.1.3. Ranong Port

Ranong Port is a strategically significant maritime gateway located on the Andaman Sea in Thailand, serving as a crucial hub for regional trade and logistics, particularly within the BIMSTEC area (Bangladesh, India, Myanmar, Sri Lanka, Thailand, Nepal, and Bhutan). This port is important for increased shipping traffic and the international shipping network in South Asia and the Middle East [46]. However, Ranong Port faces challenges in executing its sustainability initiatives, including limited financial resources and operational constraints. At this point, Ranong Port plans to accommodate ships larger and extend the berth length for smoother flows. Moreover, the Port Environmental Review System (PERS) and necessary green technologies have been applied to Ranong port to increase environmental

friendliness through renewable energy integration, waste management, and community engagement. Ranong Port aims to promote a more sustainable logistics model that lessens the environmental footprint of cargo movements. These initiatives enhance operational efficiency and align with global trends toward sustainable development in the logistics sector.

3.2. Research Method and Data Collection

3.2.1. Measurement Instruments and Questionnaires

To achieve this, the study employs an advanced mixed-methods approach One-way- ANOVA combined with a novel innovation as a geo-logistics concept. Semi-structured interviews were utilized as one of the complex analysis methods to generate the internal and external criteria. These criteria were developed through a comprehensive review of relevant literature both primary and secondary data analysis. The questionnaire was organized into 4 parts. The Frist part covered questions about the roles or job titles held by the respondents. The second and third sections included statements of internal and external related to SMPs - Songkhla Port, Map Ta Phut Port and Ranong Port. The respondents were asked to answer these criteria reflect the unique requirements and challenges of small and medium port management in Thailand. This research will break down and investigate as Yes, No and In Process (IP) adapted from Roh et al. which combine an analysis of compare mean based on the interview and literature reviews by R language program [7]. In this section, the responses will be evaluated based on the majority opinion. If most respondents agree with a higher mean of the criteria, the answer will be marked as "Yes." In contrast, if the majority disagree with the criteria (lower mean), the answer will be marked as "No." The final determination will be made by calculating the average responses across all respondents to each criterion. This methodology ensures that the results reflect the collective view of the respondents on the feasibility and relevance of each criterion in the context of small and medium port management in sustainable development and geo-logistics. The last sections focused on suggestions and feedback from the participants. In particular, the advancement of knowledge is constructed within each port to ensure a clear understanding of sustainability, geo-logistics and innovation.

3.2.2. The Respondence and Research Process

A purposive sampling technique was used to select 10 experts who possessed relevant qualifications and were actively involved in the maritime field, either in academia (7 lecturers) and top-level positions within their port organizational hierarchy (3 at the Management level). To ensure the respondents clearly understood the research objectives, the author explained the purpose of the study and provided instructions on how to complete the questionnaire. In addition, to avoid any conflict of interest, the confidentiality of the respondents' information was guaranteed. In conclusion, the questionnaires were distributed to 10 experts and received a 100% response rate, indicating no non-response bias in the results.

This research comprised the main steps, starting with comprehensive literature reviews were conducted to identify relevant variables of sustainable and geo-logistics in SMPs. The findings from the literature served as the foundation for developing the study's conceptual framework, variables, and research questions. After that, The questionnaire was constructed incorporating elements from the sustainable and geo-logistic development model. It was distributed to selected respondents for interviews and answered via phone and inbox messages to gather diverse perspectives. The question explored internal and external sustainability and geo-logistics practices in SMPs. The questions focused on real-time environmental monitoring, green policy implementation, adoption of clean technologies, stakeholder collaboration, and regulatory support in each port. All interviews and questionnaires were transcribed and analysed using compare mean in one way ANOVA and Tukey's HSD to find which groups differ. The analysis focused on identifying recurring patterns related to internal management (e.g., environmental policies, waste handling, digitalization, warehouse and procurement) and external collaboration (e.g., stakeholder engagement, regulatory compliance, ecosystem protection). By aligning these themes with policy frameworks and sustainability goals, the study evaluated each port's level of preparedness and commitment to implementing geo-logistics and sustainable practices. Additionally, this process supported the identification of actionable insights for strengthening environmental governance and engaging local communities in port development. The final phase of the study integrated both qualitative and quantitative findings to formulate strategic recommendations to advance sustainable geo-logistics practices in small and medium-sized ports (SMPs). **Figure 3** presents the conceptual process developed to integrate geo-logistics and sustainability within SMPs in Thailand.

