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Reducing greenhouse gas emissions and achieving sustainable development through low-carbon cold chain logistics: A case study in the Greater Bay Area

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Abstract
Purpose: Exploring the feasibility of adopting low-carbon cold chain logistics to reduce greenhouse gas (GHGE) emissions and promote sustainable development in the Greater Bay Area. The study presents various practical strategies, such as using energy-efficient refrigerated vehicles, optimizing logistics routes, and utilizing refrigeration equipment that saves energy. The findings demonstrate that the implementation of low-carbon cold chain logistics can significantly decrease GHGE, improve efficiency, and enhance product quality.
Design/methodology/approach: A questionnaire survey method will be utilized for data collection among cold chain logistics enterprises in 11 cities in Guangdong, Hong Kong and Macao. This study will use PLE-SEM (Partial Least Squares Structural Equation Modeling) to analyze the data.
Findings: Reduce reliance carbon footprints, it is crucial to prioritize initiatives that enhance energy efficiency and utilize renewable energy sources. such as technologies, emission reduction measures, and environmental implications. Integrating technological advancements, such as smart temperature control systems and big data analytics, significantly improves the efficiency and effectiveness of cold chain logistics. To reduce direct emissions and minimize

environmental impacts, it is essential to implement measures that control emissions, optimize transportation routes, and adopt low-carbon fuels. Proper waste management, water conservation, and biodiversity preservation also contribute significantly to the sustainability of cold chain logistics.
Research limitations/implications: Costs and technology need to be addressed. Organizations and decision-makers can make informed choices to support low-carbon and sustainable cold chain logistics systems.
Practical implications: Guidance for the development of low-carbon cold chain logistics, promoting energy utilization efficiency, and reducing greenhouse gas emissions. Enhancement of the quality of cold chain logistics services, improving the storage, transportation, and sales of agricultural products.
Originality/value: Provide valuable guidance for achieving sustainable CCL and emphasizes the importance of technological progress and economic benefits.

Keywords: Greenhouse Gas Emissions (GHGE), low-carbon(LC), cold chain logistics(CCL), Greater Bay Area(GBA), Sustainable Development(SD)

Introduction

Enhancing the efficiency of low-carbon cold chain logistics (LCCCL) can have a substantial impact on energy consumption and emissions, particularly in densely populated areas such as the Greater Bay Area (GBA). The increasing demand for fresh food in economically developed regions necessitates the establishment of an effective and environmentally friendly cold chain logistics system to meet market needs (Kabir et al., 2022).
As a solution to combat climate change and mitigate its negative consequences, the implementation of LCCCL plays a crucial role in reducing energy consumption and emissions (Wangsa et al., 2023).
A map of the approximate geographic distribution of the GBA, through which you can better understand the economic zones in which each of the GBA is situated, as well as the distances and connections between individual cities as shown in Figure 1.

