

Smart "Last-Mile" Delivery of Fresh Cold Chain based on Customer Green Preference

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Abstract

With the acceleration of urbanization and the vigorous development of fresh e-commerce, against the backdrop of the "Dual Carbon" goals, the "last-mile" delivery of the fresh cold chain has become a critical link in the logistics field. Based on customer green preferences, this paper analyzes the current situation and pain points of fresh cold chain delivery from perspectives such as cold chain logistics, and discusses the construction and optimization strategies of smart delivery models. The research provides a theoretical basis for fresh e-commerce enterprises to optimize delivery services and offers references for policymakers to promote the green and intelligent development of "last-mile" fresh cold chain delivery, supporting the high-quality development of the logistics industry.

Keywords

Circular Economy; Green Logistics; Fresh Cold Chain Logistics; Last-Mile Delivery.

1. Introduction

The booming e-commerce industry has driven the growth of fresh e-commerce. However, the highly reliant cold chain logistics face pain points: the average loss rate of fresh agricultural products in China is 25%-30%. In 2024, the comprehensive cost of long-distance transportation and storage for agricultural products in some regions of China accounted for 45.6% of the selling price, causing the gross profit margin of some fresh brands to drop by 10-15 percentage points. According to statistics, the cost of China's fresh cold chain logistics has grown consecutively from 2020 to 2024 (see Figure 1).

Statistics on the Scale of China's Fresh Cold Chain Logistics Costs 2020-2024



Figure 1. Data Chart of Cost Scale in the Fresh Produce Cold Chain Logistics Industry

Under the "Dual Carbon" goals, the logistics sector requires a green transformation. The "14th Five-Year Plan for Modern Logistics Development" calls for accelerating cold chain infrastructure construction and improving efficiency while reducing carbon emissions. Meanwhile, consumers' awareness of green consumption is awakening, and their preference for low-carbon delivery is strengthening. Concurrently, high consumer demands for fresh product quality and increasingly stringent carbon emission regulations under global carbon neutrality jointly drive the fresh cold chain logistics towards greening and efficiency, also providing space for research on "last-mile" smart delivery.

2. Domestic and International Research Status

2.1. International Research Progress on Smart Cold Chain Delivery

With the continuous development of intelligent information technology, significant progress has been made internationally in smart cold chain delivery. For example, scholars like Gajda M (2025) believe that fresh products should be efficiently utilized throughout the entire delivery process by upgrading transportation and packaging equipment, formulating strict temperature measurement requirements, and implementing real-time monitoring and anomaly alerts for the entire process to prevent accidents[1]. Experts like Yang (2016) posit that food quality depends on delivery time. By focusing on market demand and farmers' production capacity, they constructed a multi-objective delivery optimization model including delivery cost, carbon footprint, and delivery time to optimize the fresh food delivery network[2]. Furthermore, researchers like Letnik,T(2020) combined the Open Vehicle Routing Problem with gravitational simulation local search to reduce transportation costs for all vehicles in the fleet[3].

2.2. Current Status of Domestic Green Logistics Practices

Domestic green logistics practices are also advancing. In recent years, guided by policies and changing market demands, more enterprises have begun to emphasize the development of green logistics. Experts like Wang Yijie (2025) note that some logistics companies have reduced carbon emissions by adopting new energy delivery vehicles and optimizing delivery routes[4]. Simultaneously, the government is actively promoting the formulation and implementation of green logistics standards, providing policy support for green logistics development. Additionally, domestic scholars have also researched the optimization of fresh cold chain delivery paths. Scholars like Wang Sujie (2024) constructed a fresh product delivery path optimization model based on time-varying traffic conditions, aiming to minimize total economic cost[5]. To address the uncertainty of return flow, they designed a multi-objective delivery network model for fresh products, aiming to minimize delivery costs and carbon emissions while maximizing social benefits.