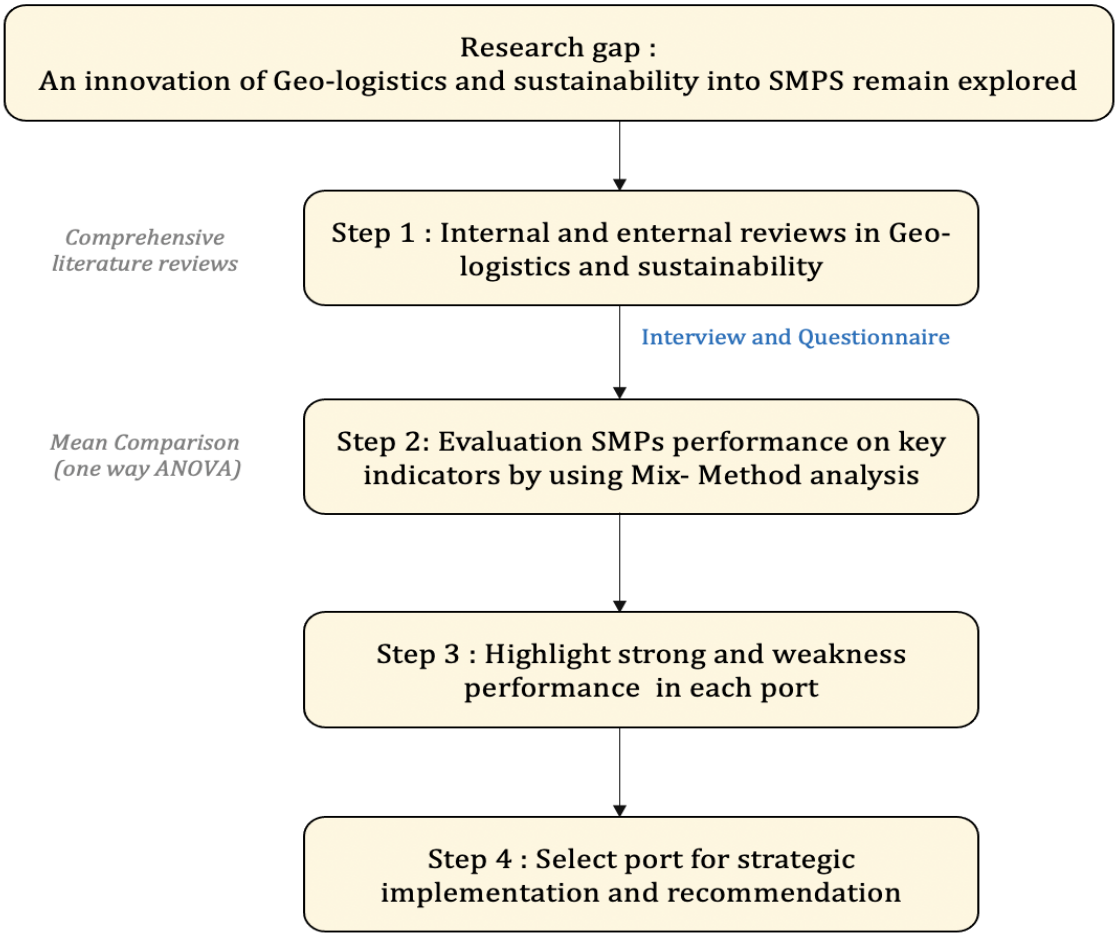

Figure 3. Research framework for integrating geo-logistics and sustainability into SMPs (Source: Authors).

3.3. Internal Management Criteria of Small and Medium Size Port in Thailand

This section outlines the key internal management criteria essential for promoting sustainability, green port and geo logistics in small and medium-sized ports in Thailand. These criteria's are designed to enhance the environment and sustainability practices including innovation and digitalization while addressing their unique challenges.