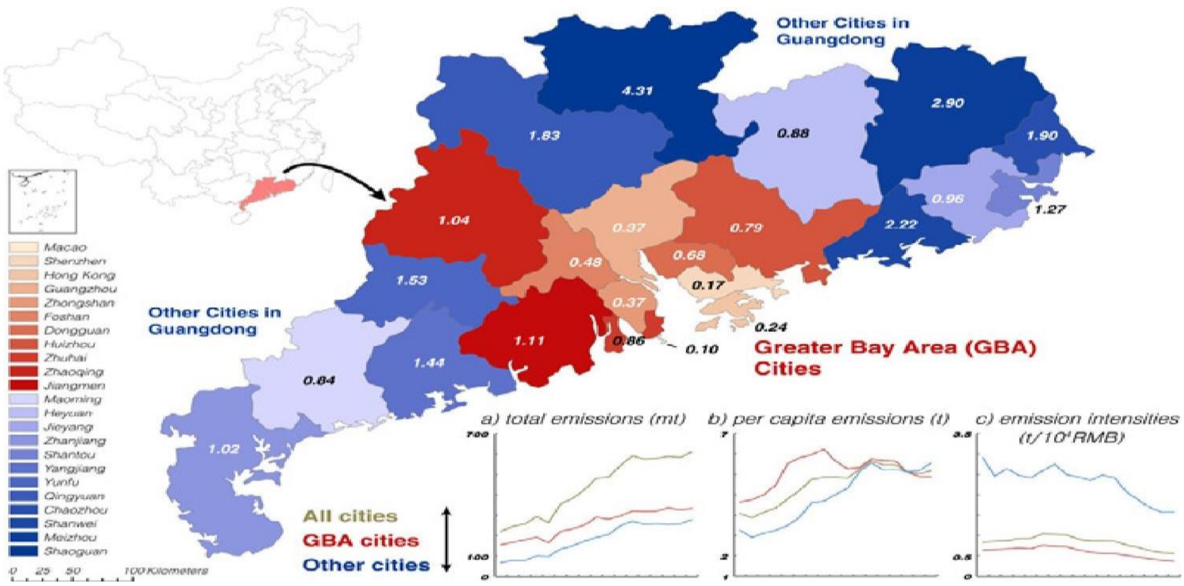

Figure 1: Regional distribution map of GBA about Reducing GGE and achieving SD

The GBA is a highly developed and thriving region in China, home to over 70 million people and with a GDP of 1.6 trillion USD. However, the rapid urbanization and economic growth in this area have resulted in environmental challenges, particularly excessive energy consumption and the release of greenhouse gases. Therefore, it is crucial to prioritize sustainable growth and reduce carbon emissions in this locality. Greenhouse gas emissions (GGE）, including major contributors such as CO_2, CH_4, and N_2O, play a significant role in the global issue of climate change.

Various industries in the GBA, such as transportation, manufacturing, and agriculture, have witnessed an increase in emissions. Addressing these harmful emissions is of utmost importance as it helps combat climate change and achieve SDG. Successfully mitigating greenhouse gas emissions requires the implementation of a wide range of strategies. These strategies should involve adopting energy-efficient technologies, promoting renewable energy sources, improving transportation infrastructure, and implementing low-carbon initiatives in logistics and industrial manufacturing. By fully embracing sustainable development practices while simultaneously reducing greenhouse gas emissions, the Greater Bay Area can effectively mitigate the adverse impacts of climate change. This endeavor would significantly improve air quality, enhance energy efficiency, and create a more sustainable and livable environment.

City	Implemented low carbon-related policy	Development goal
Hong Kong	**HK Climate Change Action Plan 2030**	**Global financial centre and logistics centre**
Shenzhen	12th Five-year-plan on SZ industrial and commercial energy conservation;Mid-and long-term plans on SZ low carbon development(2011-2020)	**International innovation service centre**
	Provisions of Carbon Emissions Management of the SZ Special Economic Zone	
	Special Funds for SZ renewable energy and new energy vehicle development;SZ Sustainabledevelopment plan(20172030)	
Guangzhou	13th Five-year-plan on GZ energy saving and carbon reduction	**Three international strategic hubs**
Dongquan	13th Five-year-plan on DG energy saving (2016-2020)	**International manufacturing service centre**
Foshan	FS constructing low carbon city plan	**International industrial manufacturing centre**
Zhuhai	12th Five-year-implementation-plan on ZH greenhouse gas emission control	**Expanding bridgehead and the innovation plateau**
Zhongshan	13th Five-year-plan on ZH green and low carbon development 13th Five-year-implementation-plan on ZS greenhouse gas emission control;12th Five-year-plan on low carbon development Interim procedures for ZS low carbon development special funds	**State-level advanced manufacturing base**

Macao	Macao environmental protection plan (2010-2020)	**World tourism leisure centre**
Huizhou	**HZ low carbon ecology plan (2014-2030)**	**Ecological tour of "green city",taking ecological responsibility of the Greater Bay Area**
Jiangmen	**JM city low carbon development strategy plan (2010-2020)**	**State-level advanced manufacturing base**
Zhaoqing	**ZQ new area low carbon development subject plan (2012-2030)**	**Agglomeration area of upgrading traditional industries**

Figure 2: Cities about low carbon-related policy and development goals

These cities are actively implementing policies to limit carbon emissions and promote sustainable development. Their main focus is on advancing and expanding low-carbon industries and technologies to effectively reduce greenhouse gas emissions. Notably, significant investments are being made in renewable energy sources like solar and wind power. Additionally, there is a strong emphasis on promoting energy-efficient building and transportation systems. The transportation sector plays a crucial role in the region's drive for low-carbon development, leading to substantial funds being allocated for enhancing public transportation infrastructure. This includes the expansion of metro networks and the development of electric and hybrid vehicles. Moreover, efforts to promote cycling and walking as alternative modes of transport are also receiving attention. Alongside emission reduction initiatives, these cities are undertaking carbon sink projects, such as afforestation and reforestation, to absorb and store carbon dioxide. Waste management systems are also being implemented to effectively reduce methane emissions from landfills.
In the context of the low-carbon development strategy in the Greater Bay Area, collaboration and knowledge sharing are crucial. The 11 cities in this area are actively partnering to exchange best practices and experiences. They are also participating in international cooperation and initiatives aimed at addressing climate change. The ultimate objective of these cities is to achieve sustainable development while effectively mitigating the impacts of climate change. Their sincere efforts are focused on creating a greener and more livable environment for their residents, serving as a role model for other regions facing similar challenges.

