การจัดการขนส่งสีเขียวและแบบลีนในการเพิ่มประสิทธิภาพอย่างยั่งยืนของผู้ให้บริการขนส่งในระบบโซ่ความเย็นอุตสาหกรรมอาหารในประเทศไทย

Lean and Green Transportation Management for Sustainable Efficiency Improvement of Transportation Service Providers in Thailand Food Cold Chain

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บทคัดย่อ

การวิจัยนี้มุ่งศึกษาผลกระทบของการขนส่งสีเขียวและการขนส่งแบบลีนต่อประสิทธิภาพการดำเนินงานอย่างยั่งยืนของผู้ให้บริการขนส่งสินค้าในระบบโซ่ความเย็นอาหารของประเทศไทย โดยใช้การวิจัยแบบผสานวิธี ประกอบด้วยการเก็บข้อมูลเชิงปริมาณจากผู้ให้บริการขนส่ง 408 ราย และข้อมูลเชิงคุณภาพจากผู้ให้ข้อมูลสำคัญ 12 ราย การวิเคราะห์ด้วยโมเดลสมการโครงสร้าง พบว่าการขนส่งสีเขียวและการขนส่งแบบลีนส่งผลในเชิงบวกต่อประสิทธิภาพการให้บริการขนส่งในระบบโซ่ความเย็นและผลการดำเนินงานอย่างยั่งยืนอย่างมีนัยสำคัญทางสถิติที่ระดับ 0.05 โมเดลที่พัฒนาขึ้นมีความสอดคล้องกับข้อมูลเชิงประจักษ์ (χ^2 = 119.077, df = 109, p = 0.240, χ^2/df = 1.092, RMSEA = 0.015, GFI = 0.969, CFI = 0.997) และสามารถอธิบายความแปรปรวนของความยั่งยืนได้ร้อยละ 74.2 การขนส่งสีเขียวซึ่งประกอบด้วยการลดการปล่อยก๊าซ การใช้ยานพาหนะที่ประหยัดพลังงาน และการประยุกต์เทคโนโลยีที่เป็นมิตรต่อสิ่งแวดล้อม ช่วยเสริมประสิทธิภาพการดำเนินงานและผลลัพธ์ด้านสิ่งแวดล้อม ขณะที่การขนส่งแบบลีน ซึ่งเน้นการจัดความสูญเปล่า การปรับปรุงเส้นทาง และความร่วมมือช่วยเพิ่มความคุ้มค่า การตอบสนอง และความน่าเชื่อถือของการให้บริการขนส่งสินค้า ผลการวิจัยชี้ให้เห็นถึงประโยชน์เชิงเสริมจากการบูรณาการทั้งสองแนวทาง โดยแนวทางลีนให้ผลลัพธ์ต่อประสิทธิภาพในระยะสั้น ขณะที่แนวทางสีเขียวสร้างผลลัพธ์เชิงสิ่งแวดล้อมในระยะยาว โมเดลนี้สามารถใช้เป็นกรอบเชิงกลยุทธ์เพื่อส่งเสริมระบบขนส่งอย่างยั่งยืนสำหรับภาคการขนส่งโซ่ความเย็นในประเทศไทย

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Abstract

This study examines the impact of green and lean transportation on the sustainable performance of transport service providers in Thailand's food cold chain. Utilizing a mixed-methods research design, quantitative data were collected from 408 providers and complemented with qualitative insights from 12 key informants. The research investigates causal relationships among green transportation, lean transportation, efficiency of transport service in cold chain, and sustainable performance. Structural

Equation Modeling (SEM) results indicate that both green and lean transportation significantly influence transport efficiency and sustainability, with direct and indirect effects observed at the 0.05 significance level. The model demonstrated a strong fit (χ^2 = 119.077, df = 109, p = 0.240, χ^2/df = 1.092, RMSEA = 0.015, GFI = 0.969, CFI = 0.997), explaining 74.2% of the variance in sustainable performance. Green transportation practices such as emissions reduction, energy-efficient vehicles, and environmentally friendly technologies were found to enhance operational efficiency and environmental outcomes. Meanwhile, lean transportation through waste elimination, route optimization and cross-functional collaboration improved cost-effectiveness, service responsiveness, and delivery reliability. Efficiency of transport service was measured through indicators such as delivery reliability, traceability, energy savings, and service quality. Sustainable performance was assessed across economic (cost savings, profitability), environmental (carbon emissions, energy usage), and social (safety, quality assurance) dimensions. The empirical findings substantiate the synergistic benefits of integrating green and lean transportation, with lean practices exerting more immediate effects on operational efficiency, while green practices yield more pronounced long-term environmental advantages. The study offers a validated conceptual model with high practical relevance, serving as a strategic framework for logistics practitioners and policymakers to advance sustainable transportation systems within cold chain logistics in emerging economies such as Thailand.

1. Introduction

The escalating emissions of carbon dioxide and other greenhouse gases (GHGs) have been widely recognized as primary drivers of global warming and climate change, leading to severe environmental disturbances worldwide (United Nations Thailand, 2022). Within the logistics sector, the food supply chain, especially temperature-controlled transportation, has emerged as a significant contributor to these emissions due to its high energy consumption in refrigeration, packaging, and vehicle operations (Leng et al., 2024). In Thailand, these concerns are particularly critical. The country's food cold chain industry is expanding rapidly in response to increasing demand for fresh and perishable products. However, substantial challenges remain. According to the Department of Internal Trade (2022), up to 30% of perishable goods are lost during transport due to delays, inadequate temperature monitoring, and substandard storage infrastructure. The Office of Trade Policy and Strategy (2022) also noted a 34.1% rise in logistics business registrations in 2021, yet many operators fail to adopt sustainable logistics practices or align with Sustainable Development Goals (SDGs). Moreover, Thailand's cold chain logistics infrastructure ranks 32nd globally (World Bank, 2023), indicating significant room for improvement in operational efficiency and sustainability integration.