Based on **Table 1**, the evaluation of internal management practices of SMPs for—Songkhla Port, Map Ta Phut Port, and Ranong Port for sustainability performance and geo-logistics in Thailand. Songkhla Port shows relatively limited progress with several criteria marked as "No" or "IP". For instance, in environmental impact monitoring and mitigation (A1), Songkhla and Map Ta Phut scored a mean equal to 1.20, indicating minimal action rather than Ranong port. In Waste Management System (A9), Songkhla scored 0.30, reflecting a lack of implementation. Additionally, Sustainable Procurement Practices (A4) received a score of 0.20 with Ranong port 0.30, indicating a significant gap in adopting sustainable procurement strategies. However, minimising environmental harm (A7), Eco-friendly and green cargo operation (A10), Lean logistics in sustainability development (A11) and planning organisation on the logistics activities (A12) show a higher performance compared to the other port. Map Ta Phut port consistently outperforms the others, For instance, the port scored Environmental considerations in green warehousing (A3), Sustainable Procurement Practices (A4), Monitoring facilitated through shared information and equipment channels (A5) and Allocate budgets for green initiatives, including awareness and promotion campaigns (A8). with highest outstanding of mean score 1.60, 1.50, and 1.90 respectively. It is demonstrating a higher level of green initiative integration.

Table 1. Internal management of small and medium size port.

Internal management Criteria	Songkhla port (SS)	Map Ta Phut port (MM)	Ranong port (RR)	Homogeneity of Variances (Sig)	References
A1: Environmental impact monitoring and mitigation in real time	IP	IP	Yes		[12]
Mean	1.20	1.20	1.50	0.693	
A2: Green port policy and comprehensive environmental policy statement.	Yes	Yes	Yes		[6,37]
Mean	1.50	1.60	1.70	0.497	
A3: Environmental considerations in green warehousing	No	Yes	No		[11,44]
Mean	0.30	1.60	0.20	0.184	
A4: Sustainable Procurement Practices	No	Yes	No		[11,44]
Mean	0.20	1.50	0.30	0.026	
A5: Monitoring facilitated through shared information and equipment channels	No	Yes	Yes		[27,34]
Mean	0.30	1.40	1.70	0.030	
A6: Environmental risk management practices.	Yes	Yes	Yes		[5]
Mean	1.90	1.80	1.90	0.374	
A7: Minimizing environmental harm	Yes	Yes	Yes		[21]
Mean	1.30	1.80	1.90	0.02	
A8: Allocate budgets for green initiatives, including awareness and promotion campaigns.	No	Yes	No		[28]
Mean	0.4	1.90	1.40	0.04	
A9: Waste management system in port	No	No	No		[43]
Mean	0.30	0.30	0.20	0.582	
A10: Eco-friendly and green cargo operation	Yes	Yes	Yes		[19]
Mean	1.70	1.70	0.4	0.680	
A11: Lean logistic into sustainability development	No	Yes	No		[8]
Mean	1.60	1.90	0.30	0.019	
A12: Planning Organization on the logistics activities	Yes	Yes	Yes		[37]
Mean	1.70	1.30	1.70	0.100	
A13: Alternative fuel in terminal equipment	IP	IP	Yes		[26]
Mean	1.40	0.90	1.70	0.053	
A14: Digitalization and Automation by Use of cleaner technology port equipment	IP	IP	IP		[29,30]
Mean	0.80	0.90	0.90	0.428	
A15: Adoption of port automation tools and technologies	No	No	No		[27]
Mean	0.30	0.20	0.10	0.147	

IP = In process. Source: Collected data by authors.

Additionally, Ranong Port has made significant progress in environmental impact mitigation (A1), receiving a 1.50 score, indicating complete adoption of environmental monitoring practices. An alternative fuels (A13) efforts scored 1.70, highlighting a promising direction towards adopting cleaner energy solutions in port operations. But still falls behind in systemic environmental planning and digital integration.