Literature Review

Degree of application of IOT technology and BD analysis

According to a study conducted by Gillespie et al. in 2023, a unique remedy was developed to monitor and notify about products in cold chain transportation in real-time by leveraging the capabilities of the Internet of Things (IoT). The researchers utilized the Digital Matter Eagle cellular data logger along with temperature sensors to achieve this novel approach. By combining wearable biosensors with IoT and Big Data, it becomes feasible to identify, transmit, store, and comprehensively analyze human physiological and biochemical information. Consequently, this integration has the potential to significantly advance the utilization of IoT technology and big data analytics in cold chain logistics systems.

Optimization degree of cold chain logistics network layout

Yuan (2022) investigates the factors that contribute to optimization by analyzing data and utilizing mathematical models. The focus of the study is a case in the Ontario region of Canada.

Wang (2023), on the other hand, conducts research on enhancing the ant colony algorithm for optimizing cold chain logistics distribution routes. To ensure the scientific validity and rationality of the algorithm, the researchers perform numerical simulations using MATLAB software. This study effectively addresses the challenge of selecting the most optimal distribution route for vehicles involved in cold chain logistics. Considering the increased demand for improved timeliness and radiation radius of cold chain logistics companies due to the impact of COVID-19, these factors are used to evaluate the level of optimization in network layouts.

Application degree of green supply chain management

The intelligent logistics platform, introduced by Lai et al. in their 2020 publication, integrates block chain technology. This platform has significantly advanced the greater bay area by improving logistics integration and facilitating the harmonious expansion of urban clusters. Additionally, Liu et al.'s recent study outlined three essential recommendations to foster cross-border energy cooperation within the GBA region.

Greenhouse Gas Emissions

In their study, Luo et al. (2023) proposed a research framework that combines the use of logarithmic mean divisor index (LMDI) and system dynamics (SD) to examine the levels of CO2 emissions in the GBA and surrounding cities from 2000 to 2019. The main objective of this investigation is to analyze the factors driving these emissions, project future trends, and assess policy implications. According to the initial scenario, regional CO2 emissions are estimated to continue increasing and reach 1.25 times the 2019 levels by 2030.

To further support the report on Wetland Conservation and Sustainable Development Goals (SDGs), Peng et al. (2023) evaluate the anticipated changes in the wetlands within the GBA from 2020 to 2035. This study also examines land degradation under four different scenarios, with a specific focus on maintaining zero growth (LDN). By introducing systematic investigations to this field of study, this research addresses an existing knowledge gap.

The study highlights the significance of changes in land use and land cover, commonly known as 'land use emissions, as major contributors to the overall carbon balance in the area.

Greater Bay Area cold chain logistics

To assess the low-carbon perspective of logistics performance in the GBA, a principal component analysis technique was utilized (Xu, 2023). The findings revealed that Hong Kong achieved the highest score, while Zhongshan obtained the lowest score (Chu et. al., 2023). This investigation aims to provide guidance on preserving the quality of rhubarb fish during its transportation in the cold chain. To ensure adherence to quality standards, it is recommended to promptly freeze the collected samples and minimize temperature fluctuations throughout the cold chain process. An established and systematically monitored cold chain logistics network is crucial due to the unpredictable nature of this procedure. Yuan's (2022) study focused on optimizing influential factors, including data analysis and the utilization of mathematical models, using the Ontario region in Canada as a specific example. Maintaining an uninterrupted cold chain is vital when shipping perishable food items such as meat, fruits, and vegetables to minimize spoilage.

Environmental efficiency theory

Yamasaki et al. (2019) conducted a recent study that provides valuable insights for policymakers in Japan regarding the evaluation of eco-efficiency in urban areas. According to Ai et al. (2020), governments should encourage business innovation, improve resource allocation efficiency, and gradually reduce environmental pollution while ensuring enterprise sustainability. However, the lack of reliable empirical indicators poses challenges when assessing the impact of these environmental policies on crucial economic outcomes such as innovation, productivity, competition, energy efficiency, and carbon emissions.

To address this issue, Galeotti and colleagues (2020) made a significant contribution by calculating various indicators to measure the severity of environmental policies and conducting a comprehensive statistical analysis to compare these indicators. Additionally, they presented real-life case studies focusing on environmental innovation and energy efficiency, demonstrating the practicality of these indicators.

Shuai et al. (2020) developed a comprehensive set of indicators to evaluate the effectiveness of environmentally conscious practices in China, utilizing panel data from different regions between 2007 and 2018. According to their findings, there is a 'U'-shaped relationship between environmental regulations and green economic efficiency, initially promoting efficiency but eventually hindering it at the national level. In their research, Song and colleagues (2021) employed a combination of super-efficiency data envelopment analysis and spatial econometric modeling to examine energy utilization efficiency while considering environmental factors.