To address these challenges, the adoption of green and lean transportation strategies has been increasingly recognized as a viable solution. Green transportation emphasizes emission reduction, clean

energy, and eco-innovation, while lean transportation targets waste minimization and process efficiency. These dual strategies can collectively enhance service quality, cost-effectiveness, and environmental responsibility, particularly in emerging economies like Thailand where logistical inefficiencies and environmental pressures co-exist. This study is theoretically grounded in the Resource-Based View (RBV) and the concept of Eco-Efficiency. The RBV explains how firms can leverage internal capabilities such as green and lean practices to achieve a sustainable competitive advantage. Eco-efficiency provides a framework for balancing economic performance with environmental outcomes through resource optimization.

Despite extensive research in advanced economies, two critical research gaps remain. First, there is limited empirical investigation of green-lean integration in emerging markets, including Thailand's food cold chain. Second, the measurement of eco-efficiency in transportation systems remains underdeveloped, with few models incorporating both environmental and service performance dimensions.

Against this backdrop, the present study aims to develop and empirically validate a SEM that explores the causal relationships among green transportation, lean transportation, efficiency of transport service, and sustainable performance in Thailand's food cold chain. The structure of the paper is as follows: literature review, research methodology, results, and discussion of the findings and implications. A gap analysis table is also introduced in the literature review to contextualize this study's unique contribution to theory and practice.

The subsequent section reviews theoretical and empirical literature related to green transportation, lean transportation, efficiency of transportation service in cold chain, and sustainable performance. Emphasis is placed on identifying research gaps and clarifying the unique context of the Thai food cold chain.

1.1 Green Transportation

Green transportation has emerged as a multidimensional strategy to enhance both environmental and operational performance in cold chain logistics, including the use of green energy (Chen et al., 2023; Zhao et al., 2023; Musolino et al., 2019), technological innovation (Calati et al., 2022; Behdani et al. 2019), route optimization (Li et al., 2019; Fang et al., 2022), and systematic transportation preparation (Khumalo et al., 2023; Jovanovic et al., 2020). These elements have been shown to reduce greenhouse gas emissions, lower operational costs, minimize product spoilage, and enhance delivery reliability. In particular, the adoption of environmentally friendly vehicles has been shown to significantly support the effectiveness of green transportation policies in reducing ecological footprints. (Rehman et al., 2023)

1.2 Lean Transportation

Lean transportation is recognized as a strategic approach to improve service efficiency, reduce costs, and enhance logistics quality by minimizing waste and optimizing transport processes. Core elements include collaboration, coordination, and efficient resource flow to lower overall transportation costs (Kurganov et al., 2021), along with integration, innovation, process flow, inventory control, and waste reduction (Lobo & Pinho, 2019). These are further supported by multimodal planning, staff collaboration, and transportation mode shifts (Colicchia et al., 2017). Improvements in road transport can be achieved

through goal-setting, technology adoption, effective resource management, and clear communication (Garza-Reyes et al., 2017). Lean principles have been shown to enhance operational quality (Kawa et al., 2019; Kuvvetli & Firuzan, 2019) and increase responsiveness to customer demands (Ponte et al., 2018), particularly when supported by standardized procedures and real-time technologies (Lobo & Pinho, 2019).

While Faheem et al. (2023) and Musolino et al. (2019) emphasize green innovation, renewable energy, and emission-reducing policies, Koson (2016) focus more on operational practices such as GPS monitoring, route planning, and minimizing fuel consumption. Similarly, lean transportation is explored in global contexts using Lean Six Sigma and value stream mapping (Kurganov et al., 2021), whereas Thai research often concentrates on waste reduction through staff participation and digital tools in SMEs.

1.3 Efficiency of transportation service in cold chain

Efficiency of transportation service in cold chain is essential for maintaining product quality, reducing energy use, and enhancing service delivery (Ma & Zhao, 2024). Key contributing factors include service level, reliability, quality control, management, traceability, and energy efficiency (Kumar, Tyagi & Sachdeva, 2023; Liao et al., 2023; Meng et al., 2023). Reliable service and freshness of perishable goods depend on timely delivery and accurate tracking (Qi et al., 2022; Samantha, Louise & Jonathan, 2022). Technologies such as real-time monitoring and traceability systems play a crucial role in minimizing risks and ensuring quality (Islam & Cullen, 2021; Óskarsdóttir & Oddsson, 2019). Effective management and energy-saving practices help reduce costs and environmental impacts while preserving product integrity (Chaitangjit & Ongkunaruk, 2019; Kumar, Tyagi & Sachdeva, 2023). Moreover, cold chain performance aligns with transportation efficiency factors such as speed, economy, safety, convenience, and punctuality (Bardi et al., 2006).

Despite substantial support for green and lean strategies, some studies have reported mixed outcomes. For example, Jovanovic et al. (2020) found that environmental constraints and lack of incentives limited green adoption in Canadian SMEs. Similarly, Iranmanesh et al. (2019) noted that lean initiatives without technological readiness may yield limited improvement. These contradictory findings suggest that context matters factors such as infrastructure, regulation, and firm capacity, may influence outcomes.

1.4 Sustainable performance

Sustainable performance in cold chain logistics is commonly evaluated through economic, social, and environmental dimensions (Leng et al., 2024). These pillars are central to sustainability frameworks in food and agricultural supply chains (Liao et al., 2023; Saulick et al., 2023). In cold chain logistics, practices such as emissions reduction, efficient packaging, and energy-saving technologies are linked to improved service and competitiveness (Bishara, 2006). Green and lean transportation strategies enhance sustainability by reducing carbon emissions, improving efficiency, and minimizing waste (Rodríguez et al., 2016).

