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Multimodal transport efficiency in agricultural supply chains: a case study of rail-road integration in Thailand's sugar logistics

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Abstract: Freight transportation is a key driver of agricultural supply chains that impacts both economic efficiency and environmental sustainability. In Thailand, sugar logistics relies heavily on road transport, leading to high operational costs, congestion, and significant carbon emissions. As the demand for cost-effective and sustainable logistics solutions grows, multimodal transport that integrate rail and road—has emerged as a promising alternative. This study evaluates the feasibility and competitiveness of rail-road combined transport for sugar logistics in Northeast Thailand, focusing on its potential to reduce costs and emissions. A geographic information system-based route optimization framework is applied to compare the transport expenses and CO_2 emissions of road-only and multimodal models. Using data from 21 sugar mills, a multimodal cost model is developed, incorporating factors such as fuel consumption, fuel price, handling fees, transport distance, number of containers, and emissions impact. The findings reveal that shifting sugar logistics to a rail-road system can reduce costs by up to 67.81% and lower CO_2 emissions by 76.50% for distances exceeding 200 km, aligning with Thailand's green logistics goals. However, infrastructure gaps and high investment costs remain barriers. To facilitate multimodal transport adoption, strategic investments, policy support, and industry collaboration are essential. This study contributes to the sustainable development of agricultural freight transport by providing data-driven insights for policymakers and industry stakeholders.

1 Introduction

Freight transportation is vital to Northeast Thailand's agricultural industry, which produces sugarcane, cassava, para rubber, and rice [1]. Efficient logistics networks are essential for connecting farms to markets, yet the region faces high transport costs, infrastructure limitations, and environmental concerns, hindering supply chain efficiency [2]. These challenges must be overcome for sustainable agricultural growth.

Sugar logistics relies heavily on road transport, but this results in high fuel costs, congestion, and emissions. Poor rural roads further disrupt supply chains, increasing lead times and product losses. A more cost-effective and sustainable alternative is needed.

Multimodal transport, integrating rail and road, offers a promising solution. Although rail is cheaper and more sustainable for long distances, it remains underutilized, constituting just 2.4% of total freight transport [3]. Key challenges—limited rail coverage, poor connectivity, and infrastructure costs—highlight the need for integrated transport strategies to optimize Thailand's sugar supply chain [2,4,5].

Thailand's Transport Infrastructure Development Plan (2022-2030) prioritizes rail expansion and multimodal integration to enhance freight efficiency [6]. International initiatives like the U.S. Trade and Development Agency partnership with Thailand's Ministry of Transport have further supported shifts of freight from road to rail, reducing carbon emissions and improving road safety [7].

However, research on Thailand's freight transport has largely focused on road optimization, with limited studies of rail-road multimodal transport for agriculture. International studies have shown that intermodal systems can lower costs and environmental impacts, particularly for bulk goods. However, adapting these strategies to Thailand requires a localized analysis of the logistics infrastructure, market conditions, and supply chain dynamics [2,4,5].

This study examines the feasibility and competitiveness of rail-road combined transport for sugar logistics in Northeast Thailand by analyzing transportation costs, environmental impact, and logistics challenges to explore how multimodal transport can enhance efficiency and sustainability in the sugar supply chain. The focus is on domestic transport of sugar exports to Laem Chabang Port (LCP), Thailand's main export hub.

2 Literature review

2.1 Rail, road, and combined transport

Road transport dominates inland freight due to its network coverage, door-to-door accessibility, and flexibility, making it the preferred choice for short- and medium-distance freight [8]. However, this has led to high logistics costs (14.1% of GDP), congestion, infrastructure deterioration, and limited carrying capacity, particularly in long-haul operations [3,9]. Additionally, road transport significantly contributes to greenhouse gas emissions and is prone to accidents and breakdowns [10,11]. Studies suggest that rail transport is superior for long-haul freight in terms of fuel consumption and cost per ton-kilometer [12].

Rail transport, historically underutilized in Thailand, is gaining attention as a sustainable alternative for bulk freight [9]. Countries like Brazil, China, and India have successfully invested in rail infrastructure to lower logistics costs and enhance supply chain reliability [13-15]. Studies indicate that for distances exceeding 300 km, rail can reduce logistics costs by 20–30%, making it a viable option for sugar and other agricultural products [9]. Thailand is expanding its rail network, including dual-track projects, to enhance freight connectivity to major logistics hubs like Laem Chabang Port and Lad Krabang Inland Container Depot. However, aging infrastructure and maintenance issues limit the effectiveness of rail transport, restricting its role in terrestrial transportation.

Multimodal transport integrating road and rail is particularly effective for high-volume and long-haul freight [16]. While road transport remains essential for short-distance deliveries, rail-road integration can reduce congestion, lower costs, and improve efficiency. Research suggests that rail-road combined transport is more cost-effective than road-only transport for distances exceeding 750 kilometers [17].

Recent studies have provided further support for intermodal transport in agricultural logistics. Centurião et al. (2024) highlight key infrastructure challenges in Latin America, while Prymachenko and Shapatina (2022) emphasize the critical role of rail in EU multimodal agricultural supply chains [18,19]. Chen and Liu (2021) identify regulatory and logistical constraints that have limited its adoption in China [20]. These findings underscore the importance of investments in intermodal infrastructure and technological advancements to enhance multimodal transport efficiency. However, there remains a lack of research on the efficiency of rail-road combined transport for sugar logistics in Thailand, presenting an important gap in multimodal transport studies.

