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Optimal Preservation Effort and Carbon Emission Reduction Decision of Three-Level Cold Chain System with Low-Carbon Advertising Effect

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Abstract: To solve the problems of the impact of carbon emission reduction and low-carbon advertising on the supply chain of fresh agricultural products, a three-level low-carbon supply chain system composed of a manufacturer, a retailer and a third-party logistics service provider is taken as the research object. The profit functions of each party under the three contracts of the manufacturer bearing, the retailer bearing and the two parties jointly bearing the advertising cost are, respectively, established to solve the optimal pricing, advertising level preservation efforts, service levels and carbon emission reduction decisions. The numerical analysis shows that, with the increase in wholesale price and the decrease in fresh-keeping price coefficient and low-carbon cost coefficient, manufacturers will choose better fresh-keeping effort level and low-carbon service level. When the proportion of advertising cost borne by the supplier increases, the benefits of all parties in the supply chain will decrease; however, when the retailer bears the advertising cost alone, the profit of the supply chain system is the largest.

Keywords: fresh agricultural products supply chain; preservation efforts; low carbon advertising; carbon emission reduction decision

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1. Introduction

In recent years, the increase in carbon dioxide emissions year by year, global climate warming, glacier melting, and other environmental problems have become increasingly serious, bringing serious harm to the health of residents [1–6]. Among them, fresh agricultural products are one of the pillar industries for people's livelihood, and residents are more inclined to buy products with higher freshness [7,8]. In order to meet people's growing material and cultural needs, and to improve their life happiness index, how to ensure product freshness, reduce carbon emissions, and achieve further development of the entire supply chain in the fresh agricultural products industry is one of the issues worthy of in-depth research [9,10].

The freshness of fresh agricultural products will gradually decline with time, thus, freshness preservation technology (the technology of delaying the decline of freshness of agricultural products and preventing spoilage by physical or chemical methods, thus, as to maintain their good freshness and quality) is required to reduce the decline [11,12]. At the same time, in order to adapt to the national carbon emission reduction decision (the decision made to reduce the carbon dioxide released to the environment by people in their lives, through production and other activities), operators in the fresh agricultural product industry chain (that is, the functional network chain structure composed of fresh agricultural products as the object, with enterprises or organizations as the core, starting from the production link of fresh agricultural products to the link of reaching consumers) will actively adopt carbon emission reduction technologies, and, under certain conditions, consumers are more inclined to pay for "low-carbon products" [13–16]. However, the production cost and selling price of low carbon fresh agricultural products are high, and

the marketing is difficult. In order to attract more consumers, we can promote the sales of goods through low carbon advertising (referring to the activities in which advertisers publicize and disseminate low-carbon agricultural products to the public through certain media or forms with the help of strategies and means of advertising operators) [17]. In this context, it has important academic and application value to study the low-carbon operation management and advertising of fresh agricultural products in the supply chain.

This paper aims to a solve the problem of the impact of carbon emission reduction and low-carbon advertising on the supply chain of fresh agricultural products. The remaining parts of this paper are organized as follows. Section 2 provides a literature review of fresh agricultural produce supply chains, carbon emission reduction technologies, and advertising decisions. In Section 3, the research questions and associated notations are defined. In Section 4, the models proposed in this study are constructed. In Section 5, the numerical analysis of the proposed model is carried out, the relevant parameters are assigned, and relevant calculation examples are constructed to further verify the correctness and applicability of the theoretical model in this paper. We summarize the conclusions and provide the future research perspective in the last section.

2. Literature Review

2.1. Studies on the Supply Chain of Fresh Agricultural Products

In the process of studying the supply chain of fresh agricultural products, many scholars studied the two-level supply chain of fresh agricultural products of manufacturers/suppliers and retailers [18–22] in the early stage, and generally adopted the form of a linear demand function. Because fresh agricultural products need high-quality preservation services and are prone to wear and tear, with large price fluctuations and high logistics costs, some fresh agricultural product manufacturers outsource transportation and preservation