Sustainable Development

The evaluation of energy efficiency is essential for policy development as it helps reduce energy consumption and pollutant emissions. Researchers conducted a study to analyze the energy efficiency of different Chinese provinces from 2008 to 2016. They utilized a three-stage model called data envelopment analysis, which focused on scale efficiency, a crucial aspect of energy efficiency, while disregarding external environmental factors. Another scholarly publication proposed an integrated assessment of eco-efficiency that considered potential emission reductions, energy savings, and resource allocation across Chinese regions. The study incorporated variables such as environmental regulations and resource disparities to identify the primary factors influencing eco-efficiency. Additionally, a quantitative analysis examined the energy efficiency, carbon dioxide emissions efficiency, and environmental efficiency of 20 industrialized nations. The results revealed the exceptional performance of Australia, China, Japan, Saudi Arabia, and Poland, while Mexico, Indonesia, Russia, and Brazil exhibited lower efficiency rankings. These significant findings have implications for energy policymakers seeking well-informed decision-making. Within this region, achieving optimal energy efficiency levels may have a more pronounced impact on environmental efficiency rather than economic efficiency.

Examine the impact of different environmental regulatory measures and their level of strictness on the overall effectiveness of energy production. We analyzed panel data from Chinese provinces covering the period from 2000 to 2017 (Guo et al., 2020) using dynamic panel regression. Our analysis focused on the diverse effects and mechanisms of various types of environmental regulations on energy efficiency. Our results indicate that environmental regulations have a significant negative impact on the efficiency of both the scale and technical aspects of energy production for regulated firms (Ai et al., 2020). To mitigate this impact, it is crucial for the government to incentivize firms to innovate and improve resource allocation efficiency, enabling them to gradually reduce environmental pollution without compromising their survival. Galeotti et al. (2020) have made significant contributions to the existing literature by (1) calculating multiple indicators to assess the strictness of environmental policies, (2) conducting a statistical comparison exercise to evaluate the consistency of these indicators, and (3) demonstrating the use of these indicators in two empirical studies focusing on environmental innovation and energy efficiency.

Shuai et al. (2020) conducted a study where they devised a series of measures to evaluate the efficacy of the green economy. Panel data from 2007 to 2018 for each province in China was and subsequently hindering it (Shuai et al., 2020). An alternate perspective was pursued by Song et al. (2021) who employed a remarkably efficient data envelopment analysis along with a spatial econometric model to examine energy utilization efficiency under environmental limitations. Their discoveries imply that the adoption of green credit has a positive impact on energy efficiency through an environmental lens in China (Song et al., 2021). Another research by Bashir et al. (2021) unfurled the uncertainty surrounding the role of environmental taxes in curbing energy consumption and intensity from 1994 to 2018. Given the recent environmental reforms and the emphasis on Sustainable Development Goals (SDGs), it becomes pivotal to investigate the influence of environmental taxes. The study concluded that environmental taxes exert a substantial influence on both energy consumption and efficiency (Bashir et al., 2021).

Hypothesis Development

Technological innovation has a positive impact on low carbon cold chain logistics efficiency (CLCDI): technological innovation can improve the energy utilization efficiency of cold chain logistics and reduce carbon emissions per unit of output, thus improving low carbon cold chain logistics efficiency.

Operation and management strategies have a positive impact on low carbon cold chain logistics efficiency (CLCDI): optimizing operation and management strategies, such as improving logistics efficiency and reducing inventory costs, can effectively reduce energy consumption and carbon emissions, thus enhancing low carbon cold chain logistics efficiency.

Infrastructure construction has a positive impact on low carbon cold chain logistics efficiency (CLCDI): perfect infrastructure construction can improve the transportation efficiency and distribution efficiency of cold chain logistics, reduce carbon emissions in the logistics process, and thus enhance the efficiency of low carbon cold chain logistics.

Policy factors have a positive impact on CLCDI: the guidance and support of government policies can promote the development of the low-carbon cold chain logistics industry, promote technological innovation and improve operation and management strategies, and then improve the efficiency of low-carbon cold chain logistics.

Carbon emission intensity plays a role as a mediating variable between technological innovation, operation and management strategies, infrastructure construction, policy factors and low carbon cold chain logistics efficiency (CLCDI): carbon emission intensity is one of the important indicators of low carbon cold chain logistics efficiency, and the independent variables such as technological innovation, operation and management strategies, infrastructure construction, policy factors and so on, may indirectly affect low carbon cold chain logistics efficiency by influencing carbon emission intensity. Logistics efficiency.

