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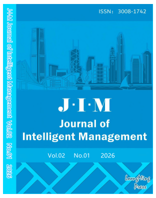

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Assessment and Mechanism Analysis of Low Carbon Efficiency in Cold Chain Logistics in the Guangdong-Hong Kong-Macao Greater Bay Area

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ABSTRACT

Cold chain logistics is essential for supplying fresh food, pharmaceuticals, and other temperature-sensitive goods in the Guangdong – Hong Kong – Macao Greater Bay Area (GBA), but its heavy reliance on refrigeration and road transport makes it energy-intensive and carbon-emissions-intensive. This study evaluates the low-carbon efficiency of cold chain logistics in the GBA and examines the mechanisms through which internal resource inputs and external conditions shape performance. We construct an efficiency assessment framework that treats carbon emissions as an undesirable output and applies a three-stage Data Envelopment Analysis (DEA): (i) initial efficiency measurement; (ii) adjustment for environmental factors and statistical noise using economic development, government support, and market environment variables; and (iii) a re-estimation of managerial (intrinsic) efficiency. Building on Resource-Based Theory, Stakeholder Theory, and Ecological Modernization Theory , we further propose a mechanism model linking capital, labor, technical investment, and energy inputs to low-carbon efficiency, with generalized total factor productivity and energy structure as mediators and external conditions as moderators. Preliminary evidence highlights the importance of technological upgrading, route and facility optimization, and policy support in improving both economic output and emissions performance. The findings provide actionable implications for targeting green technology adoption, strengthening regulatory incentives, and addressing cold-storage and refrigerated-transport capacity gaps to support high-quality, low-carbon logistics development in the GBA.

Keywords: Cold chain logistics, DEA,Efficiency,Greater Bay Area, Low-carbon

1. Introduction

The significance of cold chain logistics has grown dramatically in recent years, particularly in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), an economic center that is expanding quickly. A vital part of the supply chain for sectors including chemicals, food, and pharmaceuticals is cold chain logistics, which deals with the movement and storage of goods that are sensitive to temperature. Sustainability is severely hampered by this industry's high energy consumption and the huge rise in carbon emissions from transportation and refrigeration. Accordingly, reaching regional and international environmental targets now depends on increasing the cold chain logistics' low-carbon efficiency (Liu et al., 2023; He et al., 2023).

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The objective of this research is to assess and examine the GBA's cold chain logistics' low-carbon efficiency while taking environmental and financial performance into account. In particular, this study examines the variables that affect cold chain logistics companies' efficiency by taking into account both desired and undesirable outcomes, such as carbon emissions and freight volume and economic growth. In order to accomplish this, the study uses a Three-Stage Data Envelopment Analysis (DEA) as its main instrument for assessing cold chain logistics companies' performance. This method enables a thorough evaluation that takes into consideration external influences on efficiency as well as environmental aspects (Ma et al., 2023).

The current inefficiencies in the cold chain logistics industry and their significant contribution to regional carbon emissions are highlighted in the research's problem statement. The particular problem of lowering emissions while preserving economic performance has not yet been entirely resolved, despite considerable attempts to increase logistical efficiency (Xu et al., 2024). Improving the sustainability of the GBA's logistics operations is essential for local stakeholders as well as the region's global competitiveness, given its strategic location as a key economic center (Zhang et al., 2024).

Three major theories form the theoretical basis of this research: Ecological Modernization Theory (EMT), Stakeholder Theory, and Resource-Based Theory (RBT). RBT offers information on how logistics companies use internal resources, like labor and capital, to cut emissions and increase efficiency (Barney, 1991). Stakeholder theory emphasizes how different stakeholders, such as consumers, governments, and businesspeople, may support low-carbon activities (Freeman, 1984). EMT highlights how regulatory changes and technology developments propel sustainability in logistics (Mol & Spaargaren, 2000). When combined, these ideas offer a thorough understanding of how cold chain logistics might improve low-carbon efficiency while striking a balance between environmental and economic effects.

According to Yang et al. (2023), the research objectives are well-defined and center on evaluating the effectiveness of cold chain logistics, investigating the fundamental mechanisms that impact performance, and identifying variables like market conditions, economic development, and government support that moderate efficiency outcomes. The research questions that direct the study are also presented in this chapter, such as: How can cold chain logistics' low-carbon efficiency be quantified? Which are the main determinants of efficiency? In what ways are these interactions moderated by outside factors?

1.1 The Role and Environmental Challenges of Cold Chain Logistics in the Greater Bay Area

The Guangdong-Hong Kong-Macao Greater Bay Area (GBA) encompasses nine mainland cities alongside Hong Kong and Macao. As one of the world ' s most dynamic urban clusters, its growing demand for fresh food, pharmaceuticals, and other temperature-sensitive goods has made cold chain logistics increasingly vital. However, the energy-intensive nature of cold chain logistics, heavily reliant on refrigeration and transportation infrastructure, poses significant environmental challenges (Zhang et al., 2020).

In 2023, China ' s cold chain logistics demand reached 350 million tons, with a 6.1% year-on-year growth. Refrigerated trucks exceeded 430,000 units (a 12.8% increase), and refrigerated storage volume reached 228 million cubic meters, with high-standard cold storage accounting for 62% (Guangdong Statistical Yearbook, 2024). While cold chain logistics has spurred economic growth, balancing economic performance with environmental sustainability remains a critical challenge for the GBA (Liu et al., 2023).