Cold chain logistics abroad benefits from well-integrated infrastructure and standardized practices (Kumar et al., 2023), while Thailand faces challenges such as energy inefficiency, fragmented cold storage facilities, and inconsistent traceability systems (DITP, 2022). Sustainability performance in advanced economies is increasingly guided by the Triple Bottom Line (Cetinkaya et al., 2011). While in Thailand, the implementation of the Triple Bottom Line framework remains inconsistent, the Stock Exchange of Thailand

(SET) has attempted to promote transparency through its sustainability reporting guidelines. These guidelines encourage the preparation of annual sustainability reports that are consistent with the Global Reporting Initiative (GRI) framework (Arunee & Supakorn, 2017).

1.5 Relationship between green transportation, lean transportation, efficiency of transportation service in cold chain and sustainable Performance

The literature indicates that green transportation serves as a critical driver in improving the efficiency of cold chain logistics while simultaneously advancing sustainable performance outcomes. (Sun, Gu & Wu, 2022; Fang et al., 2022). Studies have shown that adopting green transportation can reduce environmental impacts while simultaneously improving economic and social performance across the cold chain (Trivellas et al., 2020; Qi et al., 2020). Similarly, lean transportation contributes to improved process efficiency, waste reduction, and cost savings, which positively affect both service quality and long-term sustainability (Kurganov et al., 2020; Al-Refaie et al., 2020). Lean transportation also strengthens performance through supply chain integration, employee involvement, and continuous improvement (Iranmanesh et al., 2019). In the cold chain context, lean transportation supports operational efficiency and risk mitigation while maintaining service responsiveness (Costa et al., 2020; Nedeliakova et al., 2020). Moreover, Lean Six Sigma approaches have demonstrated strong positive effects on economic, environmental, and social sustainability indicators (Barcia et al., 2022). The synergy between green and lean transportation enhances delivery reliability, reduces spoilage and emissions, and fosters sustainable business practices. (Aytekin et al., 2024; Ma & Zhao, 2024). Research further confirms that improved transportation efficiency in the cold chain, measured by factors such as service quality, reliability, and energy savings, directly contributes to sustainable performance across all three dimensions (Saulick et al., 2023; Zope et al., 2022; Leng et al., 2024).

Although many studies examine green or lean practices in isolation, few have explored their integrated effects within emerging economies, especially Thailand's cold chain sector, where current models of eco-efficiency often emphasize either economic or environmental aspects but lack holistic integration with logistics service efficiency. Hence, this study addresses the following gaps: 1) Limited empirical research on combined green-lean transportation strategies in Thai cold chain logistics 2) Insufficient modeling of eco-efficiency that incorporates service-level variables like reliability and traceability 3) Lack of standardized metrics linking logistics efficiency to sustainability performance.

Drawing from the RBV and eco-efficiency theory, this study proposes a conceptual model linking green transportation, lean transportation, efficiency of transportation service in cold chain, and sustainability performance. The hypotheses are derived from the literature review and are tested using SEM. The research model includes the following hypotheses: H1: Green transportation directly influences efficiency of transportation service in Thailand's food cold chain. H2: Lean transportation directly influences efficiency of transportation service in Thailand's food cold chain. H3: Green transportation directly influences sustainability performance of the transportation service providers in Thailand's food cold chain. H4: Lean transportation directly influences sustainability performance of the transportation service providers in Thailand's food cold chain. H5: Efficiency of transportation service in cold chain directly influences

sustainability performance of the transportation service providers in Thailand's food cold chain. H6: Green transportation indirectly influences sustainability performance of the transportation service providers in Thailand's food cold chain through efficiency of transportation service in cold chain. H7: Lean transportation indirectly influences sustainability performance of the transportation service providers in Thailand's food cold chain through efficiency of transportation service in cold chain.

Against this backdrop, the present study aims to develop and empirically test a SEM that examines the relationship between green transportation, lean transportation, and efficiency of transportation service in cold chain as predictors of sustainable performance among transportation service providers in Thailand's food cold chain. This research addresses the growing need for strategic and operational insights into how green and lean transportation can be effectively integrated to promote environmental, economic, and social sustainability in Thailand's food cold chain.

2. Methodology

Grounded in the theoretical frameworks of the Resource-Based View (RBV) and eco-efficiency theory, this study investigates the extent to which green and lean transportation practices influence the efficiency and sustainable performance of transport service providers operating within Thailand's food cold chain. To achieve this aim, a conceptual model was developed and empirically tested through a mixed-methods research design. The study is structured around three core research questions: 1) To what extent do green and lean transportation practices affect the efficiency and sustainable performance of cold chain logistics in Thailand? 2) What is the mediating role of efficiency of transportation service in cold chain in the relationship between green or lean transportation and sustainable performance? 3) What contextual insights can be drawn from qualitative interviews to enhance understanding of these relationships?

To address these questions, the study adopted a sequential mixed-methods approach that integrated both quantitative and qualitative components. The quantitative phase involved the development and testing of a structural model using SEM, while the qualitative phase was designed to supplement and enrich these findings through thematic content analysis.

The research was conducted between May and October 2024. Quantitative data were collected from July to September 2024 at the operational premises of cold chain food transport service providers using truck-based logistics across various regions of Thailand.

2.1 Quantitative Approach

A structured questionnaire was designed based on a comprehensive literature review, comprising three sections and employing a 5-point Likert scale (1 = Never or almost never, 2 = Rarely, 3 = Sometimes, 4 = Frequently, 5 = Always). The instrument was reviewed and validated by five subject-matter experts, with an Index of Item-Objective Congruence (IOC) of at least 0.70. Furthermore, a pilot study involving 30 transport firms yielded a Cronbach's alpha coefficient of 0.933, confirming the internal consistency of the instrument.

For the sampling process, the study population comprised 1,015 food cold chain transport service providers using truck-based logistics in Thailand (Department of Industrial Promotion, Ministry of Industry, 2020). A stratified random sampling strategy was employed based on company size, classified by registered capital (≥10 million THB for large enterprises and <10 million THB for small ones), in accordance with the criteria of the Department of Business Development. Consequently, the final sample consisted of 408 firms, which exceeded Hair et al. (2010) recommendation of 10–20 respondents per variable for SEM analysis, based on 17 observed variables.