2.2 *Factors affecting modal shift*

Cost is the key factor in freight mode selection, along with transit time, reliability, and flexibility [10]. Road transport costs significantly influence modal shifts, while the transition to intermodal rail transport depends on the cost-effective provision of rail services. Increased demand for dry ports and economies of scale are crucial for reducing rail transport costs and improving competitiveness [21].

Investing in infrastructure, intermodal terminals, and distribution centers strengthens the economic viability of rail transport [22]. In Thailand, freight transport still relies heavily on road networks, similar to the European Union (EU), where the integration of rail has enhanced economic resilience [23]. Sustainable freight solutions aligning with EU strategies have become a priority in Thailand's national logistics policy. However, infrastructure constraints, high capital investment, and long rail development timelines pose challenges that require policy interventions, subsidies, and incentives to encourage rail freight adoption [9,23].

Rail transport offers significant environmental advantages, such as 58% less CO_2 emissions per ton-kilometer than road transport for heavy goods and 66% less for voluminous goods [24]. It also reduces gaseous emissions by 92% and PM 2.5 emissions by 87%, while minimizing heavy metal leakage and fossil fuel dependence [25]. This makes rail a crucial tool for reducing fuel price volatility and improving sustainability in logistics [26].

Although multimodal transport lowers emissions, its effectiveness depends on travel distance [27]. Reducing overall transport demand while promoting low-carbon alternatives is essential for long-term sustainability. To expand rail in Thailand, it will be necessary to overcome infrastructure limitations and ensure efficient intermodal connectivity to maximize rail's environmental and economic benefits [23].

Researchers have confirmed the benefits of intermodal transport for cost efficiency and sustainability. Banomyong and Beresford (2001) employ a confidence index to assess modal reliability, transit delays, and risk factors, highlighting that modal shift decisions must balance economic and operational constraints [9]. Heinold and Meisel (2018) present a simulation-based comparative analysis of emission rates in intermodal rail-road transport and road-only transport in Europe, demonstrating the sustainability advantages of intermodal systems [24]. Additionally, Carboni and Dalla Chiara (2018) analyze the technical and economic competitiveness of rail-road combined transport, emphasizing that long-haul distances and efficient intermodal terminals are critical for economic viability [17]. El Yaagoubi et al. (2022) evaluate a logistic model for intermodal freight transport in France, highlighting cost competitiveness and carbon reduction benefits over all-road transport [28]. Oliveira et al. (2022) evaluate multimodal logistics from a sustainability perspective, demonstrating that intermodal transport significantly reduces logistics costs and environmental impact [29].

While studies highlight the economic and environmental benefits of multimodal transport, research on its efficiency in agricultural supply chains is limited, specifically for sugar logistics in Thailand. Addressing these gaps will provide valuable insights for policymakers, industry stakeholders, and researchers, strengthen Thailand's agricultural logistics network, and advance sustainable freight transport solutions.

2.3 *Route optimization in multimodal transport*

Effective route optimization enhances cost efficiency and operational performance in multimodal transport. Advanced models like dynamic programming [30] and genetic algorithms [31] further optimize path planning by balancing cost and sustainability. The structural optimization model [32] refines nodal optimization and route efficiency to effectively address multimodal cargo delivery challenges.

Geographic Information System (GIS) tools, extensively used for spatial data analysis, offer a more practical and visual approach to optimizing freight transport routes than mathematical models. GIS plays a critical role in route selection and transport planning, integrating geographic data, road networks, traffic conditions, and accident records to enhance distance accuracy and travel time estimation. GIS-based solutions have been widely applied. Chen et al. (2021) analyze GIS applications in fresh product logistics, emphasizing vehicle routing and cost reduction [20]. Kawasaki et al. (2025) explores how GIS enhances logistics distribution, promoting energy-efficient transportation and minimizing carbon emissions [33]. Qu (2024) presents a GIS-based optimization model for intelligent supply chain management, integrating real-time map data to improve transportation efficiency [34].

Despite its advantages, GIS has limitations. Manual data adjustments can affect accuracy, and its predictive capabilities are limited in multi-variable routing problems. Additionally, as GIS primarily focuses on route analysis, it lacks comprehensive transportation management functions. Addressing these constraints requires the integration of GIS with advanced optimization models to enhance multimodal transport planning.

3 Methodology

3.1 *Data collection*

This study focuses on domestic sugar transport in Northeast Thailand through case studies of 22 sugar mills across nine provinces (Buri Ram, Udon Thani, Mukdahan, Kalasin, Khon Kaen, Chaiyaphum, Maha Sarakham, Surin, and Nakhon Ratchasima). However, transportation costs to Laem Chabang Port were analyzed for 21 mills, as one supplies a regional processing plant.

Data were obtained from primary and secondary sources. Primary data were collected through transportation records and spatial mapping datasets from sugar producers, logistics service providers, and government agencies. Secondary data included official transport statistics, historical cost data, and prior research on sugar logistics.

