

Article

Research on Fresh Supply Chain Logistics Cooperation Strategy from the Perspective of Government Subsidy

Wei Yang ^{1,*} and Jiaxin Liu ²¹ Institute of Management and Decision, Shanxi University, Taiyuan 030000, China² School of Economics and Management, Shanxi University, Taiyuan 030000, China; 18536837151@163.com

* Correspondence: yangwei@sxu.edu.cn

Abstract

Background: Within the fresh food e-commerce supply chain, government effort-contingent subsidies and logistics partnerships critically impact order pricing, preservation, and profitability. This study aims to investigate how different logistics cooperation modes interact with effort-contingent subsidies to optimize supply chain performance under preservation effort and random demand. **Methods:** We developed three Stackelberg game models: an independent logistics model, a logistics-supplier cooperation model without subsidies and a logistics-supplier cooperative model with government effort-contingent subsidies. Equilibrium strategies were derived theoretically and analyzed through numerical simulations to examine preservation efforts and pricing. **Results:** The findings show that logistics cooperation combined with effort-contingent subsidies not only optimizes the decision-making behaviors, but also effectively shares preservation costs and mitigates double marginalization. This synergy incentivizes higher preservation efforts and lowers wholesale prices, ultimately reducing retail prices and expanding market demand. Furthermore, the analysis reveals that excessively optimistic demand forecasts (over-ordering) sharply increase systemic costs, causing a reverse drop in actual demand. **Conclusions:** Government subsidies are an effective macro-policy tool for alleviating cold-chain costs when integrated with logistics cooperation. To build a sustainable supply chain, e-commerce platforms must adopt prudent ordering strategies, while policymakers should structurally design subsidies to incentivize preservation investments rather than purely subsidizing profits.

Keywords: government subsidies; logistics partnerships; fresh food supply chain; Stackelberg game



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1. Introduction

As an important pillar of people's daily consumption, the fresh food e-commerce industry has a market size of hundreds of billions of dollars. As an important pillar of people's daily consumption, the fresh food e-commerce industry has experienced exponential growth globally, driven by shifting consumer habits and the rapid maturation of digital retail infrastructure. However, despite this immense market potential, the industry continues to grapple with severe logistical constraints. Fresh food e-commerce, as an important sub-sector of retail e-commerce, focuses on easily perishable products such as vegetables, fruits, aquatic products, meat, poultry and eggs. It conducts online transactions through internet platforms and delivers the products to consumers by relying on the logistics and cold chain systems of e-commerce, including warehouse and distribution centers, long-distance cold chain, and end-point immediate delivery. Alternatively, it completes

deliveries through various fulfillment scenarios such as in-store pickup, home delivery, and community group buying. At present, the industry mainly exhibits a situation where multiple models coexist, including the O2O model, front-end warehouse model, “store pick-up + home delivery” integrated model, community group buying model, and periodic purchase model [1].

In the actual operations of fresh food e-commerce and cold chain logistics service providers, the configuration and collaboration relationships of logistics services have given rise to various cooperation models: First, third-party cold chain logistics providers operate independently. Platforms or merchants outsource transportation and delivery to professional service providers such as SF Cold Chain, Deppon Cold Chain, and Cainiao Cold Chain. For example, fresh food merchants on the Tmall platform use SF Cold Chain to handle cross-regional deliveries. Second, suppliers take the lead in logistics, while the e-commerce platform focuses on sales. Enterprises such as Guolian Aquatic Products, CP Group, and Yili rely on their own or entrusted cold storage and distribution systems, opening flagship stores on mainstream e-commerce platforms and having suppliers’ warehouses complete the fulfillment. Third, e-commerce platforms build their own cold chain logistics systems. Dingdong Maicai, Hema, and Meituan Maicai use front-end warehouses and their own distribution networks to undertake the immediate fulfillment of self-operated fresh food. JD also relies on JD Logistics’ cold chain network to provide transportation and delivery services for self-operated fresh food. This model has developed concurrently in various scenarios, reflecting the trade-offs and optimizations made by fresh food e-commerce in terms of timeliness, cost and service quality.

The operation of the fresh food supply chain always faces several practical challenges: Firstly, it must be fast, with low losses, cost control and stable quality, and the entire process must be visible. In practice, as there are more links, coordination becomes difficult. Information among suppliers, warehouses and delivery parties is hard to synchronize, and responses often lag behind. Even a single node being stuck can reduce the freshness. Secondly, the cold chain itself is involved. Transportation is inherently a high-loss stage, and in China, the investment in cold chain construction is large, coverage is uneven, and management standards are changing. Enterprises have to withstand the heavy initial investment while also struggling to ensure stable temperature control throughout the process. These problems are interlinked and directly affect the efficiency and experience of fresh food from the farm to the table. Thirdly, the “last mile” delivery is difficult. Urban traffic congestion, scattered delivery addresses, and customers’ personalized demands for delivery time make the “last mile” delivery a major pain point for fresh food e-commerce. How to ensure timeliness while controlling costs and improving user experience is an urgent problem to be solved. Fourthly, due to the short shelf life, difficulty in storage, and high susceptibility to damage of fresh food products, high-level management is required, which leads to a long supply chain and high loss of fresh food, and ultimately results in low gross profit margins for merchants [2].

According to the ‘14th Five-Year Plan’ for the Development of Modern Logistics issued by the General Office of the State Council of China [3], the logistics development plan will prioritize high-quality development as its key objective. It will concentrate efforts on opening up two bidirectional channels for the transportation of high-quality agricultural products from the production areas to the markets, as well as for the distribution of fresh consumer goods from the markets to the consumption terminals. For fresh food e-commerce, this is not only a policy guideline but also a genuine boost. The logistics system is continuously improving. With the strong promotion of policies, infrastructure is accelerating its implementation, thereby reducing the logistics costs of enterprises and enhancing the stability of services. As a result, the industry has a more reliable foundation

for development, while consumers feel more at ease in terms of experience, which continuously injects impetus into the upgrading of agriculture and rural construction. The social value and economic effect can naturally be demonstrated.

Despite the existing literature on supply chain optimization, a critical research gap remains: most studies focus either on static subsidies or purely on internal supply chain coordination, rarely integrating government subsidies with different logistics cooperation models (e.g., independent vs. cooperative logistics) under stochastic market demand.

It is worth noting the macroeconomic context of government subsidies in this sector. Fundamentally, government subsidies are allocated from the state budget, which is generated through taxes and duties collected from enterprises and citizens. In a broad sense, this mechanism implies that the public is essentially financing the supply chain participants. However, the core rationale for this financial intervention lies in the government's strategic decision to redirect budget funds into a critical sector: food production and agricultural supply chains. Because fresh food is an essential public good, relying solely on the market may lead to underinvestment in cold-chain infrastructure and high food spoilage rates. Therefore, by reallocating public funds to this strategic sector, the government mitigates market failures, ensures the stable supply and safety of fresh food, and ultimately enhances the overall quality of life for its citizens.

To fill the research gap, this study addresses the following core research questions: (1) How do different logistics cooperation models affect preservation efforts and pricing strategies in a fresh food e-commerce supply chain? (2) How does the introduction of government subsidies alter the decision-making behaviors and profitability of supply chain participants?

Accordingly, the primary objective of this study is to comprehensively explore the decision-making mechanism of the fresh food e-commerce supply chain under multiple cooperation models, aiming to achieve coordinated optimization of the overall supply chain benefits. Specifically, this study evaluates the effects of government subsidies and supply chain cooperation models on ordering pricing decisions, product freshness levels, and supply chain profits. By constructing three Stackelberg game models, i.e., an independent logistics model, a logistics-supplier cooperation model without subsidies and a logistics-supplier cooperative model with government subsidies, this research aims to provide theoretical guidance and policy recommendations for promoting the structural optimization and operational efficiency of the fresh food supply chain.

The remainder of this study is organized as follows: Section 2 reviews the related literature and proposes the theoretical research hypotheses. Section 3 outlines the problem description, model assumptions, and constructs the three game-theoretic models under different logistics cooperation and subsidy scenarios. Section 4 conducts a numerical case analysis to simulate and validate the theoretical findings. Section 5 provides a comprehensive discussion, including theoretical implications, practical and policy implications, as well as the limitations of the study. Finally, Section 6 summarizes the main conclusions.

2. Literature Review and Research Hypotheses

In recent years, scholars both at home and abroad have conducted extensive and in-depth research on the fresh food supply chain, and have achieved rich theoretical achievements in areas such as the design of cooperation mechanisms and the impact of government subsidies.

2.1. Fresh Supply Chain

In the research field of fresh food supply chain, Zhao et al. [4] constructed a supply chain model with one manufacturer and two regional retailers, studied quality competition

and coordination of cross-regional fresh supply chains under government supervision, and proposed a cost-sharing contract to achieve Pareto improvement; Ren et al. [5] built a differential game model for a fresh supply chain with a supplier and a retailer, analyzed dynamic optimal decisions under different government subsidy and decision scenarios, and suggested dynamically adjusted government subsidy schemes for preservation initiatives; Xing and Miao [6] studied a two-tier fresh supply chain, constructed centralized and decentralized game models considering consumer information preference, freshness and misrepresentation, and designed a “cost-sharing + benefit-sharing” contract for coordination; Lin et al. [7] took a fresh supply chain with one supplier and one e-commerce enterprise as the research object, built five Stackelberg game models based on information transparency and power structure differences, and analyzed supplier misreporting behavior and its impacts; Yan and Han [8] focused on a two-echelon fresh supply chain, studied multi-period dynamic pricing and coordination through option and wholesale contracts; Li and Zhang [1] explored quality-price iteration strategies for maintaining product freshness in e-commerce, combining theoretical and empirical analysis to provide insights for online retailers to balance quality and pricing; Zhang and An [9] used differential game theory to examine a two-echelon fresh supply chain, compared equilibrium strategies under three e-commerce sales modes, and analyzed factors determining preservation technology and product greenness; Xu et al. [10] established a Stackelberg game model for the brand empowerment supply chain of fresh e-commerce platforms, and explored the impact of brand empowerment and risk sharing on decision-making; Yang et al. [11] studied a two-level fresh supply chain with a rural cooperative and a supermarket, proposed game models before and after blockchain investment to solve freshness misreporting, and designed a revenue-cost sharing contract for coordination; Qi et al. [12] investigated a fresh supply chain with a manufacturer, a retailer and a 3PL, and built four models to analyze 3PL misreporting behavior and BCT adoption decisions; He and Yang [13] constructed a decentralized decision model based on supplier altruistic fairness concern for a fresh supply chain with one supplier and one retailer, analyzed pricing decisions, and designed a cost-sharing contract based on altruistic fairness concern to achieve supply chain coordination.

From an international perspective, the operational models of fresh food supply chains vary significantly across regions, which profoundly influences preservation strategies and logistics cooperation. For instance, recent studies on the United States highlight a highly consolidated model driven by retail giants (e.g., Walmart) and capital-intensive, automated cold-chain infrastructure. This system relies on centralized distribution and IoT real-time monitoring to manage perishable food at scale, making logistics highly standardized but vulnerable to extreme weather and supply shocks [2,14]. Conversely, in Europe, particularly in Spain—a major agricultural hub—the fresh supply chain is structurally different, heavily driven by agricultural cooperatives. According to 2023 and 2024 research, the Spanish cooperative model plays a critical role in mitigating opportunism in the supply chain. It relies on highly collaborative, decentralized farmer networks to share preservation knowledge and cold-chain costs, focusing on high-quality and agile logistics rather than sheer capital scale [15]. Comparisons between these recent international practices highlight that while the U.S. model excels in standardized cold-chain capacity, the Spanish model demonstrates the resilience of cooperative networks. In the context of China’s fresh e-commerce, integrating the cooperative logic (similar to Spain) with large-scale logistics investments (similar to the U.S.) under government effort-contingent subsidies presents a highly relevant research avenue.