Data collection was conducted with appropriate ethical clearance and administrative approvals. An overall response rate exceeding 80% was achieved. Non-response bias was minimized through follow-up procedures and comparative analysis between early and late respondents. The data were analyzed using SPSS (George et al., 2019) for descriptive statistics, including skewness, kurtosis, and Pearson's correlation coefficients (George & Mallery, 2019). AMOS software was used for SEM analysis, employing the Maximum Likelihood Estimation (MLE) method to assess model fit using standard indices such as chi-square (χ^2), Root Mean Square Error of Approximation (RMSEA), Goodness-of-Fit Index (GFI), Adjusted Goodness-of-Fit Index (AGFI), Comparative Fit Index (CFI), and Root Mean Square Residual (RMR) (Hair et al., 2010; Kline, 2016).

2.2 Qualitative Approach

To deepen the understanding of the quantitative findings, qualitative data were collected from 12 key informants selected through purposive sampling, including representatives from logistics service providers, academic experts in logistics and supply chain management, and clients of cold chain food logistics services. Semi-structured interviews were conducted and audio-recorded with prior consent. Moreover, an interview guide comprising 15 questions was developed, derived from the significant variables identified in the SEM model. The interviews were transcribed and analyzed using a two-cycle coding process: initial open coding to identify emerging concepts, followed by axial coding to group these into overarching themes. To ensure analytical rigor, intercoder reliability was verified by an independent reviewer, and triangulation was employed to cross-validate findings across respondent groups.

Therefore, this mixed-methods design enabled a robust and holistic exploration of the relationships among green transportation, lean transportation, efficiency of transport services, and sustainable performance in Thailand's food cold chain.

3. Results

The quantitative analysis investigates the impact of green and lean transportation on the sustainable performance of transport service providers in Thailand's food cold chain. The findings comprise descriptive statistics, model fit evaluation and SEM, complemented by qualitative insights from industry experts to provide a comprehensive view of the key factors driving sustainable performance.

3.1 Quantitative research results

The empirical results were derived based on a research conceptual framework developed through the literature review. Descriptive statistics are presented for the observed variables, including measures of central tendency and relationships among constructs. Model fit indices are assessed to evaluate the adequacy of the measurement model. SEM results reveal the causal impacts of green transportation, lean transportation, and efficiency of transportation service in cold chain on sustainable performance. The revised structural model further delineates the enhanced causal relationships among these factors within the context of transportation service providers in Thailand's food cold chain.

Table 1 shows the descriptive analysis of the distribution of observed variable for each latent variable used in the research is shown. Descriptive statistics used were mean ($\bar{x}$), standard deviation (SD), skewness (Sk), kurtosis (Ku), and coefficient of variation (% CV). The criteria for evaluating normal distribution of data were skewness and kurtosis. The skewness must be between -3 and +3 and the kurtosis must be less than 10 (Kline, 2011).

The descriptive statistics reveal consistently high mean scores across all observed variables for Green Transportation (GT), Lean Transportation (LT), Efficiency of Transportation Service in Cold Chain (ET), and Sustainable Performance (SP), with most mean values above 3.80. This indicates a strong level of implementation of sustainable logistics practices among the participating cold chain transport firms. Sustainable Performance items (SP1–SP3), in particular, show the highest average ratings (up to 4.18), reflecting broad consensus on their significance. The relatively low standard deviations and coefficients of variation (generally under 20%) demonstrate a high degree of response consistency. Additionally, skewness and kurtosis values fall within the acceptable ranges (Skewness: −3 to +3; Kurtosis < 10), confirming normal distribution and the appropriateness of the data for further structural analysis (Kline, 2011). Most variables exhibit slight negative skewness, suggesting a general tendency toward favorable perceptions.

In Addition, the results revealed statistically significant differences in mean scores for Green Transportation and Efficiency of Transportation Service in Cold Chain. Specifically, large enterprises reported significantly higher levels of Green Transportation (M = 4.05, SD = 0.67) than small enterprises (Mean = 3.85, S.D. = 0.76), t(406) = 2.96, *p*<0.01. Similarly, Efficiency of Transportation Service was rated higher among large firms (Mean = 4.14, S.D. = 0.70) than small firms (Mean = 3.98, S.D. = 0.73), t(406) = 2.47, *p*<0.05.

Furthermore, correlation analysis of the 17 observed variables indicated that 136 pairs were statistically significant at the 0.05 level, with positive coefficients ranging from 0.368 to 0.829, indicating strong directional alignment among constructs. The Bartlett's Test of Sphericity (χ^2 = 8507.373, df = 136, *p* = 0.000) confirmed that the correlation matrix significantly differs from the identity matrix. This finding, supported by a high Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (0.940), affirms the suitability of the dataset for SEM. These findings provide a solid foundation for subsequent multivariate analysis and support the theoretical integration of green and lean transportation with efficiency of transportation service in cold chain and sustainable performance. Thereafter, the coefficient correlation analysis of observed variables is shown in Figure 1.