Nevertheless, a few positive trends are shared across all ports. It also excels in minimising environmental Harm (A7), with a mean score of 1.90, the highest among the three ports. Ranong's performance in Sustainable Procurement Practices (A4) and Eco-friendly Cargo Operations (A10) also reflects its commitment, scoring 0.30 and 0.40, respectively, showing a way for improvement but still above Songkhla's scores. However, Ranong lags in Green Warehousing (A3) and Automation (A15), with both receiving low scores, indicating limited progress in these areas. In conclusion, Map Ta Phut shows **l**eads in integrating sustainability in procurement, environmental monitoring, and green warehousing, with higher mean scores in almost all key areas, such as 1.60 for Green Warehousing and 1.90 for Budget Allocations for Green Initiatives (A8). Ranong has excelled in specific environmental criteria, such as Minimising Environmental Harm (A7) with a 1.90 score and Alternative Fuels (A13) with 1.70, but it needs further investment in automation and digital technologies. However, Songkhla lags significantly behind in various sustainability practices, with many areas marked as "No" or incomplete. It requires substantial improvement to catch up with the other two ports.

3.4. External Management Criteria of Small and Medium Size Port in Thailand

This section focuses on the external management criteria essential for ensuring the sustainability of small and medium-sized ports in Thailand. The key areas consider external collaborations and initiatives in driving sustainable practices while addressing environmental and operational challenges specific to small and medium ports.

The evaluation of external management practices across Songkhla, Map Ta Phut, and Ranong ports reveals varying degrees of sustainability engagement and highlights a significant point of sustainability ports displayed in **Table 2**. Songkhla Port shows some positive environmental initiatives, particularly in fostering sustainable maritime supply chains (B2, score of 1.80) and marine ecosystem preservation (B7, score of 1.90). However, it is behind in other areas such as Coastal communities for Eco and environment friendly. Such engine technology, waste recovery systems, (B3, score of 0.9) and Resilient maritime and port supply chains (B11, score of 0.20), highlighting significant areas for improvement and B13: Carbon neutrality with zero emissions (B13, score of 0.20), Ranong Port is similar to the others in many respects but stands out with higher scores for certain areas like Coastal Communities for Eco-Technology (B3, score of 1.20) and Pollution Prevention (B12, score of 1.80), suggesting that Ranong has a more focused approach to environmental preservation. Despite this, Ranong still falls short in adopting carbon neutrality strategies (B13, score of 0.20) and eco-friendly materials (B10, score of 0.20). Map Ta Phut Port demonstrates the most consistent performance with the majority of external criteria. particularly in fostering sustainable supply chains (B2, score of 1.90) and promoting eco-friendly services (B8, score of 1.90). However, it lags in areas like employing eco-friendly materials (B10, score of 0.10) and resilient supply chains (B11, score of 1.80), showing areas where further efforts are required. Moreover, all ports are successful in environment to foster an environmentally sustainable maritime supply chain and networks (B2), promote green port services (B5), Collaborative Coastal Zone Management and marine protected areas (B7), Eco-friendly services to attract environmentally conscious customers (B8) and Management an environmental risks and responsibilities with business partners (B9). In conclusion, all three ports are making strides toward environmental sustainability, but there are still need improvement, particularly in the implementation of eco-friendly technologies, materials, and carbon neutrality efforts. Map Ta Phut leads in areas such as sustainable supply chains and services, while Ranong shows notable efforts in pollution prevention and coastal ecosystem preservation. Songkhla needs to focus on strengthening its enforcement of environmental regulations and increasing its use of eco-friendly materials.

Table 2. External management of small and medium size port.

External Management Criteria	Songkhla Port	Map Ta Phut Port	Ranong Port	Homogeneity of Variances	References
B1: Management a ballast water from ships that contain heavy metals	IP	IP	IP		[5]
Mean	0.90	1.00	0.80	0.321	
B2: Fostering an environmentally sustainable maritime supply chain and networks	Yes	Yes	Yes		[17]
Mean	1.80	1.90	1.90	0.441	