2.2. Government Subsidies and Supply Chain Coordination

In terms of government subsidies and supply chain coordination, Zhang et al. [16] studied a dual-channel fresh agricultural product supply chain composed of a farmer and a retailer, compared optimal solutions with and without government subsidies for refrigerated storage facilities, and proposed a revenue and cost-sharing contract to coordinate the supply chain; Hu et al. [17] explored the integration of blockchain-based food traceability systems, constructed a tripartite evolutionary game model, and analyzed how government subsidies promote system evolution and supply chain coordination; Zhang et al. [18] introduced government unit product subsidies into low-carbon fresh produce supply chains, and used graph model-based conflict analysis and a three-stage game model to determine subsidy objects and provide decision suggestions; Qin et al. [19] investigated the impact of various government subsidies on agricultural supply chain decisions under adverse weather by setting centralized and decentralized models; Ren and Hu [20] analyzed low-carbon supply chains with wholesale price constraints, incorporated government low-carbon technology subsidies, and designed a Nash bargaining-based cooperation model to coordinate the supply chain; Ran and Xu [21] designed a revenue-sharing contract for low-carbon supply chains under carbon tax and government subsidies, using Stackelberg game models to verify its coordination effect; Zhang et al. [22] explored a two-stage fresh produce supply chain with multi-transportation modes, finding that government rail transport subsidies increase supply chain participants' profits and that different contracts coordinate decentralized supply chains; Yu et al. [23] studied a two-echelon biomass supply chain, analyzed the impact of government subsidies on corporate social responsibility and supply chain performance, and proposed a revenue and cost-sharing contract for coordination; Song et al. [24] established game models for power battery recycling supply chains under cap-and-trade and recycling subsidies, and explored the moderating effect of fairness concerns on subsidy effectiveness; Li et al. [25] compared two types of government subsidies under cap-and-trade mechanisms, revealing their heterogeneous effects and providing policy suggestions; Chang et al. [26] integrate the ERP mechanism with government tax subsidies to explore the potential synergistic effects between the two; Bian and Zhao [27] using a three-tier supply chain model, this study thoroughly examines the impact of carbon tax subsidies on the profits and decision-making of retailers and the entire supply chain; Sinayi and Rasti-Barzoki [28] under the premise of considering the government's role, conducted a detailed analysis of the dual effects of subsidy policies on supply chain profitability and product sustainability levels; Khosroshahi et al. [29] developed a three-stage logistics model to examine how consumer subsidies influence the government's pursuit of maximizing social welfare; Barman et al. [30] focused on dual-channel supply chain scenarios and examines the impact of government subsidies on decision-making among members; Zhu et al. [31] introduced green sensitivity into the two-tier supply chain model and analyzed the guiding effects of government carbon tax subsidies on consumers and enterprises.

To provide a broader international context, it is important to note that government intervention in the fresh food supply chain is a universal practice, though the subsidy mechanisms vary significantly across countries. In the European Union, financial support is largely channeled through the Common Agricultural Policy (CAP), which provides targeted subsidies to agricultural cooperatives and logistics providers to adopt green logistics, reduce food waste, and enhance short food supply chains (SFSCs) [32]. In the United States, rather than direct retail price subsidies, the government often employs targeted infrastructure grants—such as those distributed by the USDA—to strengthen cold-chain capacities, support local food e-commerce platforms, and build supply chain resilience against disruptions [33]. Meanwhile, in countries experiencing severe labor shortages

like Japan, government subsidies are heavily directed toward logistics service providers and retail platforms for the adoption of smart cold-chain technologies, IoT monitoring, and automated distribution [34]. These international practices demonstrate that whether focusing on sustainability (EU), infrastructural resilience (US), or technological automation (Japan), government financial intervention remains a crucial catalyst for optimizing fresh food supply chains.

2.3. Supply Chain Cooperation Game

In terms of supply chain cooperation and strategic interactions, Dan et al. [35] modeled a multistage game for a fresh produce supply chain to explore the supplier's cooperation mode choice and the platform's information sharing strategy, and designed incentive contracts to improve supply chain performance; Shi and Cheng [36] analyzed four logistics decision models for the agricultural products live streaming e-commerce supply chain using the Stackelberg game approach, found that logistics cooperation can share costs, reduce prices and improve service levels, with reasonable profit distribution being the key to successful cooperation; Anjeza Bekolli et al. [37] focused on decentralized agricultural supply chains with multiple distributors, used cooperative game theory to analyze their cooperation with farmers, and proposed a fair profit distribution method; Wu et al. [38] studied retailers' and e-commerce platforms' logistics service cooperation strategies under paid membership systems, analyzed the impact of membership service quality on contract choices and outcomes, and found the basic-service contract has a win-win interval.

While the aforementioned literature has laid a solid theoretical foundation, an analytical comparison reveals a critical research gap. Most existing game-theoretic models of fresh food supply chains predominantly focus on internal coordination contracts or treat government subsidies as static, one-time exogenous variables. Furthermore, although a few recent studies have explored subsidies, they generally assume a fixed, independent logistics operational structure. Therefore, this study is not simply another mathematical variation of existing Stackelberg models, but rather addresses a structurally distinct economic problem. The fundamental missing link in the current literature is the interplay between the structural choice of the supply chain and the macro-policy intervention under stochastic market demand. By treating the logistics service provider not merely as a passive cost center but as an active strategic partner, this study introduces the cooperation mode as a new research perspective. The theoretical contribution of this study lies in mathematically demonstrating that a government's subsidy strategy is not one-size-fits-all; its effectiveness and policy transmission mechanism are fundamentally bounded and reshaped by the underlying logistics cooperation modes. This provides a novel macro-policy perspective on how public funds should be optimally directed to alleviate the double marginalization effect in fresh food e-commerce.

To analytically demonstrate the novelty of our proposed approach, Table 1 provides a structural comparison between this study and the most relevant existing literature. As illustrated in the table, while previous studies have extensively covered internal coordination contracts or static subsidies under deterministic settings, our research uniquely integrates an effort-contingent subsidy mechanism with distinct logistics cooperation structures under stochastic demand.

Based on this, the marginal contributions of this study include the following aspects: (1) This study innovatively introduces government subsidies and supply chain cooperation simultaneously into the supply chain game model of fresh food, and explores the impact of these two factors on the ordering strategies of fresh food e-commerce and the profits of all parties in the supply chain. (2) Three supply chain game models are designed: the no-subsidy independent model, the no-subsidy logistics-supplier cooperation model, and

the cooperation model with government subsidies. To explore the application status of government subsidies and supply chain cooperation in the fresh food e-commerce supply chain, we use the backward induction method to solve the curves of the impact of preservation efforts, retail prices, market demand, and government subsidies on decision variables and total profits. (3) Through numerical examples, we obtain the optimal ordering quantity of fresh food e-commerce and the optimal profit status of all supply chain participants. The optimal solutions are presented graphically, thereby clearly and intuitively for analyzing the impact of government subsidies and supply chain cooperation on the ordering strategies of fresh food e-commerce, as well as the impact on the profits of all supply chain participants. Finally, based on the obtained conclusions, corresponding policy recommendations are proposed.

Table 1. Comparison of This Study with the Most Relevant Existing Literature.

Authors (References)	Supply Chain Structure	Cooperation Mechanism	Subsidy Type	Treatment of Uncertainty	Decision Variables	Main Contribution
Yan and Han [5]	2-echelon (Supplier, Retailer)	Cost-sharing contract	None	Deterministic	Pricing, Ordering	Coordinated multi-period dynamic pricing.
Zhang et al. [18]	2-echelon (Supplier, E-commerce)	Option contract	None	Stochastic demand	Ordering, Pricing	Balanced risk allocation under random demand.
Li and Zhang [2]	3-echelon (Supplier, Logistics, Retailer)	Revenue-sharing	Static, lump-sum	Deterministic	Quality, Pricing	Analyzed static subsidy impact on quality iteration.
Bian and Zhao [26]	3-echelon (Supplier, Manufacturer, Retailer)	None (Independent)	Effort-contingent (Carbon tax)	Deterministic	Pricing, Emissions	Examined effort-based subsidies without logistics integration.
This Study	3-echelon (Supplier, Logistics, E-commerce)	Upstream Strategic Alliance ($f_s + r$)	Effort-contingent (Preservation multiplier)	Stochastic demand (ϵ)	Pricing, Ordering (Z), Preservation (η)	Demonstrates how an effort-contingent subsidy interacts with structural logistics cooperation under demand uncertainty to mitigate double marginalization.

2.4. Research Hypotheses

Based on the above literature review and the actual operational challenges of the fresh food supply chain, it is evident that logistics cooperation and government intervention play crucial roles in supply chain optimization. To systematically investigate these mechanisms, this study proposes the following theoretical hypotheses, which will be verified through subsequent Stackelberg game models.

Hypothesis 1. *Compared with the independent model, the logistics-supplier cooperation model can effectively alleviate the double marginalization effect, enhance the preservation effort level of fresh products, lower retail prices, and ultimately improve the total profit of the fresh food supply chain.*

Hypothesis 2. *The logistics cooperation model with government subsidies can further optimize overall supply chain performance. The subsidy mechanism effectively shares preservation costs, deeply incentivizes enterprises to improve preservation efforts, and prompts suppliers to lower wholesale prices, thereby realizing a relative improvement in private profitability for all participating entities.*

Hypothesis 3. *The demand forecast level (inventory factor Z) has a non-linear impact on supply chain decision-making. While a moderately higher demand forecast initially incentivizes preservation efforts to match expected sales, an excessively optimistic demand forecast (over-ordering) will not stimulate infinite demand. Instead, it sharply increases expected excess inventory, marginal losses, and inventory mismatch costs, ultimately degrading the overall profitability of the supply chain.*

3. Problem Description and Basic Assumptions

3.1. Problem Description

Consider a fresh food e-commerce supply chain consisting of a fresh food supplier (f), a logistics service provider (s), and a fresh food e-commerce platform (r). Among them, the fresh food supplier and the fresh food e-commerce platform are completely independent decision-making entities, each aiming to maximize their own profits. In the fresh food e-commerce supply chain, the fresh food supplier, as the upstream, is responsible for the cultivation, breeding and primary processing of fresh food products, and usually holds a dominant position in terms of category resources and production capacity allocation. The fresh food e-commerce platform, as the downstream, determines the order quantity based on demand forecasts and inventory strategies, purchases goods from the supplier, and provides transportation services by the logistics service provider, ultimately selling the products to consumers. In the independent model, the fresh food e-commerce orders logistics services from the logistics service provider; in the cooperative model, the fresh food supplier collaborates with the logistics service provider to provide full temperature-controlled transportation and delivery services from the origin or the supplier's warehouse to the consumers.

In the actual operation of the fresh food supply chain, logistics service providers, as the core hub connecting the production end and the consumption end, exhibit remarkable adaptability and diversity in their operational strategies: they can independently undertake the entire process of warehousing, transportation, temperature control, etc., relying on their own facilities and technical systems; they can also form supply chain alliances with upstream and downstream entities such as fresh food suppliers and e-commerce platforms through contractual connections, information sharing, and resource complementation, thereby optimizing resource allocation efficiency, reducing systemic losses, and enhancing market adaptability. This study focuses on the three models: the independent model of logistics service providers (A), the cooperation model of unsubsidized logistics providers (B), and the cooperation model of logistics service providers with government subsidies (C).

3.2. Model Assumptions

Based on the operation mode of the fresh food e-commerce supply chain, this study abstracts the strategic interaction among fresh food suppliers, logistics service providers and fresh food e-commerce platforms as a sequential logic-based principal-agent game structure. Based on this game framework, a system of three typical operational scenario models is constructed: the independent model without subsidy (A), the model of logistics provider cooperation without subsidy (B), and the model for logistics provider cooperation with government subsidy (C), as well as the optimal decision models for each of these scenarios. By solving the Stackelberg equilibrium solutions under each model, this study analyzes how the government's subsidy intervention and cooperation models affect the ordering strategies, preservation efforts, product pricing strategies and profits of all parties in the fresh food e-commerce supply chain, and reveals the affecting paths of policy tools and organizational collaboration on the fresh food e-commerce supply chain.