This study drew data from three key datasets: GIS layers for mapping administrative boundaries, sugar mill locations, road/rail networks, and CO_2 emissions; transport data covering distance, transit times, fuel prices, consumption rates, and handling fees; and annual production volumes to analyze freight flows, identify high-traffic corridors, and assess logistical efficiency in sugar transportation.

GIS tools were central to the route analysis and the visualization of sugar transport volumes, enabling insights into logistics challenges, cost efficiency, and environmental impact.

3.2 *Scenario analysis*

Figure 1 compares two scenarios for transporting sugar from production mills to Laem Chabang Port. The first scenario, road freight transport, involves the direct transportation of sugar by trucks from the mills to the port. The second scenario, rail-road multimodal transport, consists of an initial trucking phase to a rail terminal, followed by long-haul rail transport and a final truck delivery to the port.

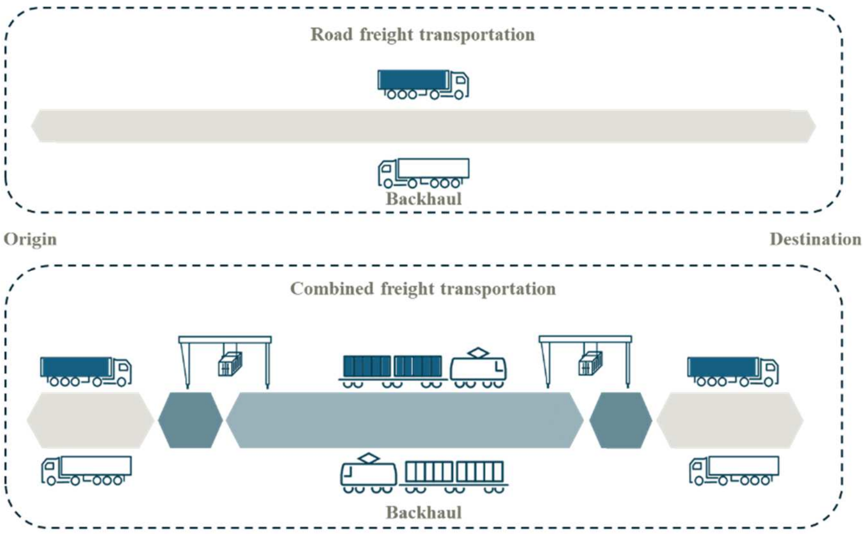

Figure 1 Two transport scenarios from sugar mills (origin) to Laem Chabang Port (destination)

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3.3 GIS-based route optimization

GIS tools were employed to map and analyze transport networks linking sugar mills to domestic markets and export ports. The analysis incorporated road and rail infrastructure, terminal locations, and topographic constraints. Key GIS processes included shortest path analyses to determine the most efficient transport routes, overlay analyses to assess road-rail connectivity, and transport volume mapping to visualize annual sugar output and identify high-demand corridors. This spatial analysis helped detect bottlenecks, calculate travel distances, and estimate transit times for each transport scenario.

3.4 Economic and environmental impact assessment

The assessment quantifies the financial and environmental impact of shifting from road-only to multimodal transport. This study identifies transport distance and the number of containers as key variables influencing freight costs and emissions levels.

The transport model calculates:

1. Road transport cost – Based on fuel consumption, fuel price, trip frequency.
2. Rail transport costs – Accounting for rail fuel consumption and handling fees.
3. CO_2 emissions – Derived from emission factors for empty and full truckloads over total trip distances.

Scenario 1: Road transport assessment

The total cost associated with truck transportation is represented by equation (1).

$$Total\ Transport\ Cost_{Ro} = \sum_{i=1}^{n} NT_i \times \left(\sum_{i=1}^{n}(FCons_i \times FPrice_i) \times \sum_{i=1}^{n} D_i\right) + Cost_{handling} \quad (1)$$

where $\boldsymbol{NT_i}$ is the number of trips used to transport goods at 32 tons per Forty-foot Equivalent Unit (FEU) from sugar mill *i* to *n*. The fuel consumption rate of Truck ($\boldsymbol{FCons_i}$) is 0.5 liters per kilometer, derived from the field survey data. The fuel price, $\boldsymbol{FPrice_i}$, as of May 2023 is 32 baht per liter. The variable $\boldsymbol{D_i}$ represents distance between the point of origin at the sugar mills to the destination at Laem Chabang Port. The handling cost, $\boldsymbol{Cost_{handling}}$, is 500 THB per container.

The carbon dioxide emissions resulting from road transport are quantified through equation (2).

$$\boldsymbol{CO_2\ Emisssions_{Ro} = \sum_{i=1}^{n} NT_i \times \left\{\left(EF_{EmptyC\_Ro} \times \sum_{i=1}^{n} D_i\right) + \left(EF_{FullC\_Ro} \times \sum_{i=1}^{n} D_i\right) + \left(EF_{FullC\_Ro}\right)\right\}} \quad (2)$$

Here, the carbon dioxide emission coefficients for empty ($\boldsymbol{EF_{EmptyC\_Ro}}$) and full truckloads ($\boldsymbol{EF_{FullC\_Ro}}$) are 0.81 and 0.04 $kgCO_2eq/km$, respectively, as reported by the Greenhouse Gas Management Organization (2014).