Table 1. Descriptive Analysis of Observed Variables

Variable	Mean	S.D.	Max	Min	% C.V.	Skewness	Kurtosis
Green Transportation (GT)							
GT1	3.95	0.70	5.00	1.67	17.72%	-0.33	-0.39
GT2	3.97	0.71	5.00	1.33	17.88%	-0.44	-0.37
GT3	3.95	0.73	5.00	1.00	18.48%	-0.42	-0.45
GT4	3.96	0.78	5.00	2.00	19.70%	-0.42	-0.24
Lean Transportation (LT)							
LT1	3.88	0.76	5.00	1.33	19.59%	-0.50	0.86
LT2	3.91	0.75	5.00	0.67	19.18%	-0.44	-0.12
LT3	3.81	0.80	5.00	1.00	21.00%	-0.43	-0.16
LT4	3.83	0.78	5.00	1.67	20.37%	-0.32	-0.54
Efficiency of Transportation Service in Cold Chain (ET)							
ET1	4.02	0.78	5.00	1.33	19.40%	-0.64	-0.09
ET2	4.04	0.77	5.00	1.33	19.06%	-0.67	0.03
ET3	4.05	0.69	5.00	1.00	17.04%	-0.66	0.38
ET4	4.06	0.68	5.00	2.00	16.75%	-0.45	-0.53
ET5	4.05	0.71	5.00	1.67	17.53%	-0.55	-0.23
ET6	4.05	0.69	5.00	0.67	17.04%	-0.61	0.46
Sustainability Performance (SP)							
SP1	4.13	0.78	5.00	1.00	18.89%	-0.76	0.11
SP2	4.16	0.76	5.00	1.75	18.27%	-0.72	-0.34
SP3	4.18	0.72	5.00	1.33	17.22%	-0.81	0.21

The correlation coefficient of the 17 observed variables of the measurement model indicated that correlation of 136 pairs of variables was statistically significant at the level of 0.05 with the values greater than zero. The correlation coefficient also showed positive relationships between the variables, which were in the same direction, with values ranging from 0.368 to 0.829. The Bartlett's Test of Sphericity showed the values of Chi-square = 8507.373, df = 136, and *p*-value = 0.000, indicating that the correlation matrix differs from the identity matrix at a statistical significance level of 0.05. This is consistent with the result of the Kaiser-Meyer-Olkin (KMO) test which showed the value a of 0.940. This proves that the variables were highly correlated and suitable for use in the analysis of SEM. The coefficient correlation analysis of observed variables is shown in Figure 1.

Variable	Correlation Coefficient																
	LT1	LT2	LT3	LT4	GT1	GT2	GT3	GT4	ET1	ET2	ET3	ET4	ET5	ET6	SP1	SP2	SP3
LT1	1.000																
LT2	0.804**	1.000															
LT3	0.774**	0.789**	1.000														
LT4	0.696**	0.741**	0.767**	1.000													
GT1	0.775**	0.766**	0.778**	0.788**	1.000												
GT2	0.637**	0.669**	0.639**	0.614**	0.745**	1.000											
GT3	0.622**	0.673**	0.648**	0.716**	0.684**	0.705**	1.000										
GT4	0.521**	0.602**	0.576**	0.570**	0.612**	0.706**	0.702**	1.000									
ET1	0.680**	0.643**	0.719**	0.641**	0.653**	0.666**	0.644**	0.597**	1.000								
ET2	0.698**	0.667**	0.699**	0.641**	0.681**	0.637**	0.655**	0.573**	0.818**	1.000							
ET3	0.740**	0.700**	0.752**	0.705**	0.748**	0.726**	0.734**	0.652**	0.829**	0.902**	1.000						
ET4	0.657**	0.620**	0.679**	0.626**	0.646**	0.553**	0.609**	0.542**	0.654**	0.698**	0.816**	1.000					
ET5	0.584**	0.566**	0.636**	0.576**	0.567**	0.468**	0.550**	0.467**	0.586**	0.636**	0.730**	0.957**	1.000				
ET6	0.693**	0.635**	0.739**	0.616**	0.691**	0.570**	0.591**	0.520**	0.723**	0.726**	0.764**	0.739**	0.694**	1.000			
SP1	0.726**	0.777**	0.728**	0.702**	0.710**	0.634**	0.661**	0.632**	0.704**	0.659**	0.724**	0.668**	0.586**	0.697**	1.000		
SP2	0.579**	0.578**	0.643**	0.628**	0.549**	0.368**	0.486**	0.492**	0.527**	0.522**	0.551**	0.538**	0.496**	0.593**	0.662**	1.000	
SP3	0.500**	0.559**	0.597**	0.611**	0.644**	0.652**	0.582**	0.597**	0.536**	0.537**	0.609**	0.468**	0.371**	0.552**	0.543**	0.422**	1.000
$\bar{x}$	3.88	3.91	3.82	3.84	3.95	3.97	3.95	3.96	4.02	4.04	4.05	4.06	4.05	4.05	4.13	4.16	4.18
SD.	0.76	0.75	0.80	0.78	3.96	0.68	0.71	0.73	0.78	0.77	0.70	0.68	0.71	0.69	0.78	0.77	0.72
Bartlett's test of Sphericity: Chi-Square = 8507.373, df = 136, p-value = 0.000, KMO = 0.940																	

Remark: **p<0.01

Figure 1. Correlation Matrix, Mean, Standard Deviation of Observed Variables of the Measurement Model

From Figure 1, the correlation matrix reveals significant positive relationships among all latent variables (*p*<0.01), indicating that the observed variables are directionally aligned and theoretically coherent. In particular, the correlation between lean transportation and efficiency of transportation service in cold chain is notably strong (r = 0.684), suggesting that efforts to streamline transportation processes, such as route optimization and waste reduction, are closely associated with improvements in service reliability, responsiveness, and overall transport quality. Although the correlations between green transportation and other variables are slightly lower, they are still statistically significant and meaningful (e.g., r = 0.638 with efficiency of transportation service in cold chain). This finding reflects the influence of environmentally responsible practices, such as emissions reduction and the use of energy-efficient technologies, on service outcomes. Furthermore, these interrelationships reinforce the structure of the conceptual model and confirm that both green and lean practices play a significant role in enhancing transport service efficiency as well as sustainable performance. The findings affirm the adequacy of the measurement model for SEM and highlight the practical synergy between lean and green approaches in advancing cold chain logistics in Thailand.