Cold chain logistics faces multiple environmental challenges due to its reliance on energy-intensive technologies. Key issues include:

High energy consumption and carbon emissions: refrigeration systems and transportation are major sources of energy use and greenhouse gas (GHG) emissions. Globally, the logistics sector accounts for approximately 24% of total CO_2 emissions, with cold chains contributing around 5% due to their reliance on fossil fuels (IEA, 2023). In the GBA, carbon emissions from refrigeration and transportation equipment have grown at an average annual rate of 3.5% (Guangdong Statistical Yearbook, 2024).

Refrigerant Use: Common refrigerants, such as hydrofluorocarbons (HFCs), have high global warming potential and significantly contribute to climate change if improperly managed (Hu et al., 2022). Studies indicate that HFC emissions from refrigerant leakage account for approximately 15% of total cold chain emissions (Wang et al., 2021).

Waste Generation: Poorly managed cold chains lead to food spoilage, wasting resources, and generating methane, a potent GHG. Additionally, outdated refrigeration equipment contributes to electronic waste (Boschiero et al., 2019).

Transportation Inefficiencies: Inefficient logistics routes and aging refrigerated vehicles increase fuel consumption and emissions. In 2023, transportation energy consumption accounted for nearly 70% of the total energy used in the GBA ' s cold chain logistics (Chen et al., 2023).

In the GBA, these challenges are further exacerbated by regional climate factors such as high ambient temperatures, which increase refrigeration energy demands. Addressing these issues requires adopting renewable energy technologies, improving efficiency through technological innovation, and strengthening regulatory frameworks (Yan et al., 2022). As the GBA continues to develop as a global logistics hub, transitioning to sustainable cold chain practices will play a pivotal role in achieving regional economic and environmental goals.

1.2 Rising Trends in Global Energy Consumption and CO2 Emissions

With an expected 37.9 billion tons of CO2 emissions in 2024—a 1.3% increase from the year before—global energy-related CO2 emissions are still on the rise (IEA, 2023a). Fossil fuel dependence is still a major element, particularly in developing nations, even though this growth rate is somewhat slower than the 3% world GDP increase (IEA, 2023b).

Fossil fuels continue to be responsible for more than 80% of CO2 emissions, which have increased by 1.9% annually on average between 2000 and 2024 (IEA, 2023b). Significant regional disparities exist: established economies such as the US and the EU have cut emissions by 2.4% and 4.2%, respectively, while Asia—particularly China and India—has witnessed an increase in emissions, with China alone accounting for 35% of global CO2 emissions in 2024 (IEA, 2023c).

Figure 1 Global Energy-Related CO2 Emissions and Annual Changes (2000-2024)

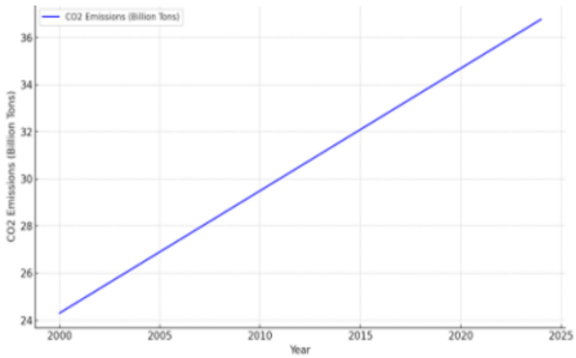


Table 1 CO2 Emissions by Region (2023-2024)

Region	2023 Emissions (Billion Tons)	2024 Emissions (Billion Tons)	Growth Rate (%)
China	12.2	12.6	3.3
India	2.5	2.6	4.0
European Union	2.4	2.3	-4.2
United States	4.2	4.1	-2.4
Rest of World	16.5	16.8	1.8

Table 1 provides a comparative view of CO2 emissions by region, highlighting the dominant contributions from China and India relative to other global regions. Developing Asia shows notable emission growth compared to reductions in developed economies like the EU and the United States (IEA, 2023a).

1.3 Key Contributors to Global CO2 Emissions: Developing Asia

In 2024, developing Asia—represented mostly by China and India—was responsible for almost 52% of the world's CO2 emissions. This significant portion emphasizes how important the area is to the dynamics of the global climate.

With 12.6 billion tons of CO2, China was the biggest emitter, accounting for 35% of world emissions and a 3.3% annual rise (IEA, 2023b). India, the third-largest emitter in the world, increased its emissions to 2.6 billion tons in 2024, a result of steady expansion fueled by energy demand and industrialization (IEA, 2023b).

Table 2 Developing Asia's CO2 Emissions, 2023 – 2024

Country	2023 Emissions (BillionTons)	2024Emissions(Billion Tons)
China	12.2	12.6
India	2.5	2.6

Table 2 highlights how China and India account for the majority of CO2 growth. Despite continuous efforts to increase the infrastructure for renewable energy, their reliance on coal and fossil fuels presents hurdles for the global carbon neutrality targets.

The rising emissions from developing Asia underscore the necessity of focused climate policies, global collaboration, and investments in renewable energy to promote sustainable development while reducing environmental stressors.

1.4 Proceeding Increase in CO_2 Emissions in the Logistics Sector in China

In recent years, China's logistics sector has been progressively expanding its CO_2 emissions. According to the National Bureau of Statistics, the CO_2 emissions from China's logistics industry were approximately 948 million tons in 2021, accounting for 9.01% of the national total emissions (National Bureau of Statistics, 2022). This number is expected to increase by 2024(National Bureau of Statistics, 2022).