Scenario 2: Combined transport assessment

Equation (3) delineates the aggregate transportation cost when utilizing a combination of freight rail and truck modalities.

$$\boldsymbol{Total\ Transport\ Cost_{Combined} = \left(\sum_{i=1}^{n} NT_i \times \left(\sum_{i=1}^{n}(FCons_i \times FPrice_i) \times \sum_{i=1}^{n} D_i\right)\right)_{Ro} + \left(\sum_{i=1}^{n} NT_i \times \left(\sum_{i=1}^{n}(FCons_i \times FPrice_i) \times \sum_{i=1}^{n} D_i\right)\right)_{TL} + \left(\sum_{i=1}^{n} NT_i \times \left(\sum_{i=1}^{n}(FCons_i \times FPrice_i) \times \sum_{i=1}^{n} D_i\right)\right)_{Ra} + Cost_{handling}} \quad (3)$$

The corresponding carbon dioxide emissions for this multimodal transportation approach are calculated via equation (4).

$$\boldsymbol{CO_2\ Emisssions_{Combined} = \sum_{i=1}^{n} NT_i \times \left\{\left(\left(EF_{EmptyC\_Ro} \times \sum_{i=1}^{n} D_i\right) + \left(EF_{EmptyC\_Ra} \times \sum_{i=1}^{n} D_i\right)\right) + \left(\left(EF_{FullC\_Ro} \times \sum_{i=1}^{n} D_i\right) + \left(EF_{FullC\_Ra} \times \sum_{i=1}^{n} D_i\right)\right) + \left(EF_{FullC\_Ro}\right)\right\}} \quad (4)$$

The emission factors for empty and full train containers ($\boldsymbol{EF_{EmptyC\_Ra}}$ and $\boldsymbol{EF_{FullC\_Ra}}$) is 0.02 $kgCO_2eq/km$, as reported by the Intergovernmental Panel on Climate Change (2014).

3.5 Correlation study

To analyze the correlation between transportation costs and distance for road and combined transport, a linear regression model was developed. This study considers transportation cost as the independent variable, while transportation distance and container numbers (measured in FEU) serve as dependent variables, enabling a comprehensive assessment of cost variations across different transport modes.

3.6 Data validation and limitations

To ensure data accuracy, the study employed GIS validation for the cross-referencing of spatial data with field surveys, cost triangulation for the comparison of estimates with historical logistics records, and environmental validation to benchmark sustainability metrics with academic and industry standards.

Despite this rigorous validation, limitations remain. Lack of real-time traffic data affected dynamic route assessments, and limited rail terminal data required scenario-based modeling for cost approximations. While comparative assessments helped mitigate these gaps, future research should integrate real-time tracking and improved rail logistics reporting for greater accuracy.