Table 2. *Cont.*

External Management Criteria	Songkhla Port	Map Ta Phut Port	Ranong Port	Homogeneity of Variances	References
B3: Coastal communities for Eco and environment friendly. Such engine technology, waste recovery systems,	IP	IP	IP		[37]
Mean	0.90	1.00	1.20	0.651	
B4: Collaborative Coastal Zone Management and marine protected areas.	Yes	Yes	Yes		[38]
Mean	1.70	1.60	1.80	0.446	
B5: Utilization Promotion of Green Port Services	Yes	Yes	Yes		[28]
Mean	1.60	1.50	1.70	0.268	
B6: Regulatory Environmental laws and enforce penalties for violations.	IP	IP	IP		[6]
Mean	1.10	0.80	1.10	0.189	
B7: Marine Ecosystem Preservation and low emission	Yes	Yes	Yes		[31,37]
Mean	1.90	1.90	1.80	0.374	
B8: Eco-friendly services to attract environmentally conscious customers	Yes	Yes	Yes		[28]
Mean	1.80	1.90	1.90	0.374	
B9: Management an environmental risks and responsibilities with business partners.	Yes	Yes	Yes		[17]
Mean	1.40	2.00	1.80	0	
B10: Employ eco-friendly materials and equipment	No	No	No		[17]
Mean	0.30	0.10	0.20	0.147	
B11: Resilient maritime and port supply chains	No	Yes	No		
Mean	0.20	1.80	0.10	0.506	
B12: Pollution Prevention and Response	IP	IP	Yes		[12]
Mean	0.90	1.10	1.80	0.530	
B13: Carbon neutrality with zero emissions	No	IP	No		[26]
Mean	0.30	1.00	0.20	0.028	

IP = In process. Source: Collected data by authors.

4. Discussion and Implementation

This discussion explores how current practices of small and medium-size ports in Thailand evolve trends of green port development and port sustainability both internal operational improvements and external collaborative strategies. Implementation for sustainable development of internal management can increase operational strategies with co-friendly infrastructure. These ports are increasingly expected to modernize their infrastructure to support energy-efficient and low-emission technologies by using hybrid and electric-powered equipment can reduce environmental impacts. This includes adopting international environmental management standards such as ISO 14001 to systematize environmental responsibility, ensuring that ports of all sizes implement continuous environmental monitoring and improvement. It is an essential step for ports like Songkhla and Ranong to standardize their sustainability practices and enhance regulatory compliance. The key action should include deploying digitalization and automation to enhance operational efficiencies such as AI-assisted cargo routing, smart energy management, and automated berth scheduling which not only optimize resource utilization but also reduce the carbon footprint [10]. Another aspect is the human factors: ports must invest in continuous staff training to build environmental awareness and technical skills necessary for implementing sustainable practices. Furthermore, establishing clear green port policies, backed by top-level commitment, ensures that sustainability is embedded in strategic and day-to-day

decision-making processes. On the other hand, expanding real-time environmental monitoring systems across all ports will help proactively mitigate environmental risks by enabling continuous data collection on air and water quality, emissions, and waste discharge, these systems support timely decision-making and regulatory compliance, ultimately enhancing the ports' environmental performance and sustainability profile. Regular Port State Control exercises must also be institutionalized to ensure adherence to international maritime standards and reduce environmental violations.

External sustainability management is a long-term environmental performance management of Thailand's small and medium-sized ports, particularly Map Ta Phut, Ranong, and Songkhla. Due to that SMPs in Thailand's ports must strengthen with several parties related to logistics providers, shipping lines, local communities, and regulatory bodies. Such partnerships are essential for developing resilient maritime supply chains that prioritize low-emission transport, waste reduction, and ecosystem preservation. Eco-friendly services such as green warehousing, shore power for vessels, and water recycling enhance the environmental sustainability of small and medium-sized ports in Thailand. These services contribute not only to reducing emissions and conserving resources but also to improving a port's attractiveness to environmentally conscious clients and international trade partners seeking low-carbon logistics solutions. Despite these advantages, Thailand's small and medium-sized ports face challenges in realizing these eco-innovations. The research indicates that lack of financial investment, limited access to green technology, and insufficient human resource capacity to manage sustainable operations are a cause for low improvement of small and medium-sized ports in Thailand for improving the long-term of sustainability the port. Consequently, Thailand's national strategy is essential in offering government incentives for green port innovations, fostering private-sector collaboration, and establishing a centralized knowledge-sharing platform where ports can access best practices, funding mechanisms, and training programs. In addition, external management practices can drive sustainability through collaborations and partnerships in the coastal zone and marine protected areas by actively addressing regional ecosystem challenges. Ports should work with local communities, regulatory bodies, and environmental organizations to develop strategies that preserve biodiversity and manage risks effectively. Additionally, fostering environmentally sustainable maritime supply chains through partnerships with business operators can lead to significant environmental benefits. Besides that, eco-friendly promoting green port services such as implementing technologies for ballast water management, and applied materials like non-toxic paints are necessary to attract environmentally conscious stakeholders and reduce the ports' ecological footprints.