From Tables 2 and 3, the SEM analysis of causal relationships among green transportation management, lean transportation management, and efficiency of transportation service affecting sustainable performance of transportation service providers in Thailand's food cold chain indicated that the goodness of fit of the model was satisfactory. This is based on fit index assessment which showed Chi – Square = 119.077, df = 109, and *p*-value = 0.240. Moreover, χ^2 was greater than 0.05 at a statistical significance level of 0.05 and χ^2/df = 1.092 which was less than 2. In addition, the other indices RMSEA = 0.015 and RMR = 0.018 had the values close to zero and GFI = 0.969, AGFI = 0.957, CFI = 0.997 had the values close to one. This proves that the SEM of causal relationships among green transportation management, lean

transportation management, and efficiency of transportation service affecting sustainable performance of transportation service providers in Thailand's food cold chain was valid. The analysis showed positive factor loadings for each variable greater than zero at a statistical significance level of 0.05. The variable with the highest factor loading was environmental performance at 0.853, while the variable with the lowest factor loading was Integrated Transportation at 0.592.

The confirmatory factor analysis (CFA) conducted for the four latent constructs, namely Green Transportation (GT), Lean Transportation (LT), Efficiency of Transportation Service in Cold Chain (ET), and Sustainability Performance (SP), demonstrated strong construct validity and model fit. All observed variables had standardized factor loadings (β) exceeding 0.60, which meets the threshold for convergent validity (Hair et al., 2010). The reliability and validity of each construct were further confirmed through composite reliability (CR) and average variance extracted (AVE) calculations. Specifically, all constructs had CR values greater than 0.70 and AVE values exceeding 0.50. For example, GT reported a CR of 0.872 and an AVE of 0.594; LT showed CR = 0.843 and AVE = 0.563; ET yielded CR = 0.917 and AVE = 0.649; and SP had CR = 0.899 and AVE = 0.742. These results confirm the internal consistency and convergent validity of the measurement model and support its use for subsequent structural equation modeling (SEM).

Table 2. Fit Index Analysis

Fit Index	Criteria of Acceptable Fit	Before Model Modification		After Model Modification	
		Value	Assessment of Fit	Value	Assessment of Fit
χ^2	p>0.05	0.000	Not Acceptable	0.240	Acceptable
χ^2/ df	< 2.00	3.517	Not Acceptable	1.092	Acceptable
GFI	≥ 0.90	0.900	Acceptable	0.969	Acceptable
AGFI	≥ 0.90	0.864	Not Acceptable	0.957	Acceptable
CFI	≥ 0.90	0.923	Acceptable	0.997	Acceptable
RMSEA	< 0.05	0.076	Acceptable	0.015	Acceptable
RMR	< 0.05	0.023	Acceptable	0.018	Acceptable

Table 3. Results of SEM Analysis

Variable	b	β	S.E.	t (C.R.)	R^2	Factor Score
GT1	0.672	0.612	0.053	12.573***	0.375	0.089
GT2	0.896	0.817	0.055	16.172***	0.667	0.336
GT3	0.733	0.640	0.056	13.027***	0.410	0.105
GT4	1.000	0.845	<- ->	<- ->	0.714	0.376
LT1	0.755	0.648	0.058	13.097***	0.420	0.111
LT2	0.686	0.592	0.058	11.863***	0.350	0.067
LT3	1.009	0.823	0.062	16.397***	0.678	0.320
LT4	1.000	0.831	<- ->	<- ->	0.690	0.342
ET1	1.217	0.763	0.086	14.209***	0.582	0.114
ET2	0.206	0.772	0.084	14.438***	0.595	0.125
ET3	1.025	0.730	0.075	13.679***	0.533	0.119
ET4	1.031	0.743	0.074	13.857***	0.552	0.167
ET5	0.986	0.683	0.077	12.861***	0.467	0.078
ET6	1.000	0.713	<- ->	<- ->	0.508	0.144
SP1	1.000	0.838	<- ->	<- ->	0.703	0.356
SP2	0.883	0.755	0.053	16.775***	0.570	0.189
SP3	0.941	0.853	0.048	19.542***	0.727	0.298

Chi-Square (CMIN) = 119.077, df = 109, *p*-value = 0.240, RMSEA = 0.015, GFI =0.969, AGFI = 0.957

Remark: β refers to factor loading, R2 refers to coefficient of determination, *p*< ***0.001, the symbol <- -> refers to constrained parameters, therefore S.E. and t (C.R.) values are not reported.

Additionally, the coefficient of determination of the variables (R^2) used to explain the covariance of the causal relationship model of green transportation management, lean transportation management, and efficiency of transportation service affecting sustainable performance of transportation service providers in Thailand's food cold chain had values ranging from 0.350 to 0.727. The R^2 of each variable is described as follows:

- Green Transportation (GT) which consisted of 4 observed variables had factor loadings ranging from 0.612 to 0.845, which were statistically significant at the level of 0.05. The observed variable with the highest factor loading was transport preparation (GT4) which had a factor loading of 0.845 and a higher covariance than other variables (R^2 = 0.714).

- Lean Transportation (LT) which consisted of 4 observed variables had factor loadings ranging from 0.592 to 0.831, which were statistically significant at the level of 0.05. The observed variable with the highest factor loading was collaboration (LT4) which had a factor loading of 0.831 and a higher covariance than other variables (R^2 = 0.690).

- Efficiency of Transportation Service in Cold Chain (ET) which consisted of 6 observed variables had factor loadings ranging from 0.638 and 0.772, which were statistically significant at the level of 0.05. The observed variable with the highest factor loading was reliability (ET2) which had a factor loading of 0.772 and a higher covariance than other variables (R^2 = 0.595).

- Sustainability Performance (SP) which consisted of 3 observable variables had factor loadings ranging from 0.755 to 0.853, which were statistically significant at the level of 0.05. The observed variable with the highest factor loading was environmental performance (SP3) which had a factor loading of 0.853 and a higher covariance than other variables ($R^2 = 0.727$).

From the SEM analysis of causal relationships among green transportation management, lean transportation management, and efficiency of transportation service affecting sustainable performance of transportation service providers in Thailand's food cold chain, it was found that the variance of the performance of transportation service providers in Thailand's food cold chain could be explained by all variables in the model at 83.90%. The factor loadings of all variables were greater than zero and positive at a statistical significance level of 0.05. The causal effect analysis of the variables is presented in Table 4.