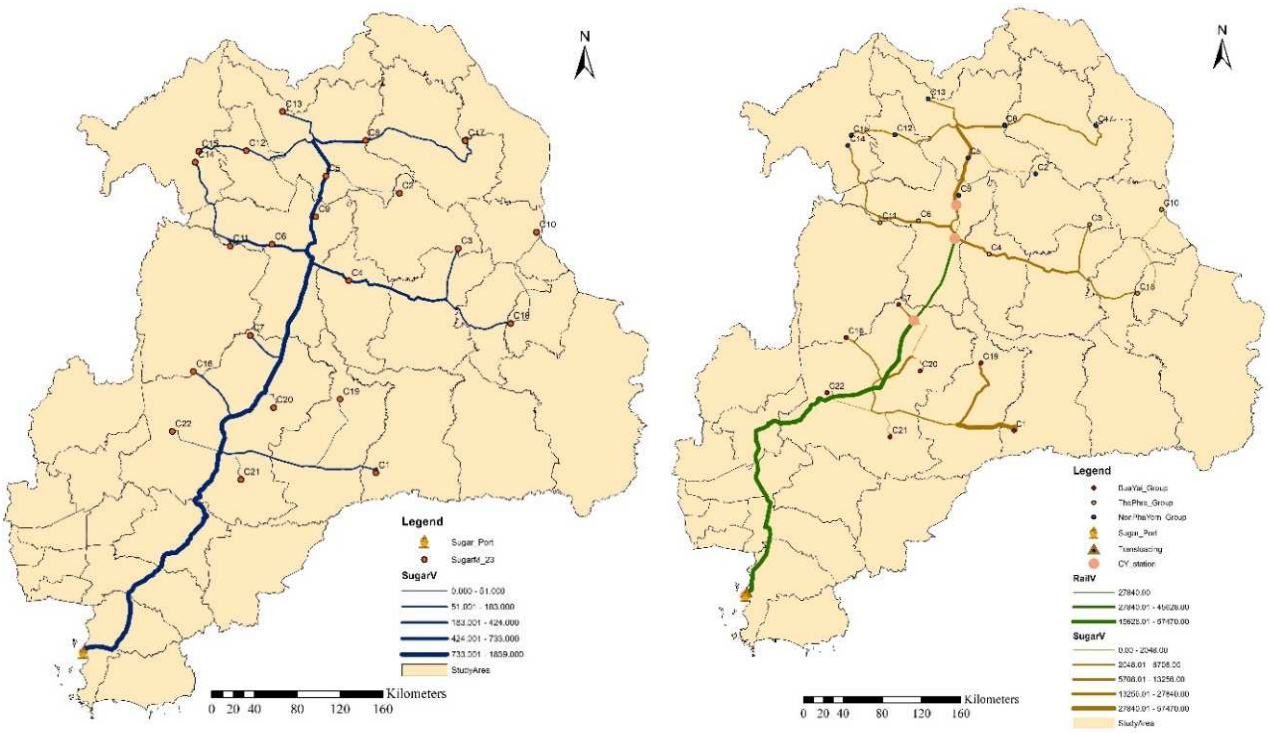
4 Results and discussion

This section analyzes the cost efficiency and environmental impact of road-only versus multimodal transport for sugar distribution in Northeastern Thailand. It examines cost and emissions comparisons (4.1), the correlation between transport costs and distance (4.2), and broader implications for logistics efficiency (4.3). The findings offer insights for optimizing the cost savings and environmental benefits of multimodal transport.

4.1 The comparison of sugar transportation

This section compares road-only and multimodal transport for sugar distribution using ArcGIS analysis. Figure 2A illustrates the shortest truck route from sugar mills to the eastern area of Laem Chabang Port, utilizing minor highways and major highways (Nos. 2, 304, and 331) for road freight transport.

Multimodal transport integrates road and rail networks, with three designated transfer stations—Non Phayom, Tha Phra, and Bua Yai—selected based on route efficiency, sugar volume, station capacity, number of freight trains, and available carriages. Each station serves a specific cluster of sugar mills: Non Phayom (C2, C5, C8, C9, C12–C15, C17), Tha Phra (C3, C4, C6, C10, C11, C18), and Bua Yai (C1, C7, C16, C19, C20, C21). At these transfer points, sugar is first transported by truck, then loaded onto freight trains before undergoing a final truck delivery to Laem Chabang Port (Figure 2B).



(A) (B)

Figure 2 The sugar volume transported by (A) road transport and (B) combined transport

Figure 2 illustrates the volume of sugar transported through the road-only and multimodal transport systems. Road transport, which involves the direct movement of sugar from mills to the port, increases the freight congestion on highways. However, the adoption of multimodal transport significantly reduces road congestion by shifting a portion of freight to rail. Consequently, the use of rail transport has increased, enhancing overall logistics efficiency and sustainability.

Figure 3 compares CO_2 emissions from sugar transport using (A) road-only and (B) rail-road combined transport, illustrating the emissions distribution across Northeast Thailand's transport network with color-coded intensities. Road transport generates high CO_2 emissions, particularly along the major highways used for long-haul freight. The most affected routes, exceeding 120–160 km, exhibit elevated emissions due to high fuel consumption and greenhouse gas output. Additionally, the limited flexibility of road transport results in emission hotspots, congestion, and bottlenecks along key corridors. Integrating rail with road transport significantly reduces CO_2 emissions, especially on long-distance routes, where rail replaces high-emission road segments (marked in green). This shift leads to more evenly distributed emissions, mitigating congestion on major highways. However, some short-distance routes still rely on road transport, albeit with lower emissions than for conventional road freight.

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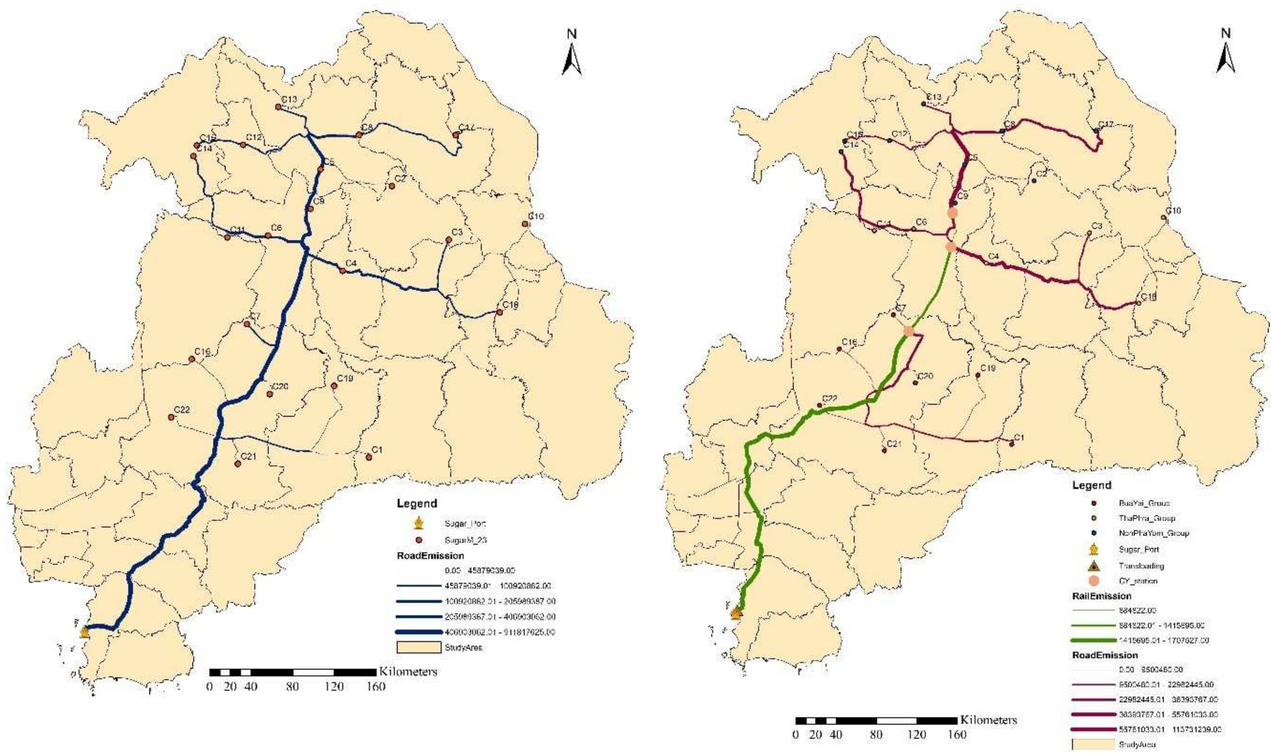