2.3. Research Review and Innovation Space

Although certain achievements have been made domestically and internationally in smart cold chain delivery and green logistics, some shortcomings remain. For instance, most existing research focuses on technology application and optimization model development, with relatively in-depth studies on consumer green preferences being scarce. Furthermore, comprehensive evaluations of smart delivery models and long-term follow-up research on their implementation effects need strengthening. Therefore, future research can further explore the influencing factors and classification of consumer green preferences, and how to better meet these preferences through smart delivery models, thereby promoting the green and intelligent development of "last-mile" fresh cold chain delivery.

3. Core Concepts and Theoretical Basis of Fresh Cold Chain Green Preference

3.1. Green Preference Behavior Theory

Green preference behavior theory primarily studies consumers' preference for environmentally friendly products and services during the purchase and use process. Consumers' green preferences are influenced by various factors, including personal values, social influence, and product characteristics. In fresh cold chain delivery, consumers' green preferences are reflected not only in the requirements for the freshness and quality of fresh products but also in their concern for the environmental impact of the delivery method. The stronger the user's sense of autonomy and the more services obtained through diversification, the higher their perceived value, thereby increasing their willingness to use[6].

3.2. Types of Customer Green Preferences

In the green development process of fresh cold chain logistics, understanding the types of customer green preferences is crucial, as it provides a basis for enterprises to formulate precise green delivery strategies. Customer green preferences can be broadly divided into the following three main types:

Price-sensitive customers are mostly middle- or lower-income earners. They are pragmatic consumers who focus on cost-effectiveness and are willing to sacrifice some packaging or timeliness for lower prices. They favor services like "packaging-free delivery" and "crowd-sourced delivery". Data shows that the proportion of fresh e-commerce users opting for packaging-free delivery rose from 8% in 2020 to 15% in 2024, with an increase of over 10 percentage points in third- and fourth-tier cities. Mass delivery order volume has seen an average annual growth of 20% over the past five years.

Environment-first customers have strong environmental awareness and a high sense of social responsibility, and their income and education levels are relatively high. They are willing to pay a premium for green delivery. They focus on the environmental impact of delivery and prefer services like "carbon-neutral certified delivery" and "real-time carbon footprint tracking." A 2024 survey indicated that over 70% of high-end fresh product consumers are willing to pay a 10%-20% premium for services delivered exclusively by electric vehicles with real-time carbon footprint tracking.

Convenience-oriented customers are mainly young office workers and homemakers with fast-paced lives. They prioritize delivery convenience and flexibility, preferring options like "nighttime low-speed delivery" and "community self-pickup lockers." In some cities, nighttime low-speed delivery has reduced energy consumption for fresh delivery by 15%-20%. After a certain fresh e-commerce platform deployed community self-pickup lockers, user satisfaction increased by 20 percentage points, and order volume grew by 30%[7].

3.3. Theory of "Last-Mile" Delivery in Fresh Cold Chain

"Last-mile" delivery in the fresh cold chain refers to the logistics process of transporting fresh products from the nearest storage point (e.g., a front warehouse) to the consumer's hands under strict low-temperature control, accurately and efficiently. It is the final critical link in the entire cold chain logistics system, directly facing consumers and significantly impacting product quality and consumer experience. It involves delivering fresh products from nearby distribution stations or front warehouses to consumers in a low-temperature environment.

The "last-mile" fresh cold chain has the following characteristics: First, strong timeliness, as fresh products are perishable and need to be delivered within a short time frame. Second, strict temperature requirements, as different fresh products have varying temperature needs, requiring precise control of the cold chain temperature. Third, high delivery costs, as the

particularity of fresh products necessitates more equipment and manpower investment for cold chain delivery[8].