Methods

Data Collection and Sample

This study adopts the questionnaire survey method as the research method, aiming to investigate and analyze the cold chain logistics enterprises in 11 cities in Guangdong, Hong Kong and Macao. A total of more than 1,000 enterprises were included in the sample, of which 100 were selected as survey respondents. By distributing the questionnaires and collecting the feedback data, this study will use PLE-SEM (Partial Least Squares Structural Equation Modeling) to analyze the data.

Theoretical framework

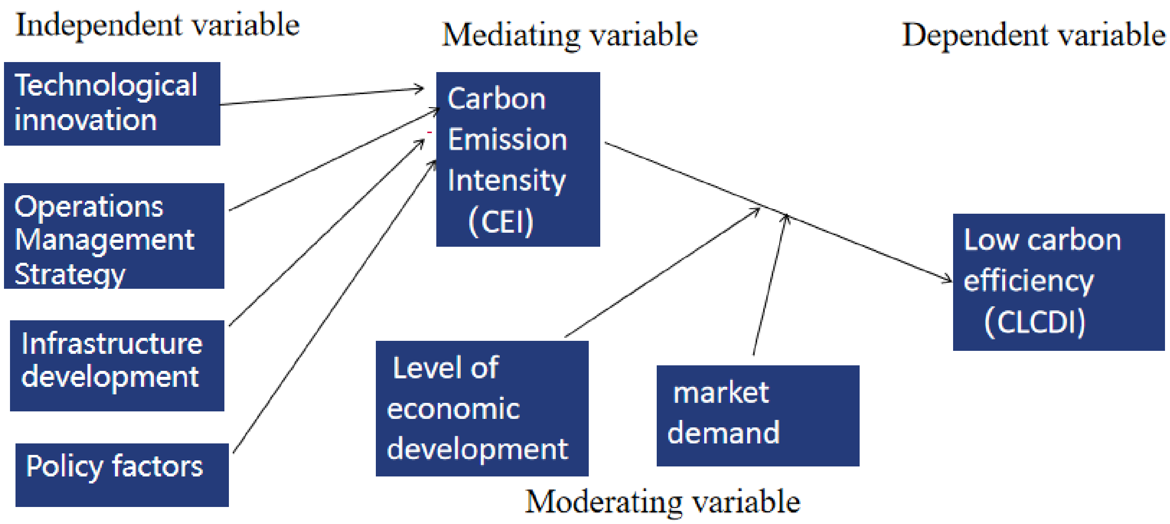

Figure 3: Theoretical framework

In the questionnaire design, this study will cover the relevant independent, dependent, mediating and moderating variables to achieve the measurement of the factors influencing the low-carbon cold chain logistics indicators. The independent variables will include the business model, technology level, and resource utilization of cold chain logistics enterprises. The dependent variable will focus on measuring the low-carbon performance of cold chain logistics, such as carbon emissions and energy consumption. Mediating variables will be used to explain the relationship mechanism between the independent variables and the dependent variables, such as enterprise management level, environmental awareness and so on. Moderating variables will be used to explore the effects of different sample characteristics (e.g., enterprise size, geographic location, etc.) on the research model.

Table 1: Research Question and Objectives

Research Questions	Research Objectives
1.What are the key factors and variables that contribute to the efficiency of CCL in the GBA?	Identify key factors for efficient CCL in the GBA.
2.What are the inter dependencies and feedback loops between these factors that influence the overall efficiency of the logistics system?	Understand the inter dependencies among factors affecting LCCCL efficiency in the GBA.
3.How can a SDM be developed and applied to capture the complexity and dynamics of the LCCCLS in the GBA?	Develop a comprehensive system dynamics model for the LCCCLS in the GBA.
4.How can the efficiency of the logistics system be accurately measured and evaluated using the SDM?	Evaluate efficiency of LCCCLS in the GBA using the developed model.
5.What insights and recommendations can be derived from the evaluation results to	Provide recommendations for improving efficiency and sustainability of LCCCL in the GBA.

improve the efficiency and sustainability of LCCCL in the GBA?	

Table 2: Methodology Quantitative

Methodology	Quantitative
Data collection method	Questionnaire (five-point Likert scale）
Sample source	Directory of GBA logistics enterprises --select 100 cold chain logistics companies and send the questionnaire. Prospect Industry Research Institute
Sample size	As of 2023, there are a total of 699 related cold chain logistics enterprises in Shen zhen and 472 in Guangzhou
Population	The cold chain logistics enterprises in GBA Big Data Panorama Analysis of Cold Chain Logistics Enterprises in Guangdong Province in 2023
Sampling method	Simple random sampling
Statistical technique	PLS-SEM method. SD model
Data analysis software	Smart PLS

Table 3: Questionnaires Development Table

Section	No	Measurements	Variables
A	3	Green Supply Chain sustainability	Independent variables
B	6	Internet of Things and Big Data	
C	4	Optimization of transport routes integration	
D	5	energy efficiency	
E	3	Low carbon cold chain logistics efficiency	dependent variables
F	4	carbon emissions and efficiency	Mediator factors
G	6	Optimization of transport routes integration	
H	5	energy efficiency	

The PLE-SEM analysis of the collected questionnaire data will enable an in-depth understanding of the low-carbon performance of cold chain logistics enterprises and their influencing factors. The methodology of this study will be presented through four graphs, which accurately show the details of survey respondents, sample selection, questionnaire design and data analysis, providing effective theoretical support and scientific basis for the study.