In doing so, promoting sustainability in Thailand's SMPs hinges significantly on enhancing internal resource efficiency and embracing external strategic innovations such as geo-logistics to the transformation of seaport sustainability with integration environmental, economic, and social dimensions into a cohesive strategy into Thailand port. In this aspect each SMPs in Thailand can assist in maximizing resource utilization, achieving a green environment, efficient handling processes and well manage resilient port model [9]. To overcome these challenges, the Port Authority of Thailand and the government should pay attention to sustainable port development, as an essential component of the port strategy of sustainability in maritime transport which fosters a consistent long-term environment and transport system.

Despite progress in certain areas, several critical aspects still require attention to ensure the long-term development of green ports in Thailand. Currently, none of the ports actively promote environmentally sustainable supply chains, manage environmental risks in collaboration with business partners, or offer eco-friendly services to customers. Additionally, the absence of eco-friendly materials and equipment across all ports undermines efforts to reduce environmental impacts. To address these gaps, ports must prioritize the development of comprehensive green policies, allocate sufficient resources for eco-friendly initiatives, and establish stronger collaborations with partners. By integrating these measures, Thailand's small and medium-sized ports can support global sustainability standards, enhance competitiveness, and contribute to a more sustainable future in the maritime sectors.

5. Geo-logistics and Sustainability in ASEAN Ports

Small and medium-sized ports in the ASEAN (Association of Southeast Asian Nations) are important in maritime network and regional trade. These ports have the potential to enhance regional connectivity and support sustainable development goals. However, many of these ports face significant challenges, including limited financial resources and inadequate infrastructure, which hinder their ability to implement sustainable practices effectively. To overcome these constraints, SMPs must adopt innovative strategies that integrate sustainability into their environmental management systems. At the same time, ASEAN member states have demonstrated strong commitment to

improving Safety, Health, and Environmental (SHE) management across participating ports. The effectiveness and efficiency of these ports can significantly influence the logistics performance of countries within ASEAN, as they often serve as critical nodes in regional supply chains. In doing so, the results of this analysis of sustainability practices in SMPs in Thailand can be compared to practices in ASEAN countries based on the internal and external management criteria. The findings summarized in **Table 3** highlights both similarities and differences in sustainability adoption and implementation, with particular attention to environmental, operational, and technological dimensions.

Table 3. Sustainability port and geo-logistics practices comparison.

Main Criteria	SMPs in Thailand	ASEAN Ports
Environmental Monitoring and Management	Limited real-time monitoring systems; It is necessary to improve	Active in real-time monitoring and ISO 14001 systems
Waste Management	Lack of operational waste management systems	Advanced waste management, pneumatic systems, and recycling
Technology and innovative	Some ports are still in process of digitalization such as Map Ta Phut port	AI-assisted cargo routing, automated berth scheduling, full digitalization
Port supply chain	The processes of green warehousing and sustainable procurement are still under development.	Advanced integration of sustainable supply chain management systems, fully automated logistics and forecasting
Marine Ecosystem and Biodiversity	Early stages of marine ecosystem protection efforts	Active marine ecosystem protection; advanced in ballast water management
Pollution Prevention and Carbon Neutrality	In-progress efforts need to enhance carbon neutrality initiatives	Active of carbon neutrality with green fuel and zero emissions strategies
Green-logistics	Green logistics practices are emerging but not yet standardized across all ports	Widespread implementation of green logistics including electric vehicles, renewable energy, and waste minimization
Law and regulation	Increasing efforts in compliance with local environmental laws and regulations	Stringent enforcement of international environmental standards, compliance with IMO, and national regulations

Source: Authors.