In the operation of the fresh food supply chain, the fresh food suppliers set the wholesale price w_f based on the unit production cost m . The fresh food e-commerce platform, considering the market demand elasticity, operating costs and competitive environment, sells the products to consumers at retail prices p . The logistics service provider, as a key link in the quality assurance, exerts an unbounded preservation effort index η ($\eta \geq 0$). Rather than representing a strict percentage of surviving freshness bounded between 0 and 1, η represents the absolute intensity of operational and capital investment in cold chain preservation. This includes measures such as the configuration of advanced cold chain equipment, optimization of transportation time, and regulation of temperature and humidity. The greater the effort η taken by the logistics service provider, the higher the terminal freshness, which subsequently stimulates market demand. The cost function generated by this effort is set as $c(\eta) = \frac{\theta\eta^2}{2}$, which adopts a quadratic increasing form to reflect the economic law that the marginal input cost accelerates to rise as the effort intensity increases. Here, θ is the cost factor of preservation effort, and similar assumptions can be found in Yu et al. [39]. There is a natural decay of freshness during the transportation of fresh food, and the preservation effort of the logistics service provider can inhibit this loss. The greater the effort taken by the logistics service provider, the higher the terminal freshness is, and the two are positively correlated. At the same time, the market demand Q of fresh food is determined by the product price p and the preservation effort η : $Q = D - \alpha p + \beta \eta + \varepsilon$. Parameter D represents the market base size, and α and β respectively reflect the sensitivity coefficients of demand to price and to preservation effort. A random disturbance term ε is introduced to depict the uncertain fluctuations of demand. For random market demand, the order quantity of the fresh food e-commerce is $q_r = D - \alpha p + \beta \eta + Z$, and it is represented by the inventory factor Z as the order level set based on prediction. According to similar assumptions in Shi et al. [40], Xu et al. [41] and Li et al. [42], we define $\Lambda(Z) = \int_m^Z (Z - u)f(u)du$, $\Phi(Z) = \int_Z^n (u - Z)f(u)du$. $\Lambda(Z)$ is the expected value of the order quantity exceeding the actual demand, and is the positive deviation of the predicted demand. $\Phi(Z)$ is the expected value of the actual demand exceeding the order quantity, and is the negative deviation of the predicted demand. In conclusion, the expected value of the sales quantity of fresh food products is $E(\min(Q, q_r)) = (D - \alpha p + \beta \eta + Z - \Lambda(Z))$. In this study, the basic unit transportation cost is deliberately normalized to zero. This is a deliberate simplifying baseline assumption adopted to maintain analytical tractability and strictly isolate the marginal incentives driven by the preservation effort (η) and the cost-sharing subsidy (λ). While introducing an actor-specific unit transportation cost would undoubtedly alter the baseline wholesale margins and absolute profit allocations among entities, this baseline simplification allows us to focus purely on the strategic value of preservation cooperation without unwieldy algebraic expansions.

It is essential to justify the Stackelberg leadership structure adopted in this study, where the fresh food supplier (or the supplier-logistics cooperation enterprise) acts as the leader and the e-commerce platform acts as the follower. While massive e-commerce platforms often exhibit strong market power in general retail, the fresh food sector operates under unique dynamics. In China's current agricultural transformation, upstream premium fresh food suppliers (e.g., large-scale agricultural cooperatives or branded origin suppliers) control the core resources: high-quality agricultural capacity and strict initial preservation capabilities. Furthermore, when suppliers form alliances with logistics providers, they control the capital-intensive cold-chain infrastructure, thereby monopolizing the supply channels of premium fresh produce. Because fresh produce cannot be easily substituted and platforms heavily rely on high-quality origins to attract consumer traffic, the supplier-logistics cooperative dictates the wholesale price and preservation level first. The e-commerce platform subsequently decides its retail price and order quantity

based on these upstream constraints. This supplier-led structure is highly representative of origin-direct-procurement and cooperative-driven supply chains, which are exactly the primary targets of the government subsidies discussed in this study.

The government (G) provides preservation subsidies to the cooperative entities composed of fresh food suppliers and logistics service providers. The e-commerce platform acts as an independent downstream follower. The subsidies are calculated according to the government subsidy coefficient λ . In this study, the government subsidy is modeled as an effort-dependent, cost-sharing multiplier mechanism rather than a fixed lump-sum grant. Specifically, the total subsidy amount fluctuates in direct proportion to the logistics service provider's preservation effort and its associated costs. Through the subsidy coefficient λ , the government responds to the enterprise's operational efforts to achieve policy objectives. The specific meanings of the relevant parameters in the model design are shown in Table 2.

Table 2. Parameter Explanation.

Symbol	Meaning
m	The production cost of products from fresh food suppliers
w_f	The wholesale price of products determined by the fresh produce supplier
w_s	Logistics wholesale price determined by the logistics service provider
η	The efforts of logistics service providers in preserving the freshness of perishable products
D	Fresh product market base size
α	The sensitivity coefficient of market demand to price
p	Retail price determined by fresh e-commerce
β	Sensitivity coefficient of market demand to preservation effort
ε	Random fluctuations in market demand
Q	Market demand, $Q = D - \alpha p + \beta \eta + \varepsilon$
q_r	Order quantity determined by fresh e-commerce
Z	The prediction and ordering levels for random demands in fresh food e-commerce
λ	The government's effort-contingent preservation-cost subsidy coefficient
θ	Preservation effort cost factor

3.3. Supply Chain Logistics Cooperation Model for Fresh Food E-Commerce Under Different Government Subsidies

To explicitly clarify the distinct organizational structures, leadership sequences, cost bearers, and policy targets across the three models, a concise summary is provided in Table 3. Throughout this study, the term “cooperative entity” strictly refers to the upstream alliance between the fresh food supplier and the logistics service provider. The e-commerce platform consistently remains an independent downstream follower.

Table 3. Organizational Structures and Entity Roles Across the Three Models.

Features	Model A (Independent)	Model B (Cooperation, No Subsidy)	Model C (Cooperation, Government Subsidy)
Decision-Makers	Supplier (f), Logistics Provider (s), E-commerce (r)	Supplier-Logistics Cooperative (fs), E-commerce (r)	Supplier-Logistics Cooperative (fs), E-commerce (r)
Leader & Follower	Supplier (Leaders), E-commerce (Follower)	Supplier-Logistics Cooperative (Leader), E-commerce (Follower)	Supplier-Logistics Cooperative (Leader), E-commerce (Follower)
Contractual Relationship	Independent outsourcing	Upstream strategic alliance (integration of f and s)	Upstream strategic alliance (integration of f and s)
Preservation Cost Bearer	Logistics Provider (s)	Supplier-Logistics Cooperative (fs)	Supplier-Logistics Cooperative (fs)
Subsidy Recipient	None	None	Supplier-Logistics Cooperative (fs)
Government Role	None	None	Provides an effort-contingent preservation subsidy to the cooperative (fs)

3.3.1. Independent Model (A)

In an independent model without government subsidies or cooperation, logistics service providers bear the responsibility for transportation and distribution alone. Many members within the fresh food e-commerce supply chain make their own decisions independently. The fresh food suppliers play the role of the primary decision-makers, determining the wholesale price w_f^A based on production costs m ; the logistics service providers are at the intermediate level, determining the logistics wholesale price w_s^A and preservation efforts η^A accordingly. Ultimately, the fresh food e-commerce company acts as the terminal decision-maker, determining the order quantity q_r^A and retail price p^A to maximize profits. This model is shown in Figure 1.

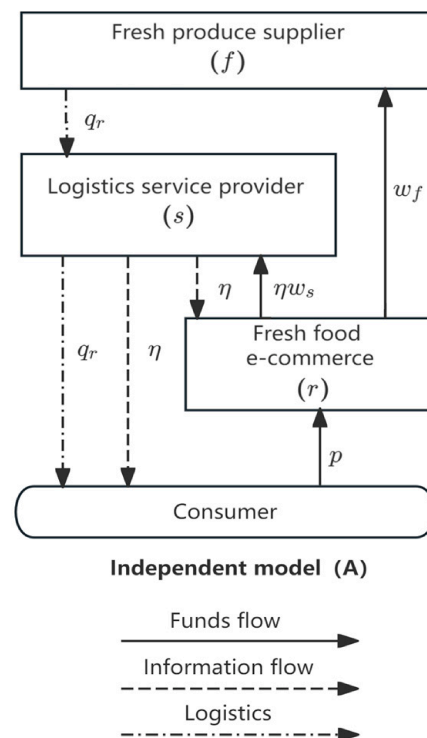


Figure 1. Independent Model (A) System Flow Chart.

Based on the above game relationship, the following decision-making model for the operation of the fresh food e-commerce supply chain can be established. The profits of the fresh food supplier (f), the logistics service provider (s) and the fresh food e-commerce platform (r) are π_f^A , π_s^A and π_r^A . The profit function is as follows:

$$\pi_f^A = w_f^A q_r^A - m q_r^A \quad (1)$$

$$\pi_s^A = \eta^A w_s^A q_r^A - c(\eta^A) \quad (2)$$

$$\pi_r^A = E(\min(Q^A, q_r^A)) p^A - q_r^A (w_f^A + \eta^A w_s^A) \quad (3)$$

Proposition 1. *In the absence of government subsidies, fresh food suppliers, logistics service providers, and fresh food e-commerce platforms act as independent decision-makers and conduct non-cooperative games with their respective optimization goals of maximizing profits. In the equilibrium state, the optimal strategy for the fresh food e-commerce supply chain is as follows:*

(1) The optimal solutions for the wholesale prices of suppliers, logistics service providers, preservation efforts, and e-commerce sales prices are as follows:

$$w_f^{A*} = \frac{m}{2} + \frac{D + Z + \Lambda}{2\alpha} \quad (4)$$

$$w_s^{A*} = \frac{2\theta}{\beta} \quad (5)$$

$$\eta^{A*} = \frac{\beta(D + Z - m\alpha + \Lambda)}{-2\beta^2 + 8\alpha\theta} \quad (6)$$

$$p^{A*} = \frac{\beta^2(D + Z + m\alpha - \Lambda) - \alpha\theta(7D + 7Z + m\alpha - \Lambda)}{2\alpha(\beta^2 - 4\alpha\theta)} \quad (7)$$

(2) The optimal profits for fresh food suppliers, logistics service providers and fresh food e-commerce companies are:

$$\pi_f^{A*} = \frac{\theta(D + Z - m\alpha + \Lambda)^2}{4(-\beta^2 + 4\alpha\theta)} \quad (8)$$

$$\pi_s^{A*} = \frac{\theta(D + Z - m\alpha + \Lambda)^2}{8(-\beta^2 + 4\alpha\theta)} \quad (9)$$

$$\pi_r^{A*} = \frac{\alpha^2(D + Z - m\alpha)^2\theta^2 + (2\beta^4 - 8\alpha\beta^2\theta + \alpha^2\theta^2)\Lambda^2 - 2(D + Z + m\alpha)\beta^4 - 4\alpha(3(D + Z) + m\alpha)\beta^2\theta + \alpha^2(31(D + Z) + m\alpha)\theta^2\Lambda}{4\alpha(\beta^2 - 4\alpha\theta)^2} \quad (10)$$

(3) The optimal solutions for the market demand for fresh products and the order volume of fresh food e-commerce are as follows:

$$Q^{A*} = \frac{2\beta^2(Z - \varepsilon) + \alpha\theta(D - 7Z - m\alpha + 8\varepsilon + \Lambda)}{8\alpha\theta - 2\beta^2} \quad (11)$$

$$q_r^{A*} = \frac{\alpha\theta(D + Z - m\alpha + \Lambda)}{-2\beta^2 + 8\alpha\theta} \quad (12)$$

Proof of Proposition 1. The solution is obtained using backward induction. Calculate the second-order partial derivative of π_r^A with respect to p^A to obtain $\frac{d^2\pi_r^A}{d(p^A)^2} = -2\alpha < 0$ and π_r^A ,

which have a maximum value. Solve for $\frac{d\pi_r^A}{dp^A} = 0$, obtaining $p^A = \frac{D+Z+\beta\eta^A-\Lambda+\alpha w_f^A+\alpha\eta^Aw_s^A}{2\alpha}$.