Table 4: 3 main factors of low-carbon cold chain logistics on Reducing Greenhouse Gas Emissions and Achieving Sustainable Development

Efficiency Measurement Factors	Definition
Transportation efficiency	The measurement quantifies the energy efficiency and emission reduction in the transportation process of CCL. This indicator takes into account various factors such as transportation distance, type of transportation (e.g., road, rail, sea, or air), and the conditions for packaging and storing goods. By improving transportation efficiency, energy consumption and emissions are reduced, leading to a decrease in greenhouse gas emissions

	and supporting sustainable development.In cold chain logistics, maintaining product quality and longevity often requires the use of refrigerants.
Refrigerant leakage rate	these refrigerants can contribute significantly to greenhouse gas emissions in high-temperature driving systems. Therefore, it is important to evaluate the variable related to the leakage rate of refrigerants in cold chain logistics. Minimizing refrigerant leakage has the potential to reduce greenhouse gas emissions and enhance the sustainability of CCL.
Energy source and technology	Assessing the impact of energy sources and technologies used in cold chain logistics on reducing emissions and promoting sustainable development is an important measure. Therefore, this measure evaluates the sustainability of cold chain logistics by assessing the environmental impact of energy sources and the effectiveness of carbon reduction technologies.

Next, I will define in detail the specific metrics for each of the three important measurement factors, the first factor is Transportation efficiency Sustainability, the metrics for judging Green Supply Chain Sustainability are shown in Table 5, and this study will define each metric in detail.

Table 5: Evaluation indicators for transportation efficiency

Evaluation indicators	Definition
Average fuel consumption per unit of distance	The cold chain logistics measure the quantity of fuel used per distance covered in the transportation process. A decreased proportion of such empty return trips indicates improved transportation efficiency, as it suggests a more efficient use of resources, reduced fuel consumption, and decreased emissions.occur when vehicles return to their starting point without transporting any goods. .
Percentage of empty return trips	A lower average fuel usage indicates higher transportation efficiency, meaning that less fuel is required for the transportation of goods. Consequently, this can lead to reduced energy consumption and greenhouse gas emissions.The indicator presented in this study corresponds to the ratio of vacant return journeys throughout the entire transportation procedure. Inadequate route mapping and logistical planning can lead to instances of vacant return trips, which occurs when vehicles go back to their starting point without transporting any goods. A decreased proportion of such empty return trips denotes enhanced efficiency in transportation, as it implies a more refined utilization of resources, reduced fuel consumption, and diminished emissions.
Delivery time reliability	This metric measures the reliability and consistency of delivery times in cold chain logistics transportation. It evaluates the The indicator presented in this study represents the ratio of vacant return journeys throughout the entire transportation procedure. Inadequate route mapping and logistical planning can result in empty return trips, which

The second factor measuring LCCCL is energy efficiency, and specific indicators on energy efficiency are shown in Table 6 which will be elaborated on each specific indicator.

Table 6: Refrigerant leakage rate evaluation indicators	
Evaluation indicators	Definition
Refrigerant leakage rate	In the realm of CCL, this metric evaluates the degree of refrigerant leakage. Enhanced transportation efficiency and environmental benevolence are implied by a reduced rate of leakage. Refrigerant leaks not only lead to energy squandering, but they also contribute to the depletion of the ozone layer and an escalation in greenhouse gas emissions. Hence, a diminished leakage rate signifies more stringent refrigerant management throughout the process of cold chain transportation, minimizing environmental hazards.
Leakage repair time	Evaluating the duration it takes to fix a detected leakage in CCL is the purpose of this measure. A decreased repair time implies enhanced transportation efficiency and eco-friendliness. Repairing leaks promptly aids in reducing wastage of refrigerants and emissions of greenhouse gases. Furthermore, shorter repair durations also mitigate the risks of merchandise loss and degradation in quality. Hence, ensuring effective control over leakages and prompt repairs play pivotal roles in advocating for LCCCL.

The third factor about RGGE and Achieving SD on LCCCL is the optimization of transport routes, and the specific evaluation indexes will be indicated in Table 7.