Table 3 presents a complex comparison between ASEAN and SMPs ports, especially regarding sustainability and the geo-logistics concept. The ASEAN ports, such as Singapore's port of Tanjung Priok, have an environmental monitoring practice to achieve high standards in real-time environmental impact management. However, this system is still lacking in the Map Ta Phut and Songkhla ports. Besides that, Waste management remains a key issue in Thai ports, with Songkhla and Ranong lacking effective systems. In contrast, larger ASEAN ports like Port Klang in Malaysia and the Port of Singapore have established comprehensive waste management systems, often using advanced technologies like pneumatic waste collection and recycling systems. Thai ports must strengthen waste management capabilities to match ASEAN standards [47]. Map Ta Phut Port leads in adopting cleaner technologies and digitalisation in ports in ASEAN, such as the Port of Singapore and Indonesia, and has been incorporating innovative port technologies such as AI-assisted cargo routing and automated berth scheduling for several years [48]. Thailand's smaller ports can implement their digital infrastructure and automation to stay competitive. For instance, the Port of Singapore, the Hong Kong port and Tanjung Priok have extensive collaborations with environmental organisations and local communities to improve sustainability. Singapore invests heavily in reducing its carbon footprint and has implemented green warehousing and shore power for vessels. In comparison, Thailand's ports are still developing partnerships to improve eco-friendly services and the potential for robust sustainability initiatives. On the other hand, ports in Singapore, Malaysia, and Indonesia have made strides in preserving marine ecosystems and low-emission practices such as ballast water management and carbon neutrality, which are still in the early stages of Thailand's ports [49]. ASEAN ports particularly in Singapore, have been more likely to pursue carbon neutrality goals than Thailand. It has adopted green port practices such as using alternative fuels and implementing carbon-neutral policies. Map Ta

Phut port in Thailand is catching up, but it still lacks a comprehensive policy framework for carbon neutrality, which remains a gap compared to leading ASEAN ports. Then, Thai ports must invest heavily in advanced green technologies and automation to drive more geo-logistics to succeed with high ports like Singapore and Port Klang, which have successfully implemented such technologies to increase operational efficiency and reduce emissions. Thailand ports need to foster partnerships with local communities to implement sustainable practices. Regarding green logistics, Thai ports are beginning to explore green logistics practices, but these initiatives are not yet standardized across all ports. In contrast, ASEAN ports have made significant strides in implementing green logistics, including the use of electric vehicles, renewable energy, and waste minimization techniques. Finally, Law and Regulation is an area where Thailand has made improvements, with increasing efforts to comply with local environmental laws and regulations including some part of IMO. However, ASEAN ports, particularly in Singapore, have stringent enforcement of international standards and are in full compliance with IMO regulations, ensuring more robust environmental performance. By doing so, It can emulate successful models from ASEAN ports that have established green logistics networks and collaborations for shared environmental goals. In conclusion, Map Ta Phut, compared to ASEAN, is outstanding in adopting advanced green technologies, environmental monitoring systems, and external partnerships.

6. Conclusions

This study presents a comprehensive analysis of the sustainability challenges and opportunities facing SMPs in Thailand, with particular attention to internal management practices, external collaborations, and the emerging role of geo-logistics. Employing a mixed-methods approach, including semi-structured interviews and comprehensive literature reviews, the research provides insights into how these ports implement sustainability criteria. The findings highlight that sustainable port development, particularly within the context of SMPs, necessitates real-time environmental monitoring, green procurement, ecosystem preservation, and the adoption of digital automation technologies. However, significant gaps remain in comprehensive green port policies, budget allocation for green initiatives, and collaborative efforts with external stakeholders. The geo-logistics have been introduced for integrating environmental, economic, and social goals offers a forward-thinking model for transformation, especially in SMPs where spatial and operational constraints are more pronounced. National strategies should focus on incentivising sustainable port development through regulatory support, funding mechanisms, and the creation of knowledge-sharing platforms. It is aligned with global decarbonization and sustainability targets; Thailand's small and medium-sized ports must shift from basic regulatory compliance to a proactive, innovation-driven approach. Moreover, external management practices like collaboration on coastal zone management, green port services, and incentivizing eco-friendly shipping activities have yet to be fully addressed. The study also noted disparities in stakeholders' perceptions of specific environmental collaborations, including compliance with international environmental standards and the adoption of eco-friendly materials and technologies. While the findings are insightful, the study acknowledges some limitations, such as a lack of data triangulation, which might have affected the accuracy of the analysis. The sample size, limited to experts within the Thai maritime sector, could limit how well the results can be applied to other contexts. Additionally, the purposive sampling method may have influenced the potential of perspectives captured.