4. Current Status of "Last-Mile" Fresh Cold Chain Delivery

4.1. Analysis of the Green Delivery Environment for Fresh Cold Chain

In recent years, with the proposal of global carbon neutrality goals, countries have strengthened regulations on logistics carbon emissions. In fresh cold chain logistics, the use of traditional fuel delivery vehicles is being restricted, prompting enterprises to accelerate the transition to new energy delivery vehicles. According to relevant data, over the past five years, China has highly prioritized the green development of the cold chain logistics industry. The "14th Five-Year Plan for Cold Chain Logistics Development" issued by the General Office of the State Council in 2021 explicitly proposed that by 2025, a cold chain logistics network connecting production areas and sales destinations, covering urban and rural areas, and linking domestic and international markets will be initially formed. It emphasized the important position of green development in cold chain logistics. A series of supporting policies have been introduced. Guided by these policies, the market share of new energy cold chain delivery vehicles in China increased from less than 5% in 2020 to about 15% in 2024, showing rapid growth.

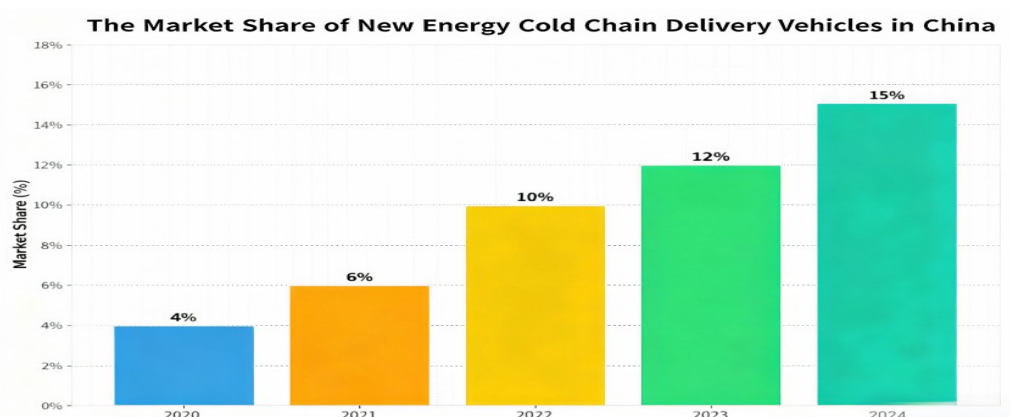


Figure 2. Data of Market Share in the New Energy Cold Chain Distribution Vehicle Industry

Consumer attention to green environmental protection is continuously increasing, which is also reflected in the choice of fresh cold chain logistics delivery services. A 2025 survey showed that 68% of young consumers are willing to pay a 5%-15% premium for green delivery. This data indicates that consumer acceptance and willingness to pay for green delivery are constantly increasing. Green delivery can not only reduce carbon emissions during transportation but also ensure that fresh products are delivered with better quality through more efficient delivery methods and advanced preservation technologies. Statistics show that the user repurchase rate of fresh e-commerce platforms offering green cold chain delivery services is 10-15 percentage points higher than that of ordinary platforms, fully demonstrating consumer recognition and preference for green delivery services[9].

With continuous advancements in technology, new energy delivery vehicles, drone/robot end-point delivery, and AI path optimization techniques are being scaled up for use in the fresh produce cold chain logistics industry. The battery life of new energy resources distribution vehicles is improved, and the charging facilities are improved. The fast charging technology shortens the charging time from several hours to 1-2 hours to improve the efficiency of distribution. The drone can shorten the end distribution time during traffic

congestion, and the robot can complete warehouse sorting and handling 24 hours without interruption, with high accuracy. The AI path optimization technology analyzes multiple types of data in real time to plan the optimal route, resulting in an average reduction of 10-15% in mileage, 15-20% in transportation time, and a decrease in energy consumption and carbon emissions.

4.2. Problems in "Last-Mile" Fresh Cold Chain Delivery

In the process of promoting green distribution, the promotion of new energy resources cold chain distribution vehicles is hindered by the expectations of environmental protection, but the purchase cost is high, 30% -50% higher than the traditional fuel vehicles, such as 4.2 tons of car price of 200,000 -25 million yuan. Fresh cold chain enterprises are thinly profitable, and SMEs are difficult to bear, and their last-mile distribution accounted for less than 10% by the end of 2024.