Table 7: LCCCL about Energy source and technology Evaluation Indicators	
Evaluation indicators	Definition
Energy efficiency	The purpose of this indicator is to evaluate how effectively energy is used in the transportation phase of CCL. LCCCL should incorporate energy-efficient technologies and equipment, including refrigeration systems that are efficient and save energy, as well as devices that recover energy. Greater energy efficiency leads to lower energy usage during transportation, which in turn reduces both carbon emissions and energy wastage. As a result, assessing energy efficiency becomes a pivotal factor in evaluating the effectiveness of LCCCL.
Proportion of renewable energy	The proportion of energy obtained from renewable sources employed in cold chain logistics is assessed by this metric. Low-carbon cold chain logistics must make efforts to enhance the utilization of renewable energy, including solar power, wind energy, and bioenergy. The augmentation of renewable energy share aids in diminishing dependence on conventional fossil fuels and mitigating greenhouse gas emissions. Consequently, assessing the proportion of renewable energy constitutes another crucial metric for evaluating LCCCL.
Technological innovation and application	The proportion of energy obtained from renewable sources employed in cold chain logistics is assessed by this metric. Low-carbon cold chain logistics must make efforts to enhance the utilization of renewable energy, including solar power, wind energy. The augmentation of renewable energy share aids in diminishing dependence on conventional fossil fuels

	and mitigating greenhouse gas emissions. Consequently, assessing the proportion of renewable energy constitutes another crucial metric for evaluating LCCCL.

For the above four tables about low carbon cold chain logistics on Reducing Greenhouse Gas Emissions and Achieving Sustainable Development. Low-carbon cold chain logistics plays a crucial role in reducing greenhouse gas emissions and achieving sustainable development. Here are the key indicators for assessing the performance of low-carbon cold chain logistics.

Energy Sources and Technologies

Energy Efficiency: Assess the utilization efficiency of transportation energy, focusing on energy-saving refrigeration systems and energy recovery equipment.

Renewable Energy Proportion: Measure the proportion of renewable energy used in cold chain logistics, reducing reliance on fossil fuels.

Technological Innovation and Application: Evaluate the application of new technologies and innovative solutions, such as smart temperature control systems, environmentally friendly refrigerants, IoT, and big data analytics.

Emission Reduction Measures

Carbon Footprint: Assess the total greenhouse gas emissions generated during the cold chain logistics process, including transportation, refrigeration, and warehousing.

Emission Control Measures: Evaluate the implementation of emission reduction measures, such as improving insulation performance, optimizing route selection, and stricter vehicle emission standards.

Alternative Fuels: Consider the use of low-carbon or carbon-neutral fuels (such as renewable natural gas or electric vehicles) to reduce direct emissions.

Environmental Impacts

Waste Management: Evaluate the management of waste generated during the cold chain process, including packaging materials and refrigerants.

Water Resources and Resource Conservation: Assess efforts to minimize water usage and optimize resource utilization.

Biodiversity Conservation: Consider the impact of logistics activities on local ecosystems and take measures to protect biodiversity.

Through a holistic consideration of these factors, we can evaluate the efficiency and long-term viability of cold chain logistics aimed at achieving carbon reduction. This evaluation encompasses the reduction of greenhouse gas emissions, the facilitation of sustainable progress, and the mitigation of environmental consequences. The purpose of this assessment is to enable organizations and decision-makers to make well-informed choices and adopt approaches that uphold both low-carbon and sustainable cold chain logistics frameworks.

Table 8: Contributions

Theoretical Significance	Practical Significance
It aids in understanding the operating mechanism, optimizing energy consumption, and reducing greenhouse gas emissions to achieve low-carbon sustainable development. In practice, specific cases and data need to be integrated to carry out system dynamics	Provision of scientific basis for evaluating and optimizing low-carbon cold chain logistics in the Greater Bay Area.

modelling and analysis, in order to guide practical operations and decision-making.	
Exploration of the factors and mechanisms influencing the efficiency of low-carbon cold chain logistics.	Guidance for the development of low-carbon cold chain logistics, promoting energy utilization efficiency, and reducing greenhouse gas emissions.
	Enhancement of the quality of cold chain logistics services, improving the storage, transportation, and sales of agricultural products.

Findings

The implementation of low-carbon cold chain logistics strategies has resulted in significant reductions in greenhouse gas emissions, improved operational efficiency and sustainable development, with positive changes in regional economies and the environment. There are tremendous opportunities for businesses, policymakers and society to further promote sustainable development and realize a greener, more efficient logistics system.