Substitute p^A into π_s^A to get $\pi_s^A = -\frac{(\eta^A)^2\theta}{2} + \eta^Aw_s^A(D + Z + \beta\eta^A + \frac{1}{2}(-D - Z - \beta\eta^A + \Lambda - \alpha w_f^A - \alpha\eta^Aw_s^A))$. The Hessian matrix with respect to r and t is

$$H_s = \begin{pmatrix} -\alpha(\eta^A)^2 & \frac{1}{2}(D + Z + 2\beta\eta^A + \Lambda - \alpha w_f^A - 4\alpha\eta^Aw_s^A) \\ \frac{1}{2}(D + Z + 2\beta\eta^A + \Lambda - \alpha w_f^A - 4\alpha\eta^Aw_s^A) & -\theta + \beta w_s^A - \alpha(w_s^A)^2 \end{pmatrix}.$$

Under the constraint condition $|H_s| > 0$, the Hessian matrix is a negative definite matrix. π_s^A is a concave function with respect to p^A . Therefore, there exists a unique optimal solution. By combining $\frac{d\pi_s^A}{d\eta^A} = 0$ and $\frac{d\pi_s^A}{dw_s^A} = 0$, we obtain the values of η^A and w_s^A when π_s^A takes the maximum value and substitute them into π_f^A to get

$\pi_f^A = -\frac{\alpha\theta(m-w_f^A)(D+Z+\Lambda-\alpha w_f^A)}{-\beta^2+4\alpha\theta}$. Take the second-order derivative of π_f^A with respect to w_f^A to obtain $\frac{d^2\pi_f^A}{d(w_f^A)^2} = -\frac{2\alpha^2\theta}{-\beta^2+4\alpha\theta} < 0$, and π_f^A has a maximum value. Let $\frac{d\pi_f^A}{dw_f^A} = 0$, and

obtain w_f^{A*} , w_s^{A*} , η^{A*} , and p^{A*} . Substituting the results back to obtain π_f^{A*} , π_s^{A*} , π_r^{A*} , Q^{A*} and q_r^{A*} . $\square$

Inference 1.1. *In the independent mode (A), w_f^{A*} decreases as α increases, unaffected by β and θ . w_s^{A*} is not influenced by α , and it is directly proportional to β and inversely proportional to θ .*

Inference 1.1 indicates that in the independent mode, fresh product suppliers only need to consider the sensitivity of market demand to price when setting prices, without having to take into account the impact of preservation efforts and preservation costs. As the sensitivity of market demand to price increases, since the logistics wholesale price is not affected by this sensitivity, the suppliers need to appropriately lower the wholesale price to maintain the relative stability of market demand. Accordingly, the logistics service providers do not need to consider the issue of market demand, but only need to focus on the impact of preservation efforts and preservation costs, and adopt matching preservation measures based on consumers' demand for freshness, and then, while ensuring profits, set reasonable logistics wholesale prices.

Inference 1.2. *In the independent mode (A), both η^{A*} and p^{A*} are inversely proportional to α and θ , and directly proportional to β .*

Inference 1.2 indicates that in the independent mode, as consumers' sensitivity to price increases, in order to maintain the existing demand, fresh food e-commerce platforms need to make concessions in terms of prices. And price-sensitive groups usually have relatively lower requirements for freshness, so they can achieve a decrease in product prices by reducing the cost of preservation. When the sensitivity of market demand to preservation increases, according to Inference 1.1, logistics service providers need to incur more preservation costs and raise the wholesale prices of logistics, and the product prices of fresh food e-commerce platforms will also increase accordingly. When the preservation cost increases, fresh food e-commerce platforms need to reduce their preservation efforts to lower costs and ensure price stability. However, the decline in freshness leads to a decrease in product competitiveness, and fresh food e-commerce platforms need to offer price discounts and promotions to maintain sales.

Inference 1.3. *In the independent mode (A), w_f^{A*} , η^{A*} , π_f^{A*} and π_s^{A*} are proportional to Λ ; w_s^{A*} does not change with Λ ; π_r^{A*} and p^{A*} increase first and then decrease as Λ increases.*

Inference 1.3 indicates that when the order quantity exceeds the actual demand, the higher the order quantity is, the higher the profits of the fresh food suppliers and logistics service providers are. At the same time, the fresh food suppliers can seize the opportunity to increase the wholesale price. However, excessive ordering may bring risks. As the ordering party, the fresh food e-commerce needs to bear this part of the risk. When the order quantity is within the controllable range, the profits and prices of the fresh food e-commerce will increase accordingly as the order quantity rises. When the order quantity exceeds the safety threshold, the storage costs and the situation of the spoilage of fresh food products will lead to a decrease in the profits and prices of the fresh food e-commerce. Therefore, the fresh food e-commerce needs to maintain a moderate optimism based on rationality regarding market demand, and try to avoid excessive ordering due to blind optimism, which may result in the loss of its own profits.

3.3.2. Unsubsidized Logistics Supplier Cooperation Model (B)

Under the model without government subsidies and with the cooperation between logistics service providers and fresh food suppliers, the logistics service providers and fresh food suppliers form a supplier cooperation enterprise (fs). The fresh food suppliers hold the leading position, while the e-commerce cooperation enterprise follows. This forms a typical two-stage Stackelberg game. The fresh food supplier cooperation enterprise determines the preservation effort η^B and the wholesale price w_{fs}^B of fresh food products based on the production cost m in advance; after observing w_{fs}^B , the fresh food e-commerce determines the retail price p^B of the products and the quantity q_r^B of product orders accordingly. This model is shown in Figure 2.

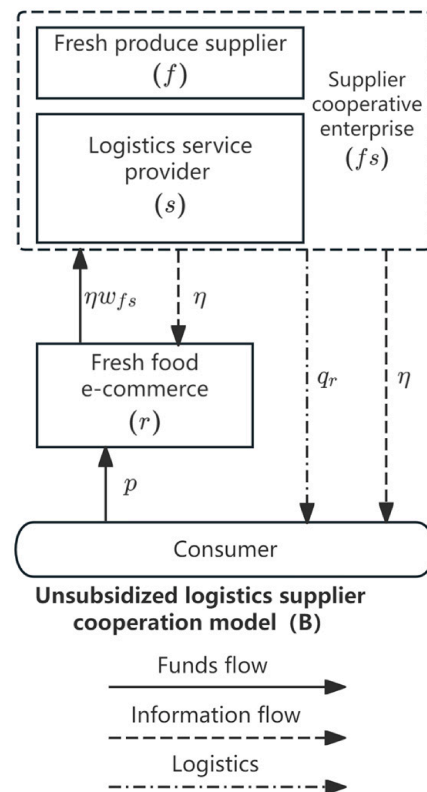


Figure 2. Unsubsidized Logistics Supplier Cooperation Model (B) System Flowchart.

Based on the above game sequence and decision variables, the following logistics supplier cooperation model can be constructed. The profits of the supplier cooperation enterprise (fs) and the e-commerce platform (r) are π_{fs}^B and π_r^B respectively. The profit functions of the two are as follows:

$$\pi_{fs}^B = q_r^B \eta^B (w_{fs}^B - m) - c(\eta^B) \quad (13)$$

$$\pi_r^B = E(\min(Q^B, q_r^B)) p^B - q_r^B \eta^B w_{fs}^B \quad (14)$$

Proposition 2. *In the absence of government subsidies, logistics suppliers, cooperative enterprises and fresh food e-commerce platforms act as independent decision-making entities, each pursuing the maximization of their own interests in making decisions. Under the equilibrium situation, the optimal strategy for the fresh food e-commerce supply chain is as follows:*

(1) The optimal solution for the wholesale prices of logistics supplier cooperative enterprises, the efforts for preservation, and the product prices of fresh food e-commerce are:

$$w_{fs}^{B*} = \frac{m^2\alpha - m\beta - 2\theta}{m\alpha - \beta} \quad (15)$$

$$\eta^{B*} = \frac{(m\alpha - \beta)(D + Z + \Lambda)}{m^2\alpha^2 - 2m\alpha\beta + \beta^2 - 4\alpha\theta} \quad (16)$$

$$p^{B*} = \frac{(D + Z)\alpha(m^2\alpha - m\beta - 3\theta) + (m\alpha\beta - \beta^2 + \alpha\theta)\Lambda}{\alpha((-m\alpha + \beta)^2 - 4\alpha\theta)} \quad (17)$$

(2) The optimal profit solutions for logistics supplier cooperation enterprises and fresh food e-commerce are:

$$\pi_{fs}^{B*} = -\frac{\theta(D + Z + \Lambda)^2}{2(-m\alpha + \beta)^2 - 8\alpha\theta} \quad (18)$$

$$\pi_r^{B*} = \frac{-(D + Z)\alpha(m(m\alpha - \beta)^3 - 4(m\alpha - \beta)(2m\alpha - \beta)\theta + 14\alpha\theta^2)\Lambda + (-m\alpha - \beta)^3\beta + 4\alpha(m\alpha - \beta)\beta\theta + \alpha^2\theta^2)\Lambda^2 + (D + Z)^2\alpha^2\theta^2}{\alpha((-m\alpha + \beta)^2 - 4\alpha\theta)^2} \quad (19)$$

(3) The optimal solutions for both the market demand volume and the order volume of fresh food e-commerce are:

$$Q^{B*} = \frac{2m\alpha\beta(Z - \varepsilon) + \beta^2\varepsilon + m^2\alpha^2(-Z + \varepsilon) - D\alpha\theta + 3Z\alpha\theta - 4\alpha\varepsilon\theta - \alpha\theta\Lambda - Z\beta^2}{(-m\alpha + \beta)^2 - 4\alpha\theta} \quad (20)$$

$$q_r^{B*} = -\frac{\alpha\theta(D + Z + \Lambda)}{(-m\alpha + \beta)^2 - 4\alpha\theta} \quad (21)$$

Proof of Proposition 2. The solution is obtained using backward induction. Compute the second-order partial derivative of π_r^B with respect to p^B to obtain $\frac{d^2\pi_r^B}{d(p^B)^2} = -2\alpha < 0$ and π_r^B , and it is found that there exists a maximum value. Solve for $\frac{d\pi_r^B}{dp^B} = 0$, obtaining $p^B = \frac{D+Z+\beta\eta^B-\Lambda+\alpha\eta^B w_{fs}^B}{2\alpha}$. Substitute p^B into π_{fs}^B to obtain $\pi_{fs}^B = \frac{1}{2}\eta^B(-\eta^B\theta - (m - w_{fs}^B)(D + Z + \beta\eta^B + \Lambda - \alpha\eta^B w_{fs}^B))$, where the Hessian matrix with respect to η^B and w_{fs}^B is $H_{fs} = \begin{pmatrix} -\theta + (m - w_{fs}^B)(-\beta + \alpha w_{fs}^B) & \frac{1}{2}(D + Z + 2m\alpha\eta^B + 2\beta\eta^B + \Lambda - 4\alpha\eta^B w_{fs}^B) \\ \frac{1}{2}(D + Z + 2m\alpha\eta^B + 2\beta\eta^B + \Lambda - 4\alpha\eta^B w_{fs}^B) & -\alpha(\eta^B)^2 \end{pmatrix}$. Under the constraint condition of $|H_{fs}| > 0$, the Hessian matrix is a negative definite matrix, and π_{fs}^B is a concave function with respect to p^B . Therefore, there exists a unique optimal solution. By combining $\frac{d\pi_{fs}^B}{d\eta^B} = 0$ and $\frac{d\pi_{fs}^B}{dw_{fs}^B} = 0$, obtain the values of η^{B*} , η^{B*} , and p^{B*} when π_{fs}^B reaches its maximum. Substituting the results back to obtain π_{fs}^{B*} , π_r^{B*} , Q^{B*} , and q_r^{B*} , and the constraint conditions for $|H_{fs}| > 0$, $\eta^{B*} > 0$, and $\eta^{B*} > 0$ are all $4\alpha\theta - \beta^2 > 0$. $\square$

Inference 2.1. Under the non-subsidized logistics provider cooperation model (B), the wholesale prices w_{fs}^{B*} and β of the logistics provider cooperation enterprises are inversely proportional to each other and directly proportional to θ , and are not affected by α .