Table 4. The Causal Effect Analysis of green transportation management, lean transportation management and efficiency of transportation service affecting sustainable performance of transportation service providers in Thailand food cold chain

Independent Variable	Effect	Dependent Variable	
		Efficiency of Transportation Service in Cold Chain (ET)	Sustainability Performance (SP)
R^2		0.839	0.742
Green Transportation (GT)	DE	0.307**	0.319**
	IE	-	0.093**
	TE	0.307**	0.412**
Lean Transportation (LT)	DE	0.399**	0.342**
	IE	-	0.121**
	TE	0.399**	0.463**
Efficiency of Transportation Service in Cold Chain (ET)	DE	-	0.303**
	IE	-	-
	TE	-	0.303**

Chi – Square = 119.077, df = 109, *p*-value = 0.240, χ^2/df = 1.092, RMSEA = 0.015, RMR = 0.018, GFI = 0.969, AGFI = 0.957, CFI = 0.997

Remark: **$p<0.05$, the symbol (–) means that there is no path for parameter estimate according to the hypothesis.

From Table 4, the main findings are as follows:

- Green transportation had a direct effect on efficiency of transportation service in Thailand's food cold chain of 0.307 at a statistical significance level of 0.05. Hence, H1 was confirmed.

- Lean transportation had a direct effect on efficiency of transportation service in Thailand's food cold chain of 0.399 at a statistical significance level of 0.05. Thus, H2 was supported.

- Green transportation had a direct effect on sustainability performance of the transportation service providers in Thailand's food cold chain of 0.319 at a statistical significance level of 0.05. Therefore, H3 was accepted.

- Lean transportation had a direct effect on sustainability performance of the transportation service providers in Thailand's food cold chain of 0.342 at a statistical significance level of 0.05. As a result, H4 was affirmed.

- Efficiency of transportation service in cold chain had a direct effect on sustainability performance of the transportation service providers in Thailand's food cold chain of 0.303 at a statistical significance level of 0.05. Consequently, H5 was substantiated.

- Green transportation had an indirect effect on sustainability performance of the transportation service providers in Thailand's food cold chain through efficiency of transportation service in cold chain of 0.093 at a statistical significance level of 0.05. Accordingly, H6 was validated.

- Lean transportation had an indirect effect on sustainability performance of the transportation service providers in Thailand's food cold chain through efficiency of transportation service in cold chain of 0.121 at a statistical significance level of 0.05. Therefore, H7 was accepted.

- The results in Table 4 reveal that both green and lean transportation have a significant positive impact on the efficiency of transportation service in cold chain. However, Lean Transportation had a stronger direct effect on Efficiency (β = 0.399) than Green Transportation (β = 0.307), indicating that lean practices such as route planning and collaboration have a more immediate operational impact, whereas green practices offer longer-term environmental benefits.

Modified structural equation model is shown in Figure 2.
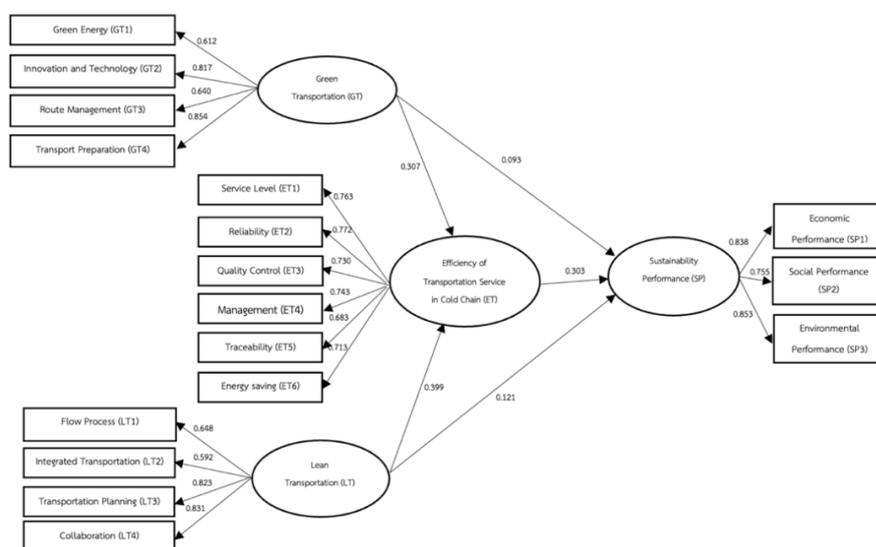
Figure 2. Modified Structural Equation Model of Causal Relationships among Lean Management, Green Transportation Management, and Efficiency of Transportation Service in Cold Chain on Sustainable Performance of Transportation Service Providers in Thailand's Food Cold Chain

3.2 Qualitative research results

The qualitative findings derived from in-depth interviews with key informants reinforce the quantitative results and provide a comprehensive understanding of the factors influencing sustainable performance of transport service providers in Thailand's food cold chain.

Green transportation was consistently perceived as a critical factor enhancing service efficiency and sustainable performance. Key informants emphasized the importance of preparation processes such as temperature-controlled packaging, quality control, and waste reduction. The integration of advanced technologies including GPS, AI-based route planning, temperature monitoring sensors, and Transport Management Systems (TMS) was highlighted as a means to improve accuracy, reduce emissions, and optimize operations. While green energy adoption (e.g., electric vehicles, solar power) was acknowledged for its long-term sustainability impact, cost and infrastructure limitations were noted as ongoing challenges.

Lean transportation was identified as having a direct and substantial impact on service efficiency by reducing waste, operational time, and costs. Informants stressed the importance of cross-functional collaboration, digital integration, and organizational learning. Lean practices contributed not only to economic performance but also to environmental sustainability by minimizing unnecessary transport trips and improving fuel efficiency through route optimization and recyclable packaging.