(A) (B)

Figure 3 Transport emissions by (A) road transport and (B) combined transport

Table 1 Domestic road freight transport

				Transport Cost (million THB/year)		CO_2 Emissions (million $kgCO_2eq$/year)	
Sugar Mills	Distance (km)	Cost (THB/FEU)	No. Containers (FEUs/year)	Round trip	Container Handling Fee	Port to Mill (Empty truck)	Mill to Port (Fully loaded)
C17	726	13,823	4,296	118.77	4.30	81.58	4.47
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
C20	355	6,759	217	2.93	0.22	2,017,946	0.11
Total	11,612		57,470	1,258.05	57.47	864.48	47.34
Total transportation cost				1,315.52			
Total emissions						911.82	

Scenario 1, presented in Table 1, examines the costs associated with domestic road freight transport by trailer. Among the sugar mills, C17 incurs the highest freight cost, accounting for 9.02% of the total transportation cost, whereas C20 has the lowest, contributing only 0.22%. In terms of CO_2 emissions, the maximum values recorded are 8.95% for empty trucks and 0.49% for loaded transport, while the minimum emissions are 0.22% and 0.01%, respectively.

The results indicate that Non Phayom, Tha Phra, and Bua Yai Stations serve as the primary container yards in Northeast Thailand, primarily due to their strategic location along the railway line connecting to Laem Chabang Port, the key export hub. Tables 2, 3, and 4 highlight the cost efficiency of these stations, emphasizing the potential for infrastructure investments to enhance rail accessibility and optimize sugar transport operations.

Table 2 Road-rail transloading at Non Phayom Station

				Transport Cost (million THB/year)		CO_2 Emissions (million $kgCO_2eq$/year)	
Sugar Mills	Distance (km)	Cost (THB/FEU)	No. Containers (FEUs/year)	Round Trip	Container Handling Fee	Port to Mill (Empty Truck)	Mill to Port (Fully Loaded)
Port-Transloading	5	190	27,840	5.29	27.84	4.36	0.24
Transloading-Station	572	10,740	928	9.97	-	0.44	0.44
Station-C5	54	2,056	1,994	4.10	1.99	2.86	0.16
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Station-C17	236	8,986	4,296	38.60	4.30	26.60	1.46
Total			27,840	171.39	55.68	112.63	6.59
Total transportation cost				227.07			
Total emissions						119.22	

Table 3 Road-rail transloading at Tha Phra Station

				Transport Cost (million THB/year)		CO_2 Emissions (million $kgCO_2eq$/year)	
Sugar Mills	Distance (km)	Cost (THB/FEU)	No. Containers (FEUs/year)	Round Trip	Container Handling Fee	Port to Mill (Empty Truck)	Mill to Port (Fully Loaded)
Port-Transloading	5	190	17,788	3.38	17.79	2.79	0.15
Transloading-Station	537	10,000	593	5.93	-	0.27	0.27
Station-C4	42	1,596	864	1.38	0.86	0.97	0.05
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Station-C3	150	5,700	4,894	27.90	4.89	19.30	1.06
Total			17,788	85.54	35.58	55.92	3.31
Total transportation cost				121.12			
Total emissions						59.23	

Table 4 Road-rail transloading at Bua Yai Station

				Transport Cost (million THB/year)		CO_2 Emissions (million $kgCO_2eq$/year)	
Sugar Mills	Distance (km)	Cost (THB/FEU)	No. Containers (FEUs/year)	Round Trip	Container Handling Fee	Port to Mill (Empty Truck)	Mill to Port (Fully Loaded)
Port-Transloading	5	190	11,842	2.25	11.84	1.86	0.10
Transloading-Station	443	8810	395	3.48	-	0.15	0.15
Station-C20	72	2,736	217	0.59	0.22	413,792	0.02
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Station-C1	205	7,790	2,691	20.96	2.69	14.48	0.79
Total			11,842	51.54	23.68	33.80	1.99
Total transportation cost				75.22			
Total emissions						35.79	

Additionally, Figure 4 highlights the cost determinants at each railway station, which are influenced by transport distance, container numbers, and associated fees. The findings indicate that Bua Yai Station has the lowest annual transportation cost, followed by Tha Phra and Non Phayom Stations. Combined transport reduces costs by 892.11 million THB annually compared to road transport, highlighting its economic advantage in long-distance logistics. Non Phayom Station incurs the highest costs due to its 572 km transport distance and high container numbers, as it serves as a key hub for rail freight.