Table 3 Projected CO_2 Emissions in China's Logistics Industry (2021-2024)

Year	CO_2 Emissions (Million Tons)	Annual Growth Rate (%)
2021	948	-
2022	990	4.4
2023	1.02 billion	3.9
2024	1.07 billion	4.2

This data reflects the steady increase in CO_2 emissions from China's logistics industry, primarily driven by increased transportation demand and the expansion of logistics scale.

Figure 2 CO_2 Emissions in China's Logistics Industry (2013-2024)

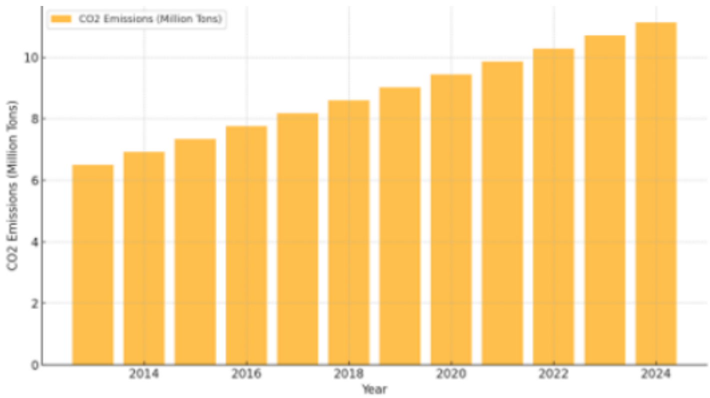


Figure 2 shows the trends in CO_2 emissions from China's logistics industry from 2013 to 2024. As demonstrated, emissions have been steadily increasing due to the growing demand for logistics services and the expansion of transport and warehouse infrastructure. This upward trend reflects not only the industrialization and urbanization of China but also the continued reliance on fossil fuels for energy, particularly in transportation and cold chain logistics.In 2021, the logistics sector contributed 948 million tons of CO_2 emissions, and it is projected to reach approximately 1.07 billion tons by 2024 (National Bureau of Statistics, 2022). The chart highlights the steady rise in emissions over the years, with significant increases observed between 2015 and 2024, driven by higher freight volumes and transportation requirements across the country.Source: National Bureau of Statistics (2022).

1.5 Rising Market Demand for Cold Chain Logistics and Facility Shortages in the Greater Bay Area

The Greater Bay Area (GBA)'s current facilities cannot keep up with the need for cold chain logistics, which is constantly increasing. The demand for cold chain agricultural goods is predicted to exceed 27.67 million tons by 2025 in all 11 of the GBA's cities. To accommodate this demand, the cold chain's current infrastructure—which includes refrigerated transportation equipment and cold storage—is woefully inadequate.

Despite a rise in investment in cold chain logistics infrastructure, the rate of infrastructure development expansion has not kept pace with the demand, according to the Guangdong Statistical Yearbook (2024).

Table 4: Cold Chain Agricultural Product Demand vs. Existing Facilities

City	Cold Chain Agricultural Product Demand (10,000 Tons)	Cold Storage Capacity (10,000 Tons)	Gap in Demand (10, 000 Tons)
Guangzhou	646.94	450	196.94
Shenzhen	620.67	500	120.67
Zhuhai	89.89	50	39.89
Dongguan	409.05	350	59.05
Zhongshan	142.81	120	22.81
Zhaoqing	151.06	110	41.06
Huizhou	199.28	170	29.28
Foshan	337.56	300	37.56
Jiangmen	170.06	140	30.06
Total	2767.32	2180	587.32

According to Table 4, the GBA's current cold storage capacity will be greatly outstripped by the demand for cold chain agricultural products by 2025, leaving a 5.87 million ton deficit. The cold chain infrastructure in the majority of cities is severely lacking, particularly when it comes to capacity for refrigerated transportation and high-standard cold storage.

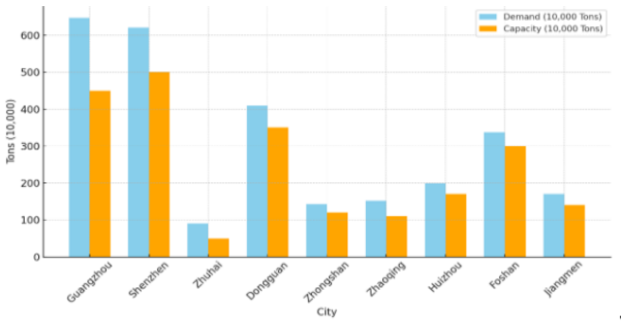
Table 5 GBA Cities' Projected Demand for Cold Chain Agricultural Products

City	Vegetables	Meat	Poultry	Aquatic Products	Eggs	Dairy Products	Fruits	Total
Guangzhou	232.23	79.27	79.60	78.58	20.71	18.75	137.80	646.94
Shenzhen	222.80	76.05	76.37	75.39	19.87	17.99	132.21	620.67
Zhuhai	32.27	11.01	11.06	10.92	2.88	2.61	19.15	89.89
Dongguan	146.84	50.12	50.33	49.69	13.09	11.85	87.13	409.05
Zhongshan	51.27	17.50	17.57	17.35	4.57	4.14	30.42	142.81
Zhaoqing	54.23	18.51	18.59	18.35	4.83	4.38	32.18	151.06
Huizhou	71.53	24.42	24.52	24.21	6.38	5.78	42.45	199.28
Foshan	121.17	41.36	41.53	41.00	10.80	9.78	71.90	337.56
Jiangmen	61.04	20.84	20.92	20.66	5.44	4.93	36.22	170.06
Hong Kong	80.50	26.94	27.00	26.70	7.03	6.37	46.85	221.39
Macau	14.20	4.75	4.80	4.75	1.25	1.13	8.32	39.20

By 2025, the Guangdong-Hong Kong-Macao Greater Bay Area (GBA)'s 11 cities' anticipated demand for cold chain agricultural products—which include fruits, vegetables, meat, poultry, aquatic products, eggs, and dairy products—is s hown in Table 5.