Efficiency of transportation service in cold chain was linked to sustainable performance in three dimensions: 1) economic (cost reduction, improved profitability), 2) social (worker safety, food quality), and 3) environmental (energy savings, emission reduction). Enhanced service reliability was found to increase customer trust and market competitiveness, while the use of digital tracking and real-time data improved transparency and traceability.

When comparing green and lean transportation, most participants agreed that lean practices had a greater immediate impact on operational efficiency, while green practices played a more prominent role in enhancing long-term environmental sustainability and corporate image. The optimal approach lies in the strategic integration of both paradigms.

Finally, beyond green and lean transportation, informants identified digital technology adoption, supply chain collaboration, and compliance with international standards (e.g., ISO 14001, HACCP, Q Cold Chain) as key enablers of both service efficiency and sustainable performance. These factors collectively strengthen competitive advantage and support long-term business resilience.

The qualitative findings provided substantial contextual confirmation of the statistical relationships identified through SEM. For example, the strong path coefficient from lean transportation to efficiency of transportation service (β = 0.399) was echoed in informant narratives emphasizing the importance of route optimization, reduction of delivery time, and collaborative logistics planning. One respondent noted, "We streamlined our routes and coordinated pickups, which cut delivery time by almost 30%." Similarly, the moderate but significant effect of green transportation (β = 0.307) was reinforced by multiple stakeholders who cited the impact of adopting fuel-efficient vehicles and cold-chain-compatible electric trucks. A logistics manager stated, "Switching to energy-efficient vehicles helped us reduce our costs and improve cold

retention." These qualitative insights demonstrate alignment with the quantitative findings and affirm that both lean and green practices contribute meaningfully to improving service efficiency and sustainability. Notably, lean practices tend to yield more immediate operational benefits, while green practices may support longer-term environmental outcomes. This integration of quantitative and qualitative data reinforces the validity of the conceptual model and enriches its practical interpretation within Thailand's food cold chain.

4. Discussion

The structural equation model (SEM) analysis confirmed that the proposed model, which comprises green transportation, lean transportation, and efficiency of transportation service in the cold chain as predictors of sustainable performance, demonstrated a good fit (χ^2 = 119.077, df = 109, p = 0.240, χ^2/df = 1.092, RMSEA = 0.015, GFI = 0.969, CFI = 0.997). This model explained 74.20% of the variance in sustainable performance among transportation service providers in Thailand's food cold chain. Both green and lean transportation significantly influenced sustainable performance, either directly or indirectly. Notably, lean transportation had a stronger direct effect on both efficiency of transportation service in cold chain (β = 0.399) and sustainable performance (β = 0.342) than green transportation (β = 0.307 and β = 0.319, respectively).

This finding aligns with previous research conducted in advanced economies such as Germany and South Korea, where lean practices (e.g., route planning, cross-functional collaboration) have been shown to improve immediate operational efficiency and responsiveness (Kurganov et al., 2021; Costa et al., 2020). By contrast, green transportation's relatively moderate impact reflects findings from China and Canada, where the adoption of environmentally friendly technologies yields longer-term sustainability outcomes but faces limitations due to high initial investment and regulatory gaps (Jovanovic et al., 2020; Rehman et al., 2023).

Comparatively, the Thailand's food cold chain context presents unique infrastructural and regulatory challenges that influence these relationships. For instance, the fragmentation of cold storage facilities, high logistics costs, and inconsistent adoption of environmental regulations limit the effectiveness of green transportation. Moreover, while lean practices such as staff collaboration and route optimization are more readily applicable in Thai SMEs, green practices often require external investment and policy incentives to be fully effective. These findings suggest that the implementation of lean transportation is more accessible and impactful in Thailand's current logistics landscape, whereas green transportation benefits are more contingent upon supportive infrastructure and policy alignment.

Additionally, subgroup analysis revealed that large enterprises implemented green and lean strategies more extensively than SMEs, likely due to superior resource availability, technological readiness, and greater pressure to align with international standards. This implies that company size and operational scale are important moderating factors in the effectiveness of sustainability interventions.

By triangulating these findings with qualitative data, this study reinforces the strategic value of integrating lean and green transportation in Thailand's food cold chain. The differentiated impact and

feasibility of each approach highlight the need for tailored policy support and capacity-building efforts, especially for smaller logistics firms. The results contribute to the growing body of knowledge emphasizing contextual adaptability and cross-country comparison in sustainable logistics research.

5. Conclusion and Recommendations

Based on the findings of this study, the derived findings should be interpreted as strategic implications for enhancing sustainable performance within cold chain logistics. The validated structural equation model, comprising green transportation, lean transportation and efficiency of transportation service in cold chain as predictors of sustainable performance, demonstrated an excellent model fit and explained 74.20% of the variance in sustainable performance. Therefore, these findings should be viewed as evidence-based indicators that emphasize the significance of integrating environmentally responsible and efficiency-driven practices into cold chain operations.

The findings confirm that both green and lean transportation are critical drivers of transportation efficiency and that they have a direct and positive influence on the sustainable performance of transport service providers in Thailand's food cold chain. Consequently, the results of this study could serve as an empirical foundation for logistics managers, policymakers, and related industries to formulate evidence-based strategies that integrate environmental responsibility with operational excellence. Green transportation initiatives such as emissions reduction and energy-efficient practices, along with lean transportation such as route optimization, fuel efficiency improvement, and the elimination of non-value-adding transport activities can support the development of more resilient, adaptive, and sustainable cold chain transportation service.

This research provides a conceptual model and empirical evidence that may inform future studies and serve as a policy framework for enhancing transportation efficiency and achieving sustainability across economic, environmental, and social dimensions in Thailand's food cold chain. Lastly, the validated structural model presented in this study may provide a reference point for subsequent empirical research as well as model replication in other logistics-intensive sectors and diverse geographical contexts.

6. Acknowledgement

7. References

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