Inference 2.1 indicates that in the cooperative model of logistics suppliers, since they do not directly interact with consumers, the wholesale prices of the cooperative enterprises are not affected by the consumers' price sensitivity. When the sensitivity of market demand to the effort of preservation increases, in order to stabilize the market demand, the cooperative enterprises can adopt the method of lowering the wholesale prices and increasing the order quantity within a short period of time. When the preservation cost factor rises, the preservation costs of the cooperative enterprises will also increase. To ensure that the enterprise's profits are not damaged, the wholesale prices should be raised simultaneously. Therefore, the logistics supplier cooperative enterprises should set the wholesale prices based on logistics and product freshness.

Inference 2.2. *Under the no-subsidy logistics provider cooperation model (B), the product price p^{B*} and the preservation effort η^{B*} are inversely proportional to α and θ , and directly proportional to β .*

Inference 2.2 indicates that under the cooperative model of logistics suppliers, when the influence of market demand on prices increases, appropriately lowering the product price becomes a necessary measure to maintain market share. Similarly, when the cost of preservation increases, in order to ensure the overall profit margin, the cooperating enterprises can reduce the level of preservation efforts. When the sensitivity coefficient of market demand to preservation efforts rises, the cooperating enterprises can moderately offer discounts while adjusting the preservation efforts reasonably, thereby enhancing market competitiveness, achieving a balance between cost control and meeting consumer demands, and effectively maintaining sales volume and profit levels.

3.3.3. Logistics Supplier Cooperation Model with Government Subsidy (C)

It is important to clarify that the government subsidy in this model is designed as an effort-dependent mechanism and analyzed through continuous policy tuning ($\lambda \in [0, 1]$) rather than a completely static flat-rate subsidy. Unlike a flat-rate subsidy, which acts as a passive profit transfer without affecting marginal decisions, the effort-dependent subsidy directly couples the payout with the firm's endogenous preservation effort. Furthermore, by continuously varying the subsidy coefficient λ from 0 to 1, we observe the progressive marginal adjustments of equilibrium pricing and preservation effort, capturing the continuous sensitivity of the supply chain to policy intensity.

When the cooperative enterprises of suppliers make efforts to preserve the freshness of fresh products to a certain extent, it will increase the procurement cost of fresh food e-commerce, thereby weakening the procurement motivation. To ensure that suppliers can obtain more favorable prices and promote the procurement of fresh products by downstream enterprises, and alleviate the inventory pressure. The government, based on the previously established standards, provides a freshness subsidy for the fresh products sold by the supplier's logistics cooperation, and the subsidy coefficient is set to λ .

Under the supplier cooperation model, the government (G) only provides subsidies to the cooperative enterprises and does not participate in the decision-making. The cooperative enterprises of fresh food suppliers (fs) and the e-commerce platforms (r) have a two-level Stackelberg game relationship. The fresh food suppliers determine the preservation effort η^C and the wholesale price w_{fs}^C of the fresh products based on the production cost m in advance; after observing w_{fs}^C , the fresh food e-commerce platforms determine the retail price p^C of the fresh products and the quantity q_r^C of product orders accordingly. As shown in Figure 3.

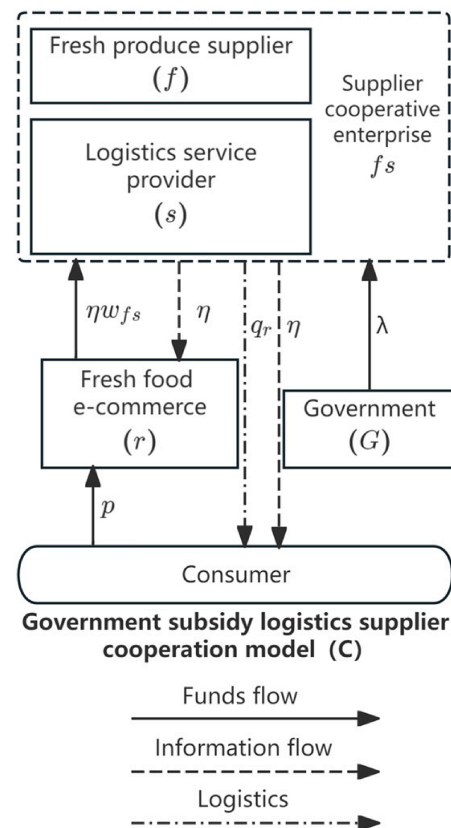


Figure 3. Logistics Supplier Cooperation Model with Government Subsidy (C) System Flowchart.

Based on the above game sequence and decision variables, the following logistics supplier cooperation model can be constructed. The profits of the fresh produce supplier (fs) and the e-commerce cooperation enterprise (r) are π_{fs}^C and π_r^C respectively. The profit functions of the two are as follows:

$$\pi_{fs}^C = q_r^C \eta^C (w_{fs}^C - m) - c(\eta^C) + \lambda q_r^C \quad (22)$$

$$\pi_r^C = E(\min(Q^C, q_r^C)) p^C - q_r^C \eta^C w_{fs}^C \quad (23)$$

Proposition 3. Under the circumstances of government subsidies, the supplier cooperation enterprises and the fresh food e-commerce platforms, as independent decision-making entities, each aim to maximize their own interests when making decisions. In their equilibrium state, the optimal strategy for the fresh food e-commerce supply chain is as follows:

(1) The optimal solutions for the wholesale prices of logistics supplier cooperative enterprises, the efforts for preservation, and the product prices of fresh food e-commerce are:

$$w_{fs}^{C*} = -\frac{m(-m\alpha + \beta) + 2\theta + \frac{((-m\alpha + \beta)^2 - 4\alpha\theta)\lambda}{D + Z + \alpha\lambda + \Lambda}}{m\alpha - \beta} \quad (24)$$

$$\eta^{C*} = \frac{(m\alpha - \beta)(D + Z + \alpha\lambda + \Lambda)}{(-m\alpha + \beta)^2 - 4\alpha\theta} \quad (25)$$

$$p^{C*} = \frac{(D + Z)\alpha(m^2\alpha - m\beta - 3\theta) + \alpha(m\alpha\beta - \beta^2 + \alpha\theta)\lambda + (m\alpha\beta - \beta^2 + \alpha\theta)\Lambda}{\alpha((-m\alpha + \beta)^2 - 4\alpha\theta)} \quad (26)$$

(2) The optimal profit solutions for logistics supplier cooperation enterprises and fresh food e-commerce are:

$$\pi_{fs}^{C*} = \frac{\theta(D + Z + \alpha\lambda + \Lambda)^2}{8\alpha\theta - 2(-m\alpha + \beta)^2} \quad (27)$$

$$\pi_r^{C*} = \frac{\alpha\Lambda(D + Z) \left(-m(m\alpha - \beta)^3 + 4(m\alpha - \beta)(2m\alpha - \beta)\theta - 14\alpha\theta^2 \right) + \left(-(m\alpha - \beta)^3\beta + 4\alpha(m\alpha - \beta)\beta\theta + 2\alpha^2\theta^2 \right) \alpha\Lambda\lambda + \alpha^2\theta^2(D + Z + \alpha\lambda)^2 + \left(-(m\alpha - \beta)^3\beta + 4\alpha(m\alpha - \beta)\beta\theta + \alpha^2\theta^2 \right) \Lambda^2}{\alpha \left((-m\alpha + \beta)^2 - 4\alpha\theta \right)^2} \quad (28)$$

(3) The optimal solutions for both the market demand volume and the order volume of fresh food e-commerce are:

$$Q^{C*} = \frac{m^2\alpha^2(Z - \varepsilon) - \beta^2\varepsilon + 2m\alpha\beta(-Z + \varepsilon) + D\alpha\theta + 4\alpha\varepsilon\theta + Z(\beta^2 - 3\alpha\theta) + \alpha^2\theta\lambda + \alpha\theta\Lambda}{4\alpha\theta - (-m\alpha + \beta)^2} \quad (29)$$

$$q_r^{C*} = \frac{\alpha\theta(D + Z + \alpha\lambda + \Lambda)}{4\alpha\theta - (-m\alpha + \beta)^2} \quad (30)$$

Proof of Proposition 3. The solution is obtained using backward induction. Compute the second-order partial derivative of π_r^C with respect to p^C to obtain $\frac{d^2\pi_r^C}{d(p^C)^2} = -2\alpha < 0$. Then, π_r^C has a maximum value. Solve for $\frac{d\pi_r^C}{dp^C} = 0$, and obtain $p^C = \frac{D+Z+\beta\eta^C-\Lambda+\alpha\eta^Cw_{fs}^C}{2\alpha}$. Substitute p^C into π_{fs}^C to get $\pi_{fs}^C = \frac{1}{2}(-(\eta^C)^2\theta + \lambda(D + Z + \beta\eta^C + \Lambda - \alpha\eta^Cw_{fs}^C) - \eta^C(m - w_{fs}^C)(D + Z + \beta\eta + \Lambda - \alpha\eta^Cw_{fs}^C))$. The Hessian matrix regarding η^C and w_{fs}^C is $H_{fs} = \begin{pmatrix} -\theta + (m - w_{fs}^C)(-\beta + \alpha w_{fs}^C) & \frac{1}{2}(D + Z + 2m\alpha\eta^C + 2\beta\eta^C + \Lambda - 4\alpha\eta^Cw_{fs}^C) \\ \frac{1}{2}(D + Z + 2m\alpha\eta^C + 2\beta\eta^C + \Lambda - 4\alpha\eta^Cw_{fs}^C) & -\alpha(\eta^C)^2 \end{pmatrix}$. Under the constraint condition $|H_{fs}| > 0$, the Hessian matrix is a negative definite matrix, and π_{fs}^C is a concave function with respect to p^C . Therefore, there exists a unique optimal solution. By combining $\frac{d\pi_{fs}^C}{d\eta^C} = 0$ and $\frac{d\pi_{fs}^C}{dw_{fs}^C} = 0$, the values of η^{C*} , w_{fs}^{C*} , and p^{C*} when π_{fs}^C takes the maximum value are obtained. Substituting the results back to obtain π_{fs}^{C*} , π_r^{C*} , Q^{C*} , and q_r^{C*} , and the constraints for $|H_{fs}| > 0$, $\eta^{C*} > 0$, and $q_r^{C*} > 0$ are all $4\alpha\theta - \beta^2 > 0$. $\square$

It is critical to clarify the economic nature of the government subsidy λ in the profit function π_{fs}^C . In this model, the government grant is not intended to directly generate corporate profit as a pure cash transfer. Instead, the subsidy is strictly designated to offset the heavy marginal costs of cold-chain preservation efforts $c(\eta) = \frac{\theta\eta^2}{2}$. By partially absorbing these public-welfare-oriented costs, the subsidy alleviates the financial burden on the logistics-supplier cooperative. This cost reduction, in turn, incentivizes the cooperative to lower the wholesale price w_{fs}^C and increase the preservation effort η^C . Consequently, the increase in the cooperative's final profit is a secondary outcome driven by the expanded market demand and higher sales volume, rather than the direct misappropriation of the public grant.

Inference 3.1. Under the logistics supplier cooperation model with government's subsidy (C), the wholesale prices w_{fs}^{C*} , β , and λ of the logistics supplier cooperation enterprises are inversely proportional to each other and directly proportional to θ , and they are not affected by α .