Guangzhou has the biggest demand (6.47 million tons), followed by Shenzhen (6.21 million tons), as the GBA keeps expanding. A large portion of the demand for cold chain logistics is driven by these cities because they are important economic centers. Cities like Zhuhai and Macau, on the other hand, have smaller demands—0.89 million ton s and 0.39 million tons, respectively.

Figure 3 Cold Chain Storage Capacity vs. Demand in the Greater Bay Area



The Greater Bay Area (GBA) cold chain storage capacity and demand comparison for 2025 is depicted in the chart. The orange bars display the storage capacity (in 10,000 tons) across different cities, whereas the blue bars show the demand (in 10,000 tons). The greatest demand and capacity are found in Guangzhou and Shenzhen, but in many places, including Zhuhai and Dongguan, the demand is more than the capacity, indicating serious deficiencies in the cold chain logistics infrastructure. This disparity highlights the necessity of further cold chain facility development to satisfy the expanding demand in these areas.

Table 6 Policies and Development Goals in GBA Cities

City	Policy Focus	Development Goal
Guangzhou	13th Five-Year Plan on Energy Saving and Carbon Reduction	Three International Strategic Hubs
Shenzhen	12th Five-Year Plan on Low Carbon Development	International Innovation Service Center
Zhuhai	Greenhouse Gas Emission Control Implementation Plan	Expanding Bridgehead and Innovation Plateau
Foshan	Low Carbon City Construction Plan	International Industrial Manufacturing Center
Dongguan	13th Five-Year Plan on Industrial Energy Saving	International Manufacturing Service Center
Zhongshan	Green Development Strategy Plan	State-Level Advanced Manufacturing Base
Huizhou	Low Carbon Ecology Plan	Green City and Eco-Tourism Hub
Jiangmen	Low Carbon Development Strategy Plan	State-Level Advanced Manufacturing Base
Zhaoqing	Low Carbon Development Subject Plan	Traditional Industry Upgrading Zone
Hong Kong	HK Climate Action Plan 2030	Global Financial and Logistics Center
Macau	Macao Environmental Protection Plan	World Tourism and Leisure Center

2 Literature Review

2.1 Importance of LCCCL in GBA

On February 18, 2019, China published the GBAon Development Plan Outline. In their examination of the GBA, LIU (2020) sheds light on its background, significance in assimilating HKM into China, relationship to the OBOR project, the MIC2025 plan, and China's overall economic growth. Furthermore, LIU (2020) looks to the GBA's future and highlights the challenges that still need to be addressed. In the realm of blockchain technology, Lai et al. (2020) have built a blockchain-based intelligent logistics platform that might be a useful reference point for the GBA in encouraging the harmonious expansion of city clusters and easing the integration of logistics.

2.2 Greenhouse Gas Emissions

In order to investigate the levels of CO2 emissions in the GBA and neighboring cities between 2000 and 2019, Luo et al. (2023) suggested a research methodology that combines the usage of system dynamics (SD) and the logarithmic mean divisor index (LMDI). Analyzing the causes of these emissions, forecasting future patterns, and evaluating the policy consequences are the primary goals of this study. The first scenario predicts that regional CO2 emissions will rise further, reaching 1.25 times the 2019 levels by 2030.

The expected changes in the wetlands inside the GBA between 2020 and 2035 are assessed by Peng et al. (2023) in order to bolster the report on Wetland Conservation and Sustainable Development Goals (SDGs).

2.3 Greater Bay Area cold chain logistics

A principal component analysis approach was used to evaluate the logistics performance in the GBA from a low-carbon perspective (Xu, 2023). According to the results, Zhongshan had the lowest score and Hong Kong the highest (Chu et al., 2023). The purpose of this study is to offer recommendations for maintaining the quality of rhubarb fish while it is being transported in the cold chain. It is advised to limit temperature changes during the cold chain process and to rapidly freeze the obtained samples in order to guarantee adherence to quality requirements. Given the unpredictability of this process, a well-established and routinely monitored cold chain logistics network is essential. Yuan's (2022) study employed the Ontario region to optimize important variables, such as data analysis and the usage of mathematical models.

2.4 Environmental efficiency theory

A recent study by Yamasaki et al. (2019) offers important information to Japanese officials about how to assess eco-efficiency in cities. Governments should support business innovation, increase the effectiveness of resource allocation, and progressively lower environmental pollution while maintaining enterprise sustainability, claim Ai et al. (2020). However, evaluating how these environmental regulations affect important economic outcomes like innovation, productivity, competition, energy efficiency, and carbon emissions is difficult due to the lack of trustworthy empirical evidence.