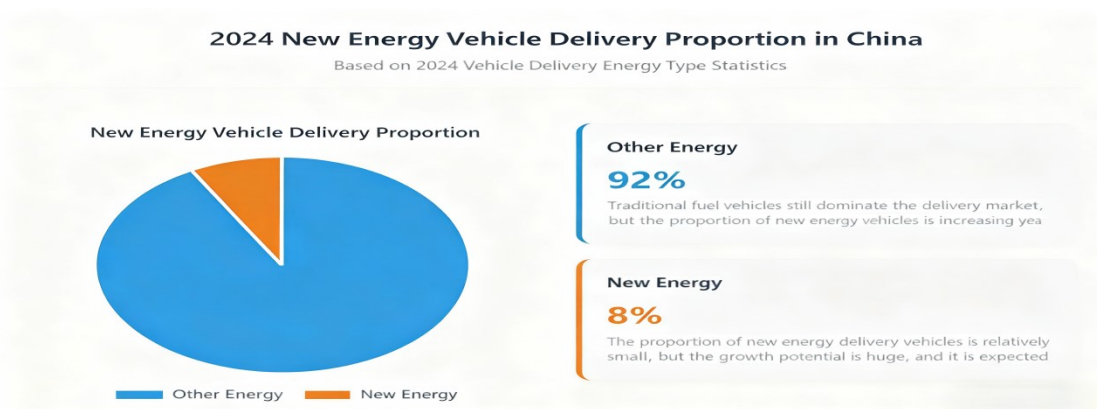


Figure 3. Data Chart of Market Share in the New Energy Vehicle Delivery Industry

New energy cold chain vehicles face numerous charging facility challenges. They rely on charging infrastructure, but the layout is uneven and insufficient: while there are many charging piles in urban core areas, queues are common; coverage in suburbs and rural areas is low or even non-existent. In 2023, the ratio of public charging piles to new energy vehicles in China was 1:7, reaching over 1:15 in urban-rural fringe areas, causing range anxiety and affecting delivery efficiency.

In summary, driven by policy, consumer demand, and technology, significant progress has been made in green delivery for the fresh cold chain. However, challenges such as the high cost of new energy vehicles, inadequate charging facilities, and insufficient management and supervision remain. Future efforts require collaboration between government, enterprises, and society to achieve sustainable industry development.

5. Optimization Strategies for the "Last-Mile" Smart Delivery Model

5.1. Optimizing Smart Logistics Delivery Paths and Resource Allocation

In "last-mile" fresh cold chain delivery, the choice of delivery path directly affects delivery efficiency, cost, and the quality of fresh products. Unreasonable path planning may lead to prolonged delivery times, increasing the risk of fresh product spoilage, while also increasing transportation costs and carbon emissions. Therefore, based on customer green preferences, the following delivery path optimization strategies can be adopted:

5.1.1. Application of Dynamic Route Adjustment based on Multi-Objective Factor Models and Delivery Optimization

During the delivery process, it is necessary to comprehensively consider multiple objective factors such as delivery cost, delivery time, and carbon emissions. Due to real-time changes in traffic conditions and temporary adjustments in customer demands, dynamic path adjustment capability is required. By recalculating the optimal path and sending the new path information to the delivery personnel in real time[10].For example, JD Fresh, during its delivery process, utilizes its self-developed intelligent target delivery system algorithm to achieve dynamic adjustment of delivery paths, improving delivery efficiency and customer satisfaction.

Its core formula is:

Minimize Total Delivery Cost (Min C)

$$C = \sum_{i=1}^n \sum_{j=1}^m c_{ij} x_{ij} + \sum_{k=1}^p f_k y_k + \sum_{i=1}^n h_i q_i$$

Minimize Total Delivery Time (Min T)

$$T = \max_{k=1}^p \left(\sum_{i=1}^n \sum_{j=1}^m \frac{d_{ij}}{v_k} x_{ij} + t_{k0} + \sum_{j=1}^m t_{kj} \right)$$

Variable Explanation:

$c_{\{ij\}}$:Unit transportation cost from distribution center i to customer j;

$x_{\{ij\}}$:Delivery volume from distribution center i to customer j;

f_k :Fixed usage cost of the k-th delivery vehicle;

y_k : 0-1 variable ($y_k=1$ indicates using the k-th vehicle, $y_k=0$ otherwise);

h_i : Inventory holding cost per unit goods at distribution center i;

q_i : Remaining inventory quantity at distribution center i.