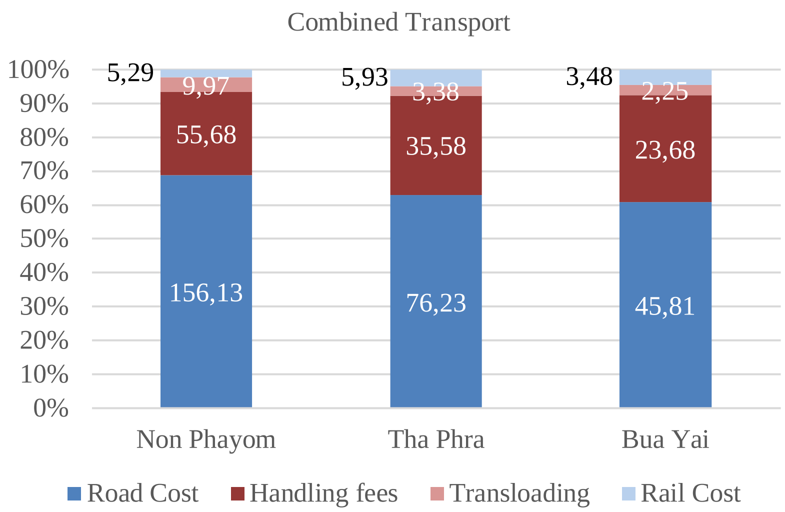

Figure 4 The details of the cost factors at each railway station

Environmentally, Bua Yai Station records the lowest CO_2 emissions, followed by Tha Phra and Non Phayom Stations. The integrated transport model reduces emissions by 697.58 million kilograms annually, reinforcing its sustainability benefits over road transport.

The assessment reveals variations in freight transfer station accessibility and service availability across the three stations. Non Phayom Station, a recently refurbished facility, can accommodate a wide range of commodities, and increased freight traffic is expected. Tha Phra Station, located near a village, requires road expansion and load-bearing capacity improvements to support larger freight volumes. Bua Yai Station, also near a village, maintains a clear distinction between passenger and freight transport, yet ingress and egress routes need enhancement to facilitate efficient vehicle movement.

Figure 5 illustrates the cost distribution between road and combined transport, revealing a notable reduction in road transport costs with a concurrent increase in handling fees. Additionally, rail transport and transloading costs account for a smaller proportion of the total expenditure, highlighting the cost reallocation associated with multimodal transport integration. Table 5 presents the total freight costs and emissions associated with the integration of transport modes, showing a notable reduction in overall freight expenses and carbon emissions.

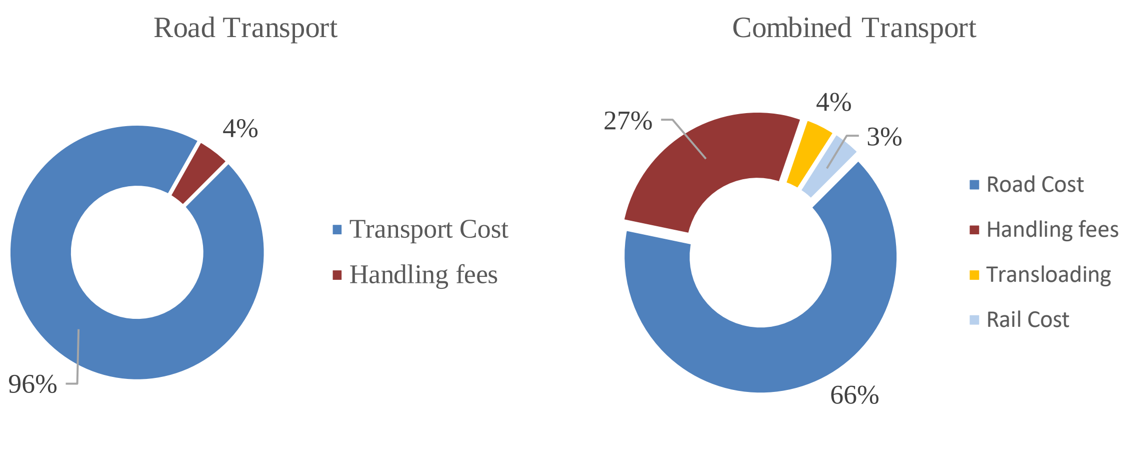

Figure 5 The proportion of transport cost by (A) road transport and (B) combined transport

Table 5 Freight transport comparison of cost and emissions by road and combined transport

	Transport Cost (THB/year)	CO_2 Emissions (kg/year)
Road Transport	1,315,517,284	911,817,625
Combined Transport	423,405,875	214,241,423
% Change	67.81	76.50

4.2 The correlation between transport costs and distance

The findings demonstrate a distinct cost disparity between road freight transport and combined freight transport across varying distances. Table 6 illustrates that road freight costs increase proportionally with distance due to cumulative operational expenses, including fuel consumption, fuel prices, number of containers, and handling fees. In contrast, combined freight transport maintains a cost advantage over longer distances, as multimodal integration mitigates cost escalation. Cost savings increase with distance, with the gap widening beyond 200 km and nearly 50% savings at 900 km. The shift toward multimodal solutions enables logistics planners to optimize both economic efficiency and environmental sustainability.