By computing a number of measures to gauge the seriousness of environmental regulations and carrying out an extensive statistical study to compare these indicators, Galeotti and colleagues (2020) significantly contributed to the solution of this problem. They also provided real-world case studies that highlighted energy efficiency and environmental innovation.

2.5 Sustainable Development

Since energy efficiency lowers emissions of pollutants and energy consumption, it is crucial for policy development. From 2008 to 2016, researchers examined the energy efficiency of several Chinese provinces. They employed a three-phase approach known as data envelopement analysis, which ignored exterior environmental influences in favor of concentrating on scale efficiency, a critical component of energy efficiency. An integrated evaluation of eco-efficiency that took into account possible emission reductions, energy savings, and resource allocation across Chinese areas was presented in another academic study. In order to determine the main elements influencing eco-efficiency, the study took into account variables including resource disparities and environmental legislation. Furthermore, a quantitative research looked at 20 developed countries' environmental, energy, and carbon dioxide emissions efficiency.

3 Research Methodology

3.1 The Three-stage DEA methodology

The Three-Stage Data Envelopment Analysis (DEA) methodology is an advanced technique used in operational research and economics to evaluate the efficiency of decision-making units (DMUs), such as companies, hospitals, or educational institutions. This method extends the traditional DEA approach by incorporating external environmental variables and statistical noise, which might affect the performance measurements. Here's a breakdown of how it works:

Stage 1: Traditional DEA

In the first stage, DMUs are evaluated using the standard DEA model (either input-oriented or output-oriented). This model measures the efficiency of each DMU relative to an efficiency frontier, which represents the best performance observed in the dataset. The efficiency score is calculated based on the ratio of weighted outputs to weighted inputs, and DMUs are classified as efficient or inefficient based on this score.

Stage 2: Adjusting for External Variables

The second stage involves regression analysis to account for the influence of external environmental variables and random noise that could affect the initial efficiency scores calculated in Stage 1. This stage aims to separate the effect of these variables from the performance of the DMUs. By doing so, the efficiency scores are adjusted to reflect the performance of the DMUs more accurately, isolating the effects of factors beyond their control.

Stage 3: Adjusted DEA Model

In the third stage, the DEA model is reapplied using the adjusted efficiency scores from Stage 2. This reapplication provides a new set of efficiency scores that are corrected for statistical noise and external environmental influences. The final scores offer a more precise evaluation of the intrinsic efficiency of each DMU.

The three-stage DEA methodology is particularly useful in environments where external factors significantly impact the performance but are not directly controllable by the DMUs. It provides a more nuanced understanding of efficiency by:Allowing managers and policymakers to recognize areas for improvement that are within their control. Supporting fair comparisons among DMUs by considering the impact of external and uncontrollable factors.

3.2 Variable Category evaluate Cold Chain Logistics Efficiency

In assessing the efficiency of cold chain logistics, a comprehensive set of variables was selected to capture both the input and output dimensions of the system, as well as environmental factors that influence its performance. The evaluation framework incorporates input variables such as capital investment, labor, and energy, output variables related to economic performance and scale, and undesirable environmental outputs like carbon emissions. Additionally, environmental variables, including economic development level, government support, and market environment, were considered to account for the broader contextual influences on cold chain logistics efficiency. Table 7 below summarizes the selected evaluation indicators.

Table7 Selection of Evaluation Index of Cold Chain Logistics Efficiency

Variable Category	Selected Variable	Indicator Name	Unit
Input Variables	Capital Investment	Total Fixed Asset Investment in Cold Chain Logistics	100 million CNY
	Labor Investment	Number of Employees in Cold Chain Logistics	person
	Composite Technical Investment	Road Mileage	km
		Warehouse Capacity	10,000 tons
		Refrigerated/Insulated Storage Capacity	10,000 tons
		Number of Refrigerated/Insulated Vehicles	units
	Energy Input	Annual Energy Consumption	10,000 tons of coal equivalent
Output Variables	Economic Output	Cold Chain Logistics Flow	100 million CNY
	Scale Output	Turnover Volume of Freight Transport	tons
Undesirable Output	Environmental Output	Total Carbon Emissions of Cold Chain Logistics	10,000 tons
Environment Variables	Economic Development Level	Regional GDP	100 million CNY
	Government Support Level	Government Support Intensity	%
	Market Environment	Market Openness Level	%

The variables selected for the cold chain logistics efficiency evaluation are designed to provide a comprehensive overview of the system's operational, economic, and environmental performance. The input variables reflect the resources invested into the logistics operations, including financial capital, labor, technical infrastructure (e.g., road mileage, warehouse and vehicle capacity), and energy consumption. These indicators are crucial in understanding the resource allocation necessary for the functioning of cold chain logistics.

The output variables focus on the economic performance of the logistics system. Economic output is measured by the total value of cold chain logistics flow, while scale output is captured by the turnover volume of freight transport, representing the volume of goods handled within the system. The undesirable output accounts for the environmental costs, with total carbon emissions representing the negative externalities associated with the logistics process.

Finally, the environment variables include factors that influence the broader context of logistics operations, such as the economic development level (represented by regional GDP), the intensity of government support (measured by fiscal or policy incentives), and the market environment, which reflects the openness of the market to logistics operations. These variables are critical for understanding how external factors, such as government policy and regional economic conditions, shape the efficiency of cold chain logistics. Together, these variables provide a robust framework for evaluating the overall performance and sustainability of cold chain logistics operations.