$d_{\{ij\}}$:Transportation distance from distribution center i to customer j;

v_k : Average speed of the k-th delivery vehicle;

$t_{\{k0\}}$: Preparation time before departure for the k-th vehicle;

$t_{\{k j\}}$:Unloading time of the k-th vehicle at customer j.

5.1.2. Path Planning based on Real-Time Traffic Data and Customer Location Distribution

Utilize big data technology to collect real-time traffic information, including road congestion status, traffic accidents, temporary traffic control measures, etc. Combine this with customer location distribution data and use intelligent algorithms to plan the optimal delivery path. For instance, by obtaining real-time traffic data through APIs provided by Amap, Baidu Maps, etc., when encountering road congestion, the algorithm automatically adjusts the route, selecting roads with less traffic flow to reduce delivery time and fuel consumption. Taking a fresh delivery company as an example, after applying real-time traffic data for path planning, the average delivery time per trip was shortened by 15-20 minutes, and fuel consumption was reduced by 10%-15%[11].

5.1.3. Precise Demand Prediction and Optimal Path Resource Allocation Using Big Data Technology

The application of big data technology in fresh cold chain delivery is mainly reflected in the precise prediction of delivery demand and the optimal allocation of delivery resources. In terms of delivery resource allocation, big data technology can analyze data on delivery routes, delivery times, and delivery volumes. Enterprises can determine the optimal delivery plan, improve vehicle load factor, reduce empty mileage, and thus lower transportation costs and

energy consumption[12]. A certain cold chain logistics enterprise, after optimizing delivery resource allocation through big data analysis, increased vehicle load factor by 20% and reduced empty mileage by 15%, effectively improving delivery efficiency, reducing operational costs, and practicing the concept of green delivery. Simultaneously, big data technology can also be used to monitor and evaluate delivery service quality. By collecting consumer feedback data, delivery timeliness data, product damage rate data, etc., enterprises can promptly identify problems in the delivery process and take targeted measures for improvement, enhancing customer satisfaction.

In summary, empowering fresh cold chain delivery with smart logistics technology, optimizing delivery paths, and applying technologies like block-chain, AI, and big data bring new opportunities. They enhance efficiency, ensure quality, optimize resources, and promote green delivery, laying the foundation for sustainable industry development. Future integration of technological innovations will provide higher quality, more efficient, and greener services.

5.2. Promoting Delivery Carrier Upgrades and Demand-Side Collaborative Management

The collaborative management between the green performance of delivery carriers and the demand side is the core to balancing efficiency, cost, and environmental protection goals in the "last-mile" delivery of fresh produce cold chains. These two parties need to form a linkage to match customers' green preferences, and it is recommended to advance development from the following specific dimensions:

5.2.1. Innovative Upgrading and Green Transformation of Delivery Vehicles and Equipment

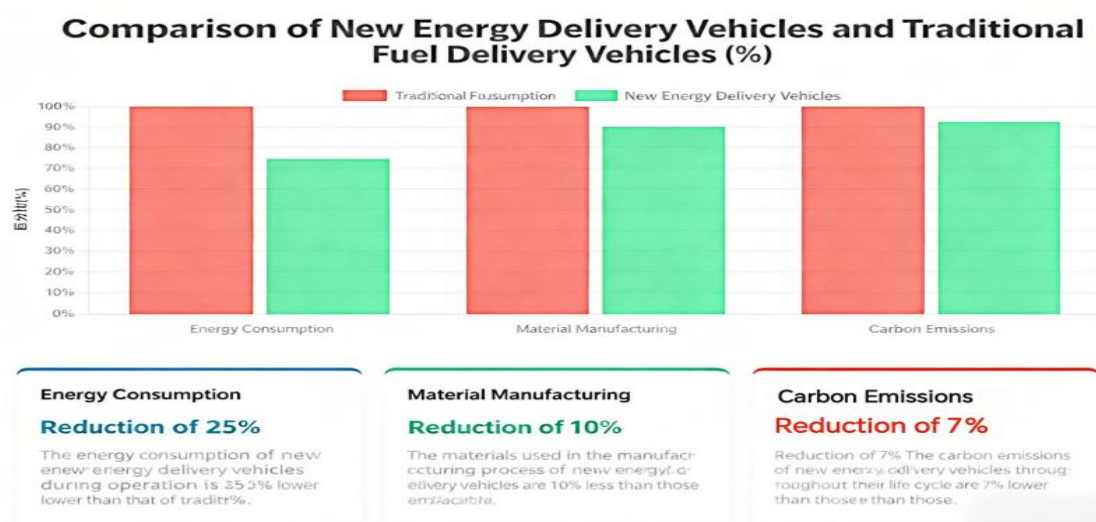


Figure 4. Data Comparison Chart of New Energy Vehicles vs. Traditional Fuel Vehicles

Leverage contemporary scientific technologies like energy-saving power sources to promote the large-scale application of new energy vehicles. Prioritize the use of pure electric, hydrogen fuel cell, and other new energy delivery vehicles, which can reduce carbon emissions by 40%-60% compared to traditional fuel vehicles and have lower operating costs. Promote energy efficiency improvements in cold chain equipment. Adopt equipment such as vacuum insulation panels and intelligent refrigeration systems in vehicles and delivery boxes to reduce cooling loss and energy waste[13]. Related practices show that such equipment can reduce energy consumption in cold chain delivery by 15%-25%. Adopt lightweight vehicle design. Using lightweight materials like aluminum alloys and carbon fiber to replace

traditional steel, combined with aerodynamic optimization, can reduce vehicle weight by 20%-30%. For every 10% reduction in vehicle weight, fuel consumption and carbon emissions can be reduced by 6%-8%.

5.2.2. Improving and Adjusting Collaborative Management between the Demand Side and Delivery

Optimize adjustments based on delivery time and related basic elements. Offer flexible time windows (e.g., morning, afternoon, evening) for customers to choose from, and conduct centralized delivery based on order volume within each window to reduce vehicle idle trips and delivery frequency. Implement bidirectional development integrating demand forecasting and inventory. Based on big data and machine learning technologies, integrate historical orders, user behavior, and other real-time predictive data to optimize inventory layout and plan delivery schedules in advance, reducing energy consumption and carbon emissions from unnecessary delivery. Establish incentive mechanisms for customer green behaviors. Provide price discounts, points rewards, and other incentives to customers who choose self-pickup, off-peak delivery, or green packaging. This stimulates corresponding customer demand, guides customer participation in green delivery, alleviates peak delivery pressure, and reduces carbon emissions[14].

6. Conclusion

Based on customers' green preferences, this paper systematically analyzes the practical challenges and optimization paths of the "last-mile" delivery in the fresh produce cold chain. The research shows that under the guidance of the "dual carbon" goals and policy impetus, smart logistics technologies such as AI route planning, big data demand forecasting, and the application of new energy vehicles have become key means to improve delivery efficiency and reduce carbon emissions.

Meanwhile, identifying and responding to the green preferences of different types of customers-such as price-sensitive, environmental protection-prioritizing, and convenience-oriented customers-helps enterprises implement targeted strategies and enhance service adaptability. However, there are still practical constraints such as high purchase costs of new energy vehicles and insufficient charging facilities.

In the future, it is necessary to continuously promote the optimization of delivery routes, the green transformation of vehicles, and the collaborative management of the demand side through government-enterprise collaboration, so as to build an efficient, low-carbon, and intelligent end-to-end cold chain delivery system. This will realize the organic integration of economic, social, and environmental benefits, and contribute to the high-quality and sustainable development of the fresh produce cold chain logistics.

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