Discussion and Conclusion

The effectiveness and performance of this logistics can be evaluated by examining key indicators such as energy sources, technologies, emission reduction measures, and environmental implications. To reduce reliance on fossil fuels and carbon footprints, it is crucial to prioritize initiatives that enhance energy efficiency and utilize renewable energy sources.

Integrating technological advancements, such as smart temperature control systems and big data analytics, significantly improves the efficiency and effectiveness of cold chain logistics. To reduce direct emissions and minimize environmental impacts, it is essential to implement measures that control emissions, optimize transportation routes, and adopt low-carbon fuels. Proper waste management, water conservation, and biodiversity preservation also contribute significantly to the sustainability of cold chain logistics.

By carefully considering and addressing these indicators, organizations and decision-makers can make informed choices to support low-carbon and sustainable cold chain logistics systems. This approach will lead to a reduction in greenhouse gas emissions, promote sustainable development, and mitigate environmental impacts associated with the cold chain logistics process.

Theoretical Implications

The deepening of low-carbon logistics theory:

This thesis verifies the applicability of low-carbon logistics theory in the field of cold chain logistics through empirical research. Low-carbon logistics theory emphasizes the reduction of energy consumption and carbon emission in the logistics process, while cold chain logistics is more challenging in energy utilization and carbon emission control due to its special characteristics. The findings of this thesis not only provide new practical cases for the low-carbon logistics theory, but also enrich its theoretical connotation and provide a reference for its application in other fields.

Expansion of sustainable development theory:

The theory of sustainable development emphasizes the coordinated development among economy, society and environment. In the field of cold chain logistics, realizing sustainable development means reducing energy consumption and carbon emissions while ensuring food safety and logistics efficiency. Through case studies, this thesis demonstrates how to achieve the goal of sustainable development in the field of cold chain logistics through technological innovation and management optimization. This result not only expands the application scope of sustainable development theory, but also provides ideas and methods for its application in more fields.

Innovation of greenhouse gas emission reduction mechanism:

Greenhouse gas emission reduction is an important means of global response to climate change. The research of this thesis shows that greenhouse gas emissions can be effectively reduced through the development of low-carbon cold chain logistics. This result not only provides a new way for GHG emission reduction, but also promotes the innovation of related technologies and policies. For example, carbon emissions from cold chain logistics can be significantly reduced by promoting new energy transportation means, optimizing transportation routes, and adopting low-carbon packaging materials, etc. Meanwhile, governmental policy support and guidance are also of great significance in promoting the development of low-carbon cold chain logistics.

Practical and Social Implications

The development of low-carbon cold chain logistics is of great practical significance. It can not only promote the green transformation and sustainable development of the cold chain logistics industry, but also promote energy conservation, emission reduction and environmental protection, enhance the quality of cold chain logistics services, promote regional economic development, and enhance the social responsibility and image of enterprises. Therefore, we should actively promote and apply the concept and technology of low-carbon cold chain logistics, and jointly contribute to building a green, low-carbon and sustainable future.

Limitations and Suggestions for Future Research

Geographical limitations

This study has only conducted a case study for the Greater Bay Area, which may not fully reflect the current status and challenges in the development of low-carbon cold chain logistics globally or in the wider region. Geographical differences may lead to differences in cold chain logistics strategies and technology choices in different regions, and therefore the findings of this study may not be directly applicable to other regions.

Dynamics of technological progress

Cold chain logistics technology is constantly advancing and new technologies and management strategies are emerging, and this study may not be able to cover all the latest technological developments and applications.

The dynamic nature of technological advances may result in the conclusions and recommendations of this study being outdated or no longer applicable in some areas.

Focus on the latest advances in technological innovation

Future research could focus more on the latest progress in technological innovation, including the development and application of new cold chain logistics technologies.

By studying the latest technological innovations and application cases, it can provide more forward-looking guidance for the development of low-carbon cold chain logistics.

Strengthening Policy Research and Formulation

Future research can strengthen the exploration of policy research and formulation, including the role of policy in promoting the development of low-carbon cold chain logistics and its constraints.

By studying the impact and mechanism of policies on low-carbon cold chain logistics, it can provide a more scientific basis and reference for policy formulation.

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Guangdong Provincial Philosophy and Social Sciences: Research on the Dynamic Mechanism, Standard System and Policy Design of Green Supply Chain under Dual Carbon Target (GD24CGL26)、Guangdong Province Philosophy and Social Science Planning Youth Project (GD23YGL28)
School-level Research Project of Guangzhou College of Technology and Business: Research on Cold Chain Logistics Efficiency Measurement and Influence Mechanism in GBA under Low Carbon Perspective (KYYB202328); Provincial Research Cultivation Project: Research on the Coupling and Synergy of Digital Economy and Intelligent Cold Chain Logistics(CCL) High Quality Development in GBA (GLXYKYPY002)
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