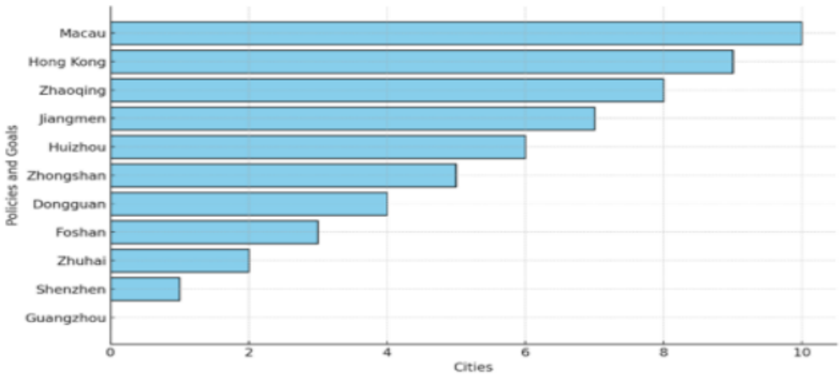
3.3 Key Insights from Policy and Development Goals

The policies and development goals in the GBA illustrate diverse regional focuses and strengths. The following table summarizes the key insights drawn from these policies, highlighting the roles and priorities of different city groups.

Table8 Key Insights from Policy and Development Goals

City Group	Focus	Characteristics
Guangzhou, Shenzhen, Dongguan	Becoming international hubs with strong industrial and innovation infrastructure	Prioritize carbon reduction while focusing on global connectivity and innovation hubs
Foshan, Zhongshan, Jiangmen	Emphasizing manufacturing and industrial development	Integrate green strategies with traditional and advanced manufacturing bases
Zhuhai, Zhaoqing	Balancing industrial upgrades with low-carbon goals	Play supportive roles in industrial and economic upgrading within the GBA
Hong Kong, Macau	Financial, logistics, and tourism sectors	Combine sector-specific economic goals with low-carbon practices for global positioning

Figure 4: Policy Focus and Development Goals in GBA Cities



A chart has been created that summarizes the development objectives and policy focus for each of the Greater Bay Area's (GBA) eleven communities.

The Function of Resource-Based Theory and Technological Innovation

Adopting cutting-edge technologies is essential to improving cold chain logistics' low-carbon efficiency. Businesses with valuable, uncommon, and unique resources—like cutting-edge technologies and highly qualified perso nnel—can achieve long-term competitive advantages, claims the Resource-Based Theory (RBT) (Barney, 1991). Energy -efficient refrigeration systems, real-time tracking tools, and route optimization algorithms are examples of technologi cal resources that are crucial to lowering carbon emissions and increasing operational effectiveness in the context of c old chain logistics.

Energy-efficient refrigeration systems, for example, drastically reduce energy use in logistical processes, which in turn lowers greenhouse gas emissions.

3.3 Research Gaps and Developing an Integrated Framework

Despite the increasing recognition of the importance of low-carbon cold chain logistics, significant research gaps persist in understanding the mediating role of generalized total factor productivity (GTFP) and the moderating effects of external factors. GTFP, as a measure of the efficiency with which inputs are transformed into outputs, provides valuable insights into how resources such as labor, capital, and energy are utilized in the logistics sector (Liu et al., 2023). However, existing studies have rarely examined GTFP within the specific context of cold chain logistics, leaving ample room to explore its impact on low carbon efficiency.

Furthermore, while it is widely acknowledged that external factors—such as government policies, economic condit ions, and market environments—play a role in shaping low-carbon initiatives, their functions as moderating variables r emain underexplored. Research has indicated that regions with stronger government support and more competitive markets are more likely to adopt low-carbon logistics practices (Yan et al., 2022). Nevertheless, there is a lack of syste matic analysis on how these external factors interact with internal inputs and mediators such as GTFP, particularly wit hin the GBA's unique socio-economic and environmental context.

To address these gaps, this study aims to develop an integrated framework that combines data envelope analysis (DEA) and structural equation modeling (SEM). The framework will examine the relationships between capital investment, labor input, composite technical investment, and energy input while incorporating the mediating roles of GTFP and energy structure. Furthermore, the framework includes external moderating factors, providing a holistic perspective on the drivers of low carbon efficiency in cold chain logistics. By filling these research gaps, this study seeks to advance theoretical understanding and offer actionable insights for policymakers and industry stakeholders.

4 Findings

This study evaluates the low-carbon efficiency of cold chain logistics in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) using Data Envelopment Analysis (DEA) and reveals the key drivers of low-carbon efficiency, including technological upgrades, optimization of infrastructure and transportation networks, and government policy support. The specific findings are as follows:

4.1 Technological Upgrades

The adoption of green technologies, such as advanced refrigeration and intelligent logistics systems, plays a crucial role in reducing energy consumption and carbon emissions while improving operational efficiency. The adoption of these technologies significantly reduces the carbon footprint of cold chain logistics.

4.2 Optimization of Transportation Networks and Facilities

Optimizing the cold chain logistics network layout and transportation routes, especially by centralizing cold chain hubs and storage facilities, can effectively reduce carbon emissions during the logistics process and improve overall operational efficiency.

4.3 Policy Support

Government policy support, including financial subsidies, tax incentives, and green certification measures, significantly promotes the adoption of low-carbon technologies and the development of green logistics. These policies not only directly affect the low-carbon transformation of enterprises but also guide the green development of the industry.