On the other hand, this method and framework are applicable to Thailand, which provides an in-depth understanding of the challenges and opportunities related to sustainability and geo-logistics. However, the findings may not be directly transferable to other countries with different economic, regulatory, and technological environments. Additionally, the study is focused on a specific subset of regional ports, which may not fully capture the diversity of sustainability practices across various types of ports globally. To increase the broader applicability of the conclusions, future research could expand its scope by incorporating ports from diverse geographical regions and operational models. This would ensure that the insights gained are more relevant to an international audience.

To enhance the applicability of this research, future studies should involve comparative case analyses from various perspectives about regional ports or small and medium-sized ports in each region, such as Southeast Asia, Latin America, and Africa. This approach would validate the model across diverse sustainability and trade and promote knowledge-sharing among port authorities worldwide. Additionally, insights gained from international collaboration could refine the geo-logistics model, incorporating innovation and best practices from a broader range of port development strategies.

Author Contributions

Conceptualization, N.N., R.M., W.A. and P.S.; literature reviews, W.A.; methodology, N.N.; software, W.P. and R.M.; validation, W.P., N.N., P.S., W.A. and N.C.; formal analysis, N.N., R.M.; investigation, N.C.; resources, P.S.; data curation, P.S. and R.M.; writing—original draft preparation, N.N.; writing—review and editing, P.S., W.P., R.M. and N.C.; supervision, P.S.; project administration, N.N.; funding acquisition, N.N. All authors have read and agreed to the published version of the manuscript.

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All authors disclosed no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Questionnaire for Assessing Sustainability and Geo-Logistics in Small and Medium-Sized Ports in Thailand.

Part 1: Respondent Information

- Full Name:
- Position:
- Organization:

Part 2–3: Internal and External Management Criteria of Small and Medium Size Port in Thailand.

Internal Management	Songkhla Port	Map Ta Phut Port	Ranong Port
1. Is real-time monitoring and mitigation of environmental impacts implemented at the port?			
2. Does the port have a green port policy and a comprehensive environmental policy statement?			
3. Does the port have process of environmental in Green warehouse?			
4. Sustainable procurement practices have been implemented at the port?			
5. Is environmental monitoring facilitated through shared information and equipment channels?			
6. Does the port have environmental risk management practices in place?			
7. Does the port have strategies to minimize environmental harm?			
8. Does the port allocate budgets for green initiatives, including awareness and promotion campaigns?			
9. Does the port have a waste management system in place?			
10. Does the port implement eco-friendly and green cargo operations?			
11. Is lean logistics incorporated into sustainability development at the port?			
12. Is there effective planning and organization of logistics activities to ensure sustainability?			
13. Is alternative fuel used in terminal equipment?			
14. Is digitalization and automation used with cleaner technologies for port equipment?			
15. Has the port adopted automation tools and technologies for operations?			

External Management	Songkhla Port	Map Ta Phut Port	Ranong Port
1. Is ballast water management implemented to address heavy metals contamination?			
2. Is there an effort to foster an environmentally sustainable maritime supply chain and networks?			
3. Is the port or company involved in fostering eco-friendly engine technology and waste recovery systems in coastal communities?			
4. Is there collaboration for coastal zone management and marine protected areas?			
5. Are green port services actively promoted and utilized at the port?			
6. Are regulatory environmental laws enforced with penalties for violations?			
7. Is marine ecosystem preservation practiced with a focus on low emissions?			
8. Does the port provide eco-friendly services to attract environmentally conscious customers?			
9.Is there management of environmental risks and responsibilities with business partners?			
10. Is there a policy to employ eco-friendly materials and equipment?			
11. Are there efforts to make maritime and port supply chains more resilient?			
12. Are there measures in place for pollution prevention and response?			
13. Is carbon neutrality and zero emissions being pursued at the port or maritime operation?			

Part 4: Suggestion

- What do you see as the key challenges in implementing sustainability practices in your port?
- What are the long-term sustainability goals for your port, and how do you plan to achieve them?
- How do you think geo-logistics and green technologies could further enhance sustainability in your port? Any suggestions or recommendations?
- Other suggestion.

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