Inference 3.1 indicates that in the cooperative model of logistics suppliers, the wholesale price decisions of the cooperative enterprises are not influenced by the sensitivity of terminal market prices because they do not directly face end consumers. When the sensitivity of market demand to the effort of preservation increases, in order to stabilize market demand, the cooperative enterprises can adopt the method of lowering the wholesale price and increasing the order quantity within a short period of time. When the government provides subsidies to the cooperative enterprises, due to the sharing of preservation costs, the enterprises can lower the wholesale price while ensuring their own profits, thereby promoting the reduction in terminal prices on the fresh food e-commerce platforms and indirectly benefiting consumers. At the same time, the decline in terminal prices leads to an increase in demand, enabling the enterprises to obtain more e-commerce orders and achieve a positive improvement in profits. When the cost factor of logistics preservation increases, the supplier cooperatives increase their expenditures on preservation. To maintain the profit level, the cooperative enterprises also raise the wholesale prices they sell to fresh food e-commerce platforms. Therefore, when formulating wholesale prices, the logistics supplier cooperatives should carefully weigh the dual mechanisms of the cost investment in the logistics link and the impact of product preservation demand on the price system.

Inference 3.2. *Under the logistics supplier cooperation model with government subsidy (C), the relationships between p^{C*} , η^{C*} and α , θ are inverse, while the relationships between them and β , λ are direct.*

Inference 3.2 indicates that as the sensitivity of market demand to price increases, moderately reducing the product price becomes a necessary measure to maintain market share. When the cost of preservation rises, to ensure the overall profit margin, the cooperative enterprises can reduce the level of preservation efforts. When the sensitivity coefficient of market demand to preservation efforts increases, the cooperative enterprises can moderately offer discounts for pricing while maintaining reasonable preservation efforts, thereby enhancing market competitiveness, achieving a balance between cost control and meeting consumer demands, and effectively maintaining sales volume and profit levels. When the government provides subsidies for the preservation costs of the cooperative enterprises, the preservation efforts are directly strengthened. The wholesale price is inversely proportional to the increase in subsidies and directly proportional to the product price. The subsidy effect is ultimately driven by the price transmission mechanism to push down the terminal selling price, benefiting consumers and enhancing the operational stability and market competitiveness of the supply chain in responding to market fluctuations.

4. Numerical Case Analysis

This section conducts a numerical case analysis of the game in the fresh food e-commerce supply chain using the MATLAB R2023a simulation software. We focus on simulating the ordering strategies of the fresh food e-commerce and the changes in profits of each member in the supply chain under different government subsidy policies and different logistics cooperation models. To closely resemble the actual operational scenario, the simulation is set as follows. The fresh food e-commerce entrusts a third-party logistics service provider to transport goods and bears the transportation costs. It combines historical sales experience to predict market demand, thereby determining the order quantity and making corresponding efforts to preserve freshness. The government, in order to promote the circulation of fresh products and implement the assistance policies for farmers, provides preservation-cost-sharing subsidies to logistics service providers or fresh food supplier-logistics cooperative enterprises. The previous propositions are applicable to all probability distributions of ϵ . For the convenience of research, it is assumed that ϵ follows a

uniform distribution on $[-1, 1]$, with $f(u) = \frac{1}{2}$ and $\Lambda(Z) = \int_{-1}^Z (Z - u)f(u)du = \frac{(Z + 1)^2}{4}$, $\Phi(Z) = \int_Z^n (u - Z)f(u)du = \frac{(Z - 1)^2}{4}$. Other parameters are set as shown in Table 4. The simulation analysis helps to intuitively analyze the impact of different subsidy strategies and cooperation models on all parties in the fresh food supply chain, and provides a basis for the government to formulate subsidy policies.

Table 4. System parameter assignment.

D	Z	α	β	θ	ε	m	λ
1.5	0.3,0.3	0.5,0.6	0.5,0.7	1	0	0.1	0.5

To ensure the reliability and validity of the numerical simulation, the initial parameters were carefully assigned based on a synthesis of existing literature on fresh food supply chains (e.g., [16,21,32]), industry operational realities, and the mathematical constraints required to ensure the existence of a game equilibrium (i.e., maintaining the concavity of profit functions and ensuring positive demand and prices). While these values are illustrative, their relative magnitudes closely reflect the cost structures and price elasticities typical of perishable goods. Furthermore, regarding the random disturbance term ε , while the theoretical model incorporates demand uncertainty to capture real-world volatility, we follow standard simulation practices (e.g., [8,35]) by setting $\varepsilon = 0$ during the numerical execution.

It is important to clarify the treatment of the random demand disturbance ε in our numerical execution. As noted in the theoretical section, sales and inventory mismatches are non-linear functions of realized demand. Therefore, to isolate the structural impacts of the effort-contingent subsidy rates and logistics cooperation modes without the confounding effects of stochastic dispersion, we follow the established practice of setting $\varepsilon = 0$ to establish a deterministic benchmark. Consequently, the numerical results presented in this section do not simulate the full stochastic distribution or dispersion measures, but rather illustrate the deterministic mean-value trajectories. This deterministic benchmark allows for a transparent and focused comparison of the relative ordering of private profitability and preservation outcomes among Models A, B, and C.

4.1. Analysis of the Impact of Preservation Effort Sensitivity on Decision Variables

To explore the mechanism by which the consumer's freshness sensitivity coefficient affects the decision variables of the supply chain. Figure 4 depicts how the change in the consumer's perception of product freshness β influences the effort for preservation, product price, and market demand, presenting the changes in these three aspects intuitively.

As consumers' sensitivity to investment in product freshness gradually increases, under the three logistics models, the optimal freshness level, product retail prices, and market demand all show an upward variation trend simultaneously, and they present a synchronous pattern. The reasons for this phenomenon lie in the gradual improvement of consumers' requirements for the quality of fresh products and their increasing willingness to pay for product freshness, which in turn enables the effective demand to expand accordingly. To adapt to market changes, logistics service providers increase their investment in freshness, while fresh food e-commerce, driven by the joint promotion of quality improvement and increased demand, appropriately raises selling prices to optimize revenue. However, as shown in Figure 4, the matching between price and freshness varies significantly in different models. When in mode B and mode C, where logistics providers cooperate and the government provides subsidies, consumers can obtain a relatively moderate price with a high degree of product freshness, achieving a "high quality, high price"

state. While in mode A, where there is no cooperation and no subsidies, consumers have to pay a higher price but can only obtain a lower level of freshness. This comparison implies that when introducing the logistics cooperation mechanism and combining it with policy subsidies, the supply chain successfully reduces the loss rate and fulfillment costs, improves operational efficiency, and thereby has the ability to control the terminal price while enhancing the freshness quality, creating a more competitive “quality-price” combination. Furthermore, the analysis results shown in Figure 4 indicate that these two models not only significantly reduce retail prices but also greatly promote the substantial growth of market demand. This fully confirms the dual benefits brought by collaborative operations and policy support: first, through resource integration and cost sharing, service quality is improved; second, by benefiting consumers through efficiency gains, supply-side optimization and demand-side expansion achieve a virtuous cycle.

These simulation results perfectly align with the theoretical derivations and verify Hypothesis 1 and Hypothesis 2, proving that logistics cooperation combined with government subsidies creates a positive feedback loop for the supply chain.

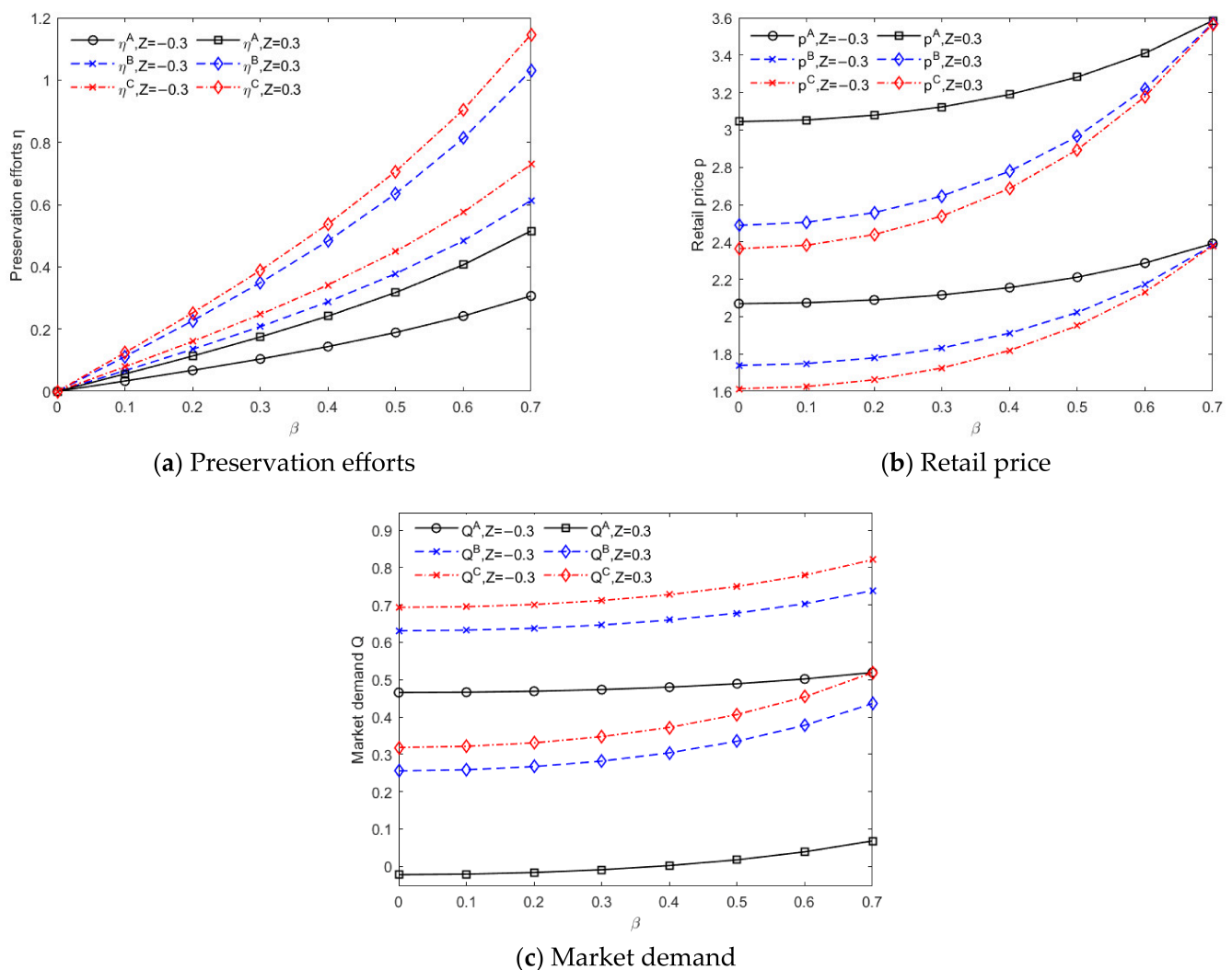


Figure 4. Variation trends of preservation efforts, retail prices and market demand with β .

4.2. Analysis of the Impact of Inventory Factors on Decision Variables

The relationship between the inventory factor Z and the impact on preservation efforts, product prices and market demand is shown in Figure 5.