4.4 External Environmental Factors

The economic development level and market environment have a significant impact on the low-carbon efficiency of cold chain logistics. In more developed regions, cold chain logistics companies are more motivated to adopt green technologies and optimize operations. In less developed areas, green transformation faces greater obstacles due to economic pressures and technological barriers.

The findings of this study provide valuable insights for policymakers and business managers in the cold chain logistics industry of the GBA, emphasizing the importance of technological innovation, infrastructure construction, and policy guidance in improving low-carbon efficiency. By increasing investment in green technologies, improving logistics infrastructure, and strengthening policy support, low-carbon logistics efficiency can be effectively enhanced, contributing to the high-quality, low-carbon development of the GBA.

5 Discussion and Conclusion

5.1 Discussion

This study reveals the key drivers of low-carbon efficiency in cold chain logistics in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) through the use of Data Envelopment Analysis (DEA). The findings show that technological innovation, infrastructure optimization, and policy support are critical factors for improving low-carbon efficiency. First, the study demonstrates that technological upgrades are the primary drivers of low-carbon efficiency in cold chain logistics. The adoption of advanced refrigeration technologies and intelligent transportation systems enables enterprises to reduce energy consumption and carbon emissions, providing a solid technological foundation for the development of green logistics.

Second, the optimization of cold chain logistics networks and facilities is also a key factor in improving low-carbon efficiency. A well-planned logistics network and precise transportation routes can significantly reduce energy consumption during transportation while improving resource utilization and operational efficiency. The optimization of infrastructure, particularly in terms of cold chain hubs and storage facilities, can effectively reduce the carbon footprint of the logistics process and further drive the development of low-carbon cold chain logistics.

Government policy support is equally crucial in promoting low-carbon logistics. The study finds that policy measures such as tax incentives, subsidies, and green certification have a significant impact on the adoption of low-carbon technologies. These policies not only provide financial incentives to enterprises, reducing the initial investment cost of green technologies, but also guide the industry towards a low-carbon transformation by setting industry standards and green regulations.

However, the study also reveals that external environmental factors, such as economic development levels and market conditions, influence the development of low-carbon cold chain logistics. In more developed regions, enterprises are more likely to adopt green technologies and optimize logistics processes, while in less developed regions, low-carbon transformation faces significant economic and technological barriers. This finding highlights regional disparities and suggests that low-carbon development policies should be tailored to the specific conditions of each region.

5.2 Conclusion

This study provides a comprehensive assessment of the low-carbon efficiency of cold chain logistics in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA) by developing an efficiency evaluation framework and applying the Data Envelopment Analysis (DEA) method. The key conclusions drawn from the study are summarized as follows:

5.2.1 Technological Innovation is the Core Driver of Low-Carbon Efficiency

The study underscores that technological innovation is a central driver for enhancing the low-carbon efficiency of cold chain logistics in the GBA. The adoption of high-efficiency refrigeration technologies, intelligent transportation systems, and the integration of renewable energy sources into logistics operations have proven to be effective strategies for reducing carbon emissions. Advanced refrigeration systems, for instance, offer energy savings by improving the cooling process and minimizing refrigerant leakage, while smart logistics systems enable better route optimization and real-time monitoring, thereby reducing fuel consumption and emissions during transportation. Green energy alternatives, such as solar-powered facilities and electric vehicles, further contribute to the reduction of carbon footprints. This technological transition is vital not only for enhancing operational efficiency but also for aligning with global sustainability goals, providing a pathway for the cold chain logistics industry to transition toward greener practices.

5.2.2 Optimization of Cold Chain Facilities and Transportation Networks

The study also highlights that optimizing cold chain infrastructure and transportation networks plays a crucial role in reducing carbon emissions while improving operational efficiency. Rational planning of cold chain facilities, such as refrigerated warehouses and transportation hubs, ensures that logistics operations are carried out in a more energy-efficient manner. For example, consolidating cold storage facilities and strategically locating them along major transport routes can reduce transportation distances, resulting in less fuel consumption and lower emissions. Moreover, optimizing transportation routes and improving load planning ensures that vehicles operate at maximum capacity, further enhancing resource utilization and reducing the overall environmental impact. By implementing efficient infrastructure and transportation systems, logistics companies can not only cut costs but also significantly improve their carbon performance, paving the way for sustainable logistics operations.

5.2.3 Policy Support Provides Strong Guarantee for Low-Carbon Transformation

Government policy support plays a critical role in enabling the low-carbon transformation of cold chain logistics. The study finds that policy incentives, such as tax reductions, subsidies, and green certifications, are essential in promoting the adoption of low-carbon technologies within the logistics industry. These incentives help offset the initial high investment costs associated with adopting advanced technologies, thereby reducing the financial burden on businesses. Moreover, regulatory frameworks that set clear environmental standards and provide green logistics certifications create a favorable environment for companies to invest in sustainable practices. In addition to providing financial support, government policies can help create a level playing field for all industry players, encouraging the widespread adoption of green practices and driving the overall transition towards low-carbon logistics.