Table 6 Freight transport cost: a distance-based comparison of road and rail modal choices

Distance (km)	Road freight cost (THB/FEUs/Round Trip)	Combined freight cost (THB/FEUs/Round Trip)	% Change
100	3,808	4,177	-9.69
200	7,616	5,924	22.22
300	11,424	7,671	32.85
400	15,232	9,419	38.17
500	19,040	11,166	41.36
600	22,848	12,913	43.48
700	26,656	14,660	45.00
800	30,464	16,407	46.14
900	34,272	18,155	47.03

4.3 Discussion

This study confirms that rail-road combined transport significantly reduces logistics costs and environmental impact in sugar freight transport. The comparative analysis highlights substantial cost variations between road-only and multimodal transport, demonstrating the economic advantage of integrating rail into logistics networks. Beyond the cost benefits, shifting freight to rail aligns with global sustainability targets by reducing fossil fuel dependency and environmental impact.

The results indicate that incorporating rail into long-distance transport can yield cost reductions of 67.81% and CO_2 emissions reductions of 76.50%, reinforcing the viability of multimodal solutions. These findings align with those of Carboni and Dalla Chiara (2018), who reported that intermodal freight systems yield cost savings of up to 40% compared to road transport [17]. Furthermore, this study supports the conclusions of Islam et al. (2016) regarding the significant role of multimodal strategies in reducing carbon footprints [22].

The assessment reveals infrastructure disparities at the three freight transfer stations that impact their capacity and efficiency. Non Phayom Station, as a modernized facility, can accommodate diverse commodities and increases in freight traffic, whereas Tha Phra Station requires road expansion to support higher freight volumes and improved access routes are needed at Bua Yai Station for efficient vehicle movement. These infrastructural limitations highlight the need for coordinated investment to support modal shifts, as noted by Rodrigue and Notteboom (2020), who emphasize the role of rail-based logistics in enhancing energy efficiency and reducing emissions [8]. However, as rail transport faces capacity constraints, government-private sector collaboration is needed to expand intermodal facilities and optimize logistics planning, as noted by Islam et al. (2016). To enhance multimodal logistics, policies should be implemented to strengthen rail connectivity, expand terminals, and develop intermodal hubs, ensuring cost efficiency and environmental sustainability in freight transport [22].

The analysis of transportation costs in relation to distance indicates that road freight expenses increase progressively with distance due to cumulative operational costs. In contrast, combined transport exhibits more stable cost trends past a specific threshold distance, making it a more efficient and economically viable option for long-haul freight operations. A combined transport mode for sugar freight over distances exceeding 200 kilometers can yield a 22% reduction in transportation costs, aligning with the findings of Carboni and Dalla Chiara (2018), who report that for distances under 300 kilometers, road transport remains the most advantageous option, while for distances beyond 750 kilometers, combined transport is the most economical option [17].

5 Conclusions and future research

This study assesses the feasibility and competitiveness of rail-road combined transport for sugar logistics in

Northeast Thailand, demonstrating its potential to enhance logistics efficiency and sustainability. While truck transport remains dominant, its high costs, congestion, and environmental impact pose long-term challenges. Multimodal transport integrating rail and road presents a cost-effective and eco-friendly alternative by reducing fuel dependency, transport costs, and carbon emissions.

Using a GIS-based route optimization framework, the study shows that shifting from a road-only system to an integrated rail-road network can lower total cost (i.e., fuel costs, handling fees, and bogie rental expenses) and carbon emissions, thus making sugar logistics more resilient and cost-efficient. Additionally, multimodal transport can contribute to Thailand's green logistics strategy by helping reduce the carbon footprint of agricultural supply chains. However, barriers such as inadequate rail infrastructure, poor intermodal connectivity, and high initial investment costs must be addressed to maximize multimodal efficiency.

To promote its adoption, strategic investments in railway infrastructure, intermodal hubs, and supportive policies are essential. Government support, industry collaboration, and financial incentives will be key to facilitating the transition toward sustainable and efficient freight transport solutions.

Further studies should incorporate real-time transportation data, including transit times, rail service reliability, and dynamic fuel pricing, to refine the cost model. Expanding the scope to other agricultural commodities could offer broader insights into multimodal feasibility across Thailand's agricultural sector. Real-time GPS tracking data, as suggested by Goncalves et al. (2019), could enhance the accuracy of cost models and improve logistics decision-making [13].

Additionally, researchers should examine policy frameworks that incentivize multimodal transport adoption. Comparative studies of international best practices, such as those by Rodrigue and Notteboom (2020), could provide insights into regulatory and financial mechanisms that support efficient multimodal integration [9].

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