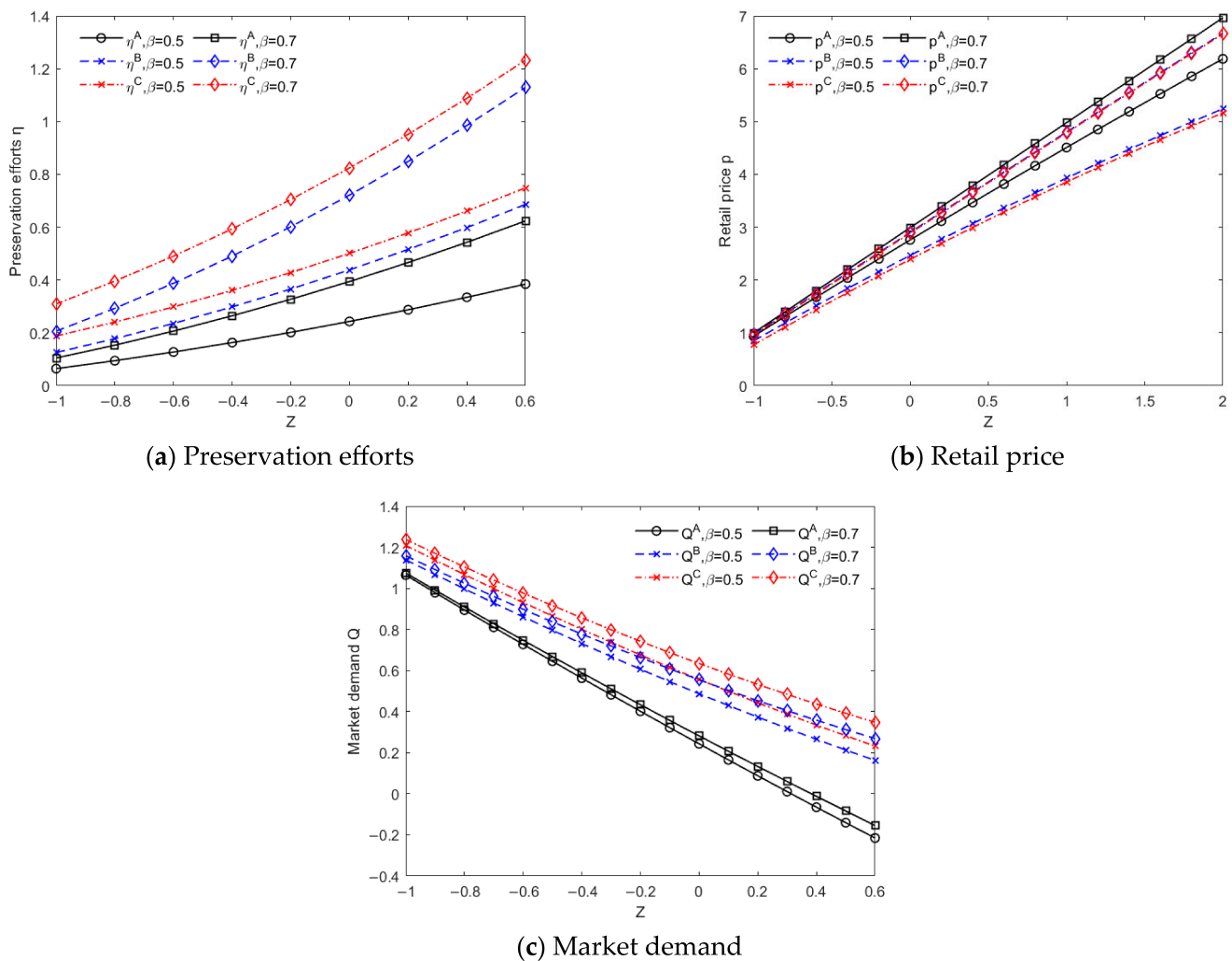


Figure 5. Variation trends of preservation efforts, retail prices and market demand with Z .

As shown in Figure 5, as the inventory factor Z gradually increases, the efforts of freshness preservation in the three models of fresh food e-commerce continue to rise. This indicates that when the order quantity is at a relatively low level, the cooperative enterprises of logistics service providers and suppliers have a more prominent resource regulation capability, which can concentrate limited resources to enhance the management level of the cold chain and the intensity of freshness preservation, thereby ensuring the excellent quality of the products. At this stage, the efficiency brought by the investment in freshness preservation is relatively considerable. This measure is conducive to controlling the loss situation from the very beginning and enhancing the competitiveness of the products themselves. However, Figure 5 shows that the fresh food e-commerce platform overly optimistically increases the demand forecast and significantly increases the order quantity, while the actual market demand not only does not increase but also shows a downward trend. The possible reasons are that excessive inventory leads to inventory backlog, the freshness of the products decreases, and the consumers' experience is adversely affected, ultimately suppressing the purchase intention and resulting in the paradox of "supply exceeding demand but the demand is in a shrinking trend". Uncontrolled expansion of order scale is not beneficial to the cultivation of the market and the stability of operations. In contrast, in the B mode and C mode, where logistics service providers and suppliers cooperate and there is a collaborative mechanism supported by government subsidies, the supply chain has a stronger ability to share risks and operational flexibility. At this moment,

enterprises can use precise prediction and collaborative optimization to select appropriate and reliable order strategies. This strategy can avoid losses caused by insufficient inventory due to insufficient preparation and at the same time prevent quality deterioration and demand loss caused by excessive stockpiling. This strategy can ensure that consumer purchases can be met, maintain a continuous and stable state of market demand, and promote the supply chain to complete the transformation and improvement from “passively responding” to “actively regulating”, helping fresh food e-commerce find the best balance in terms of quality, efficiency, and response to the market.

This phenomenon explicitly confirms Hypothesis 3, indicating that fresh food e-commerce platforms must adopt prudent ordering strategies rather than blind expansion.

4.3. Analysis of the Impact of Government Subsidy Coefficient on Decision Variables

The relationship between the change in the government subsidy coefficient λ and the impact on preservation efforts, product prices, and market demand is shown in Figure 6.

As shown in Figure 6, there is a significant positive correlation between the government subsidies and the efforts made by logistics supplier partnership enterprises in preserving freshness, as well as the market demand of fresh food e-commerce. There is also a significant negative correlation with the retail prices of fresh food e-commerce. As the coefficient of government subsidies continues to increase, the willingness of logistics supplier partnership enterprises to invest in the preservation process has significantly strengthened. Given that the subsidies effectively share the high operating costs in areas such as cold chain transportation, temperature-controlled storage, and the application of preservation technologies, the cost pressure faced by enterprises has thus been alleviated, enabling them to have stronger capabilities and more sufficient motivation to enhance their efforts in preservation. The impact of higher investment in preservation is multifaceted. It not only extends the shelf life of fresh products but also reduces losses during the circulation process, and significantly promotes the stability of the quality of terminal products. Based on this, logistics supplier partnership enterprises are more willing to adjust the wholesale prices provided to fresh food e-commerce platforms downward. The reduction in wholesale prices leads to a decrease in retail prices for consumers, thereby significantly enhancing the price competitiveness of the products, stimulating consumers' purchasing desires, especially in price-sensitive consumer groups, and effectively driving the overall market demand to rise. At the same time, the improvement in product freshness and the dual advantages in terms of price have further strengthened consumers' trust and loyalty towards the platform, thereby establishing a positive feedback mechanism.

Therefore, the implementation of government subsidies not only enables consumers to enjoy higher-quality fresh products at more affordable prices, thereby enhancing the overall supply chain surplus, but also allows all participants in the supply chain, such as logistics providers and fresh food e-commerce platforms, to achieve revenue growth through increased sales, improved operational efficiency, and accumulation of brand value. The overall operational efficiency of the supply chain is optimized, resource misallocation is reduced, the loss rate decreases, and ultimately, the profits along the entire chain achieve coordinated growth. Thus, it can be seen that government subsidies are not only a short-term fiscal incentive measure, but also a long-term structural policy tool. It can effectively guide the behaviors of supply chain entities towards high quality, and high operational efficiency, and has important practical significance and policy value for promoting the high-quality development of fresh food suppliers.

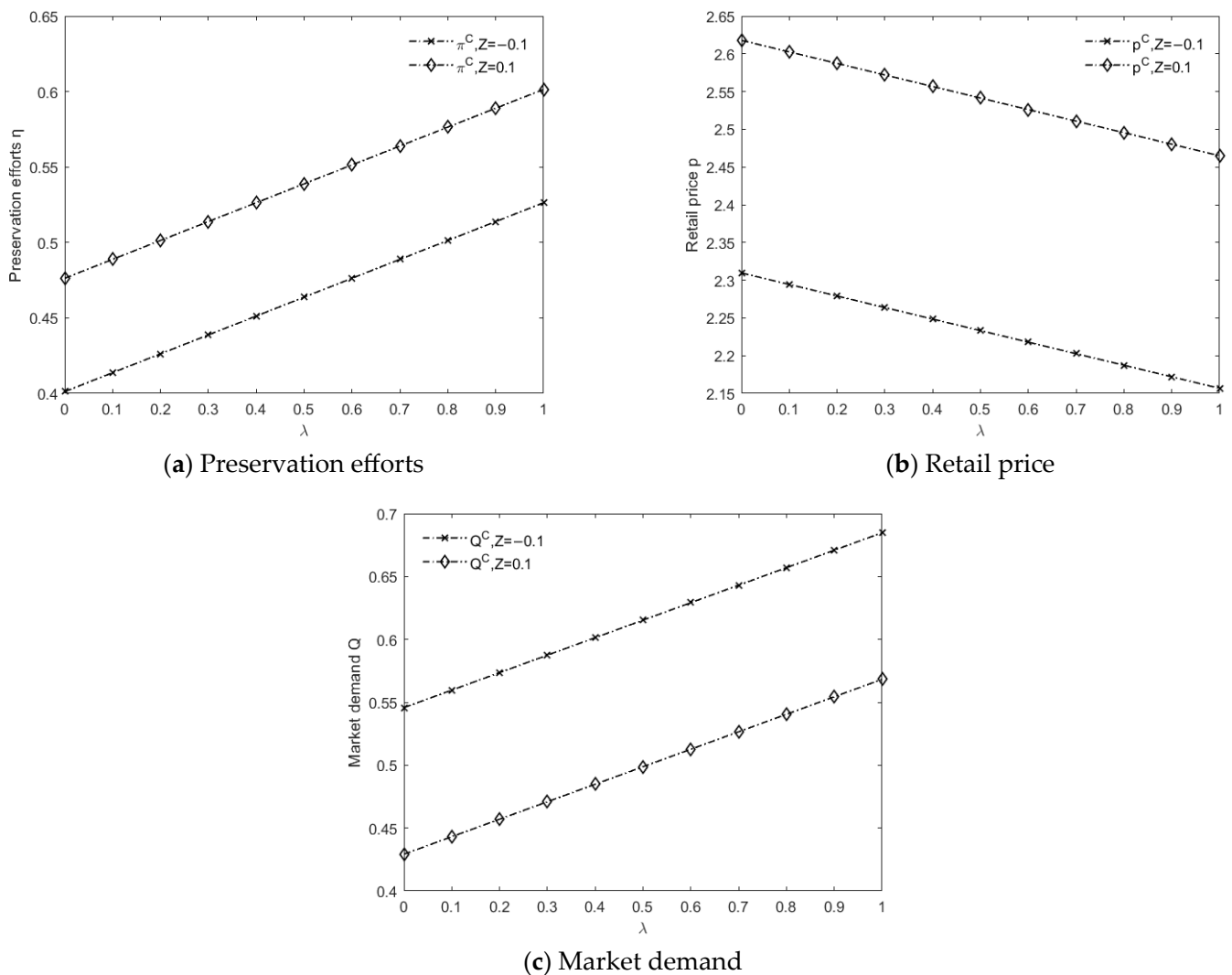
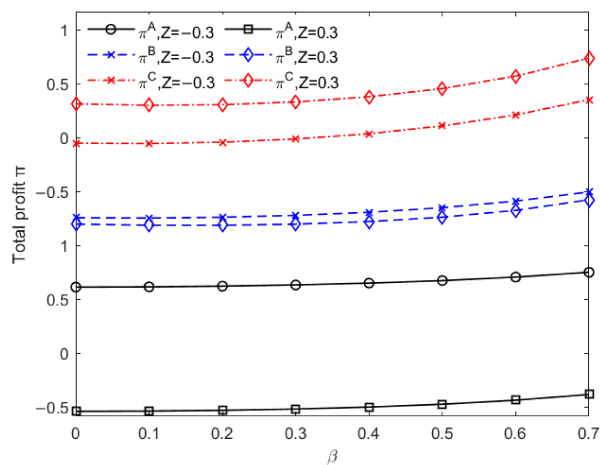


Figure 6. Variation trends of preservation efforts, retail prices and market demand with λ .