5.2.4 External Environmental Factors Impact Low-Carbon Efficiency

The study also reveals that external environmental factors, such as the level of economic development and the market environment, significantly influence the implementation and success of low-carbon cold chain logistics. Regions with higher levels of economic development tend to have more advanced infrastructure, greater access to green technologies, and a more supportive policy environment, which facilitates the transition to low-carbon logistics. In contrast, less developed regions may face challenges such as limited access to funding, outdated infrastructure, and insufficient policy support, which hinder the adoption of low-carbon practices. This highlights the need for region-specific policies that account for the local economic conditions, infrastructure capabilities, and market characteristics. For example, while financial incentives might be highly effective in more developed regions, developing regions may require additional support in terms of capacity building and technology transfer to effectively implement low-carbon logistics solutions.

This study provides both theoretical foundations and practical guidance for advancing the low-carbon development of cold chain logistics in the GBA. The insights gained from this study can serve as a valuable reference for policymakers, businesses, and researchers aiming to enhance the sustainability of cold chain logistics systems. Future research could further explore how to achieve balanced low-carbon cold chain logistics development across different regions, taking into account the varied challenges and opportunities present in each context. Additionally, research could investigate international cooperation models for low-carbon cold chain logistics, particularly in the context of global green supply chains. As the logistics industry becomes increasingly globalized, fostering cross-border collaborations and knowledge exchange will be essential for advancing the adoption of low-carbon technologies and practices worldwide. Furthermore, future studies could examine the long-term impacts of low-carbon logistics on the broader supply chain, including its economic, social, and environmental effects, to provide a more holistic understanding of its benefits and challenges.

5.3 Limitations and Suggestions for Future Research

5.3.1 Limitations

5.3.1(a) Data Availability and Generalizability: One of the primary

limitations of this study is the reliance on available data from the Guangdong-Hong Kong-Macao Greater Bay Area (GBA). The data on energy consumption, carbon emissions, and cold chain logistics performance is not always consistent across different regions and sectors, which may hinder the accuracy and generalizability of the findings. Furthermore, the study is limited by the availability of data for certain parameters, especially on the environmental and social factors influencing logistics efficiency. This lack of comprehensive and reliable data limits the ability to draw broader conclusions for other regions or to assess the full scope of low-carbon logistics.

5.3.1(b) Geographic and Contextual Focus

While the study provides valuable insights into the cold chain logistics system in the GBA, its findings are largely context-specific and may not be directly applicable to other regions with different infrastructure, economic development levels, or policy environments. The GBA's unique characteristics—such as its advanced economic status, well-established logistics infrastructure, and regional policies—may not reflect the challenges faced by other regions, e specially in less developed or developing countries. Future research should consider expanding the geographic scope t o compare different regions or countries, particularly those with diverse logistical needs and differing economic condi tions.

5.3.1(c) Model Limitations and Scope of External Factors

The study uses Data Envelopment Analysis (DEA), which, although effective for efficiency evaluation, relies on certain assumptions that may limit the robustness of the results. DEA assumes that the data on inputs and outputs is accurate and that the production frontier is properly represented. However, external factors such as supply chain disruptions, climate change, and technological advancements may not be fully accounted for, which could affect the overall results. Moreover, the study does not explore the potential effects of other environmental and social variables, such as shifts in climate policies, technological disruptions, or evolving societal expectations, which could influence the future development of low-carbon cold chain logistics.

5.3.2 Suggestions for Future Research

5.3.2(a) Expansion to Broader Regions and Long-Term Analysis

Future research should consider expanding the study to include a broader range of regions, particularly those with different levels of economic development, infrastructure, and policy landscapes. This would allow for cross-regional comparisons and a better understanding of how low-carbon cold chain logistics can be optimized under varying conditions. Additionally, longitudinal studies that track changes in low-carbon efficiency over time would provide insights into the long-term impacts of technological advancements, policy changes, and other factors on cold chain logistics sustainability.

5.3.2(b) Incorporation of Emerging Technologies and Comprehensive Models

Future studies could explore the role of emerging technologies, such as blockchain for supply chain transparency, artificial intelligence for route optimization, and renewable energy sources in reducing carbon footprints. By incorporating these innovations, researchers can assess how technological progress can further enhance the efficiency and sustainability of cold chain logistics. Additionally, more comprehensive models that integrate environmental, economic, and social factors could offer a holistic view of low-carbon logistics and provide more actionable insights for industry stakeholders and policymakers.

5.3.2(c) Policy Evaluation and Tailored Recommendations

Future research could focus on evaluating the effectiveness of specific policy measures aimed at reducing the carbon footprint of cold chain logistics. Simulation models and policy evaluation frameworks could be developed to assess the impact of various interventions, such as financial incentives, regulatory frameworks, and green certification programs. By tailoring these policy recommendations to the specific needs of different regions or sectors, future research can guide policymakers in creating more effective strategies for promoting low-carbon logistics across various contexts.

Secondly, the current research landscape is heavily concentrated in China, reflecting both the country's rapid development in digital finance and its strong manufacturing-based supply chain ecosystem. However, there is a notable absence of cross-country comparative studies that examine the institutional, cultural, and regulatory factors shaping the adoption and impact of SCF in other regions, such as Southeast Asia, Africa, Latin America, and Europe. It is recommended that future research explore these diverse contexts in order to ascertain how regional differences influence SCF mechanisms and innovation outcomes.

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3.Higher Education Teaching Reform Project：The Construction of Cold Chain Supply Chain Course Cluster and Competency Map with a Focus on Carbon Neutrality and ESG (Environmental, Social, and Governance) Orientation, and Course Mapping Research;

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