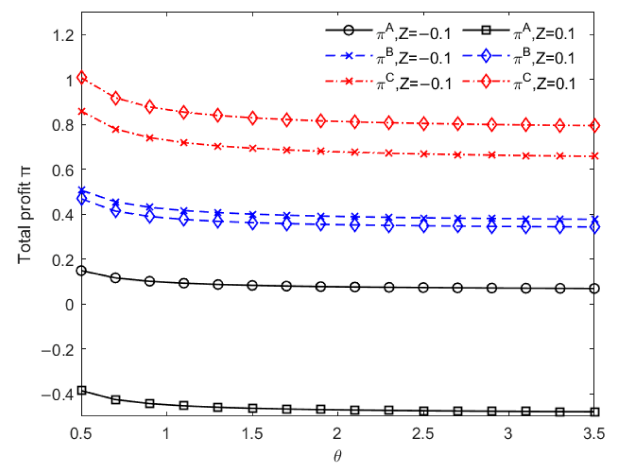
4.4. Analysis of Total Profit Changes in the Supply Chain

The impact of changes in the consumer's sensitivity coefficient β to the efforts made for preserving fresh products, the cost factor θ of such efforts, the product order quantity Z , and the government subsidy ratio λ on the total profit of the supply chain is shown in Figure 7.

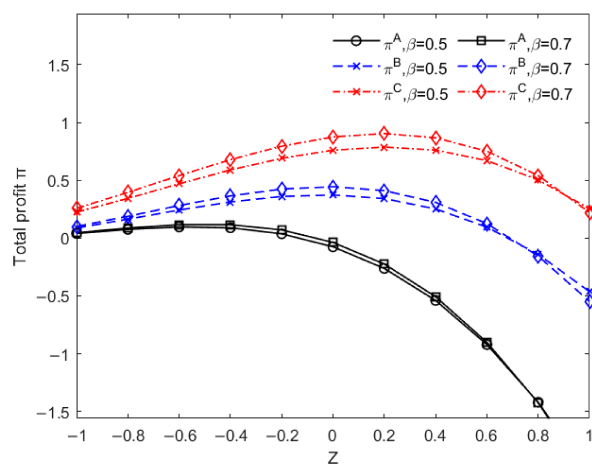
As shown in Figure 7, the impact of different operation models on the total profit of the fresh food e-commerce supply chain varies significantly. Under Model C, where government subsidies and logistics suppliers collaborate, the overall profit of the supply chain is at a relatively high level, while in the independent operation model (A), the profit is relatively weak. This comparison clearly demonstrates that, with the dual assistance of the logistics cooperation mechanism and government subsidy policies, resources can be efficiently integrated, divisions of labor can be optimized, losses can be reduced, and thus the overall operational efficiency and profitability of the supply chain can be significantly improved.



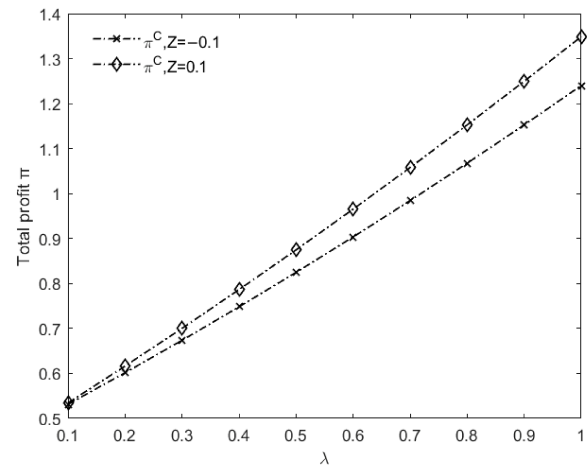
(a) The sensitivity of preservation efforts



(b) Freshness preservation effort cost factor



(c) Inventory factor



(d) Government subsidy ratio

Figure 7. Variation trends of the total profit of the fresh food supply chain with β , θ , Z , λ .

From the perspective of influencing factors, there is a clear pattern of change in the total profit of the supply chain: when the sensitivity of consumers to the effort of preservation, represented by β , increases, the total profit of the supply chain rises, while as the cost factor of preservation effort θ increases, the total profit of the supply chain actually decreases. This is because an increase in β can enhance consumers' willingness to pay for freshness improvement and effective demand, thereby increasing overall revenue; however, an increase in θ pushes up the unit preservation and fulfillment costs, thereby squeezing the profit margin. Within the scope of ordering strategies, the overall profit of the three modes is associated with the inventory factor, and the overall profit shows a similar inverted U-shaped trend of increasing first and then decreasing as the inventory factor increases. This indicates that moderately increasing the order quantity is conducive to leveraging the scale effect and reducing unit costs, but excessive inventory preparation, due to the perishable nature of fresh products, will cause high losses and high storage costs, ultimately leading to a decline in profits. It is worth noting that in modes B and C, the profit curve shows an overall upward movement, with a higher peak and a larger optimal order quantity. This indicates that with the cooperation of logistics suppliers and the assistance of government subsidies, the risk resistance ability of the supply chain is enhanced, enabling enterprises to implement more proactive and controllable ordering strategies, and ultimately achieve the maximization of profits while ensuring market supply. From Figure 7, it can be clearly observed that as the government subsidy intensity continues

to increase, the total profit of the supply chain shows a monotonically and continuously upward trend. This not only confirms the direct incentive effect of fiscal support, but also demonstrates that the subsidy policy has a positive spillover effect. This effect can not only alleviate the financial pressure of enterprises, but also drive more efficient operational decisions and closer entity collaboration. Therefore, scientifically designing the subsidy mechanism and guiding multiple parties to carry out collaborative cooperation is the core approach to promoting the high-quality development of the fresh food supply chain.

To ensure the robustness of our theoretical findings, this study conducted a structured sensitivity analysis across a wide range of critical parameters, rather than relying on a single static point. Specifically, Sections 4.1–4.4 systematically simulate how the equilibrium outcomes (preservation efforts, pricing, and total profits) evolve across varying ranges of demand sensitivity (β), inventory factors (Z), and government subsidy rates (λ). As demonstrated in Figures 4–7, despite the continuous variation of these parameters within plausible industry bounds, the relative ordering of private profitability and operational outcomes among the models remains consistently stable: Model C uniformly dominates Model B, which in turn strictly dominates Model A in terms of total supply chain profitability and preservation levels. This extensive sensitivity tracking confirms that the core conclusion—that government subsidies combined with logistics cooperation yield the optimal supply chain performance—is structurally robust and not a fragile artifact of the specific initial parameter selection.

5. Discussion

Approached from a modern product life-cycle and circular economy perspective, the supply chain of fresh products extends far beyond the traditional one-way movement from origin cultivation, post-harvest processing, long-distance transportation, and urban distribution, to final sales. It also encompasses the critical management of biological and packaging waste generated at every node of the supply chain, as well as post-consumption disposal. Because it involves numerous links, participants, and a complex structure, problems such as overall low efficiency, high resource waste (food loss) during transportation, ecological footprint concerns, and unstable cooperative relationships are particularly prominent. Therefore, systematic improvement and collaborative governance—especially strategies aimed at reducing food loss at the source through preservation efforts—are urgently needed to build a sustainable and circular fresh food supply chain.

5.1. Implications for Theory

This study makes several theoretical contributions to the literature on supply chain optimization. By analytically comparing three strategic models—no subsidy/no cooperation (A), no subsidy/logistics supplier cooperation (B), and government subsidy/logistics supplier cooperation (C)—this study theoretically confirms that logistics cooperation fundamentally mitigates the double marginalization effect. More importantly, this study conceptually redefines the subsidy mechanism. We theoretically demonstrated that government intervention is not a direct profit transfer, but rather a cost-sharing multiplier that profoundly reshapes the equilibrium of preservation efforts and pricing strategies. This provides a novel theoretical framework bridging macroscopic public policy with microscopic Stackelberg game under stochastic demand.

5.2. Implications for Practice and Policy

Based on our findings, we propose the following practical and policy implications for the fresh food supply chain:

- (1) Excessively high market demand forecasts (over-ordering) do not inherently stimulate consumer demand, but rather lead to a severe accumulation of excess inventory and mismatch costs. Therefore, in an environment where demand is highly random, fresh food e-commerce platforms should adopt more stable and prudent ordering strategies to avoid causing massive spoilage losses due to blind expansion. They must dynamically calibrate predictions and orders to balance consumer demand satisfaction with stringent mismatch cost control.
- (2) The cooperation between logistics service providers and fresh food suppliers can significantly improve overall efficiency. It is recommended that both parties establish long-term stable cooperative relationships, clearly define responsibility boundaries and SLA/KPI, and enhance delivery efficiency and preservation level through information, technology and resource sharing, achieving mutual benefit and win-win results.
- (3) Implement targeted government subsidies oriented towards supply chain optimization. As our findings suggest, government subsidies can effectively motivate entities to enhance preservation efforts and increase supply. However, policymakers must recognize that these subsidies are essentially a strategic redistribution of tax revenues from the state budget. Therefore, the ultimate goal of subsidizing this strategic sector is not merely to expand corporate profit margins, but to alleviate supply chain preservation costs, reduce agricultural waste, and improve product quality. It is recommended that governments implement conditional and assessable subsidies—directing funds specifically towards preservation technology innovation, cold chain infrastructure construction in underdeveloped areas, and green logistics—to maximize the operational efficiency of the fresh food supply chain.
- (4) When the government provides subsidies to logistics supplier cooperation enterprises, it can achieve price reduction by lowering wholesale costs, benefiting consumers, and achieving the effect of “stabilizing prices and providing benefits to the people”. The government can precisely select subsidy recipients based on the subsidy target.

5.3. Limitations of the Study and Future Research Directions

Finally, several limitations of this study must be acknowledged. First, the findings and policy recommendations presented in this study are derived entirely from game-theoretic modeling and numerical simulations under specific structural assumptions. The results provide theoretical insights and analytical references rather than direct empirical evidence. Furthermore, setting the basic unit transportation cost to zero serves as a deliberate baseline simplification. In reality, the heterogeneous incidence of unit transportation costs could affect the exact baseline margins and the viability of profit allocation between the supplier and the logistics provider. The simulation parameters, while illustrative, have not been formally calibrated using real-world financial or operational datasets from specific fresh food e-commerce platforms. Therefore, macroeconomic implications regarding broader consumer welfare or supply chain resilience should be interpreted as theoretically plausible hypotheses rather than empirically validated facts. Moreover, a critical theoretical limitation is that this stylized model focuses exclusively on comparative private-profit implications. It does not incorporate a formal government objective function, the fiscal cost of subsidies, the taxpayer burden, or food-waste externalities. Therefore, it cannot formally identify an optimal public subsidy policy or mathematically establish a true macroeconomic Pareto improvement once public expenditure is considered. Future research should focus on collecting primary industry data to empirically calibrate these game-theoretic models and validate the actual transmission mechanisms of subsidies in practice.

6. Conclusions

In conclusion, the analytical derivations and numerical simulations in this study demonstrate that both effort-contingent government subsidies and logistics cooperation can enhance the operational efficiency and profitability of the fresh food supply chain. In particular, under the subsidy and logistics cooperation model (Model C), the government effectively alleviates the preservation costs of cooperative enterprises. Within the boundaries of this stylized model, this cost-sharing mechanism incentivizes a reduction in wholesale prices, which subsequently drives up e-commerce order volumes and terminal freshness. As a result, the overall supply chain discourse power is consolidated, and a relative improvement in private profitability for all participating entities is achieved compared to the independent baseline. Ultimately, the combination of targeted government intervention and deep logistics partnerships proves to be a highly effective approach for optimizing preservation efforts and mitigating double marginalization within the fresh food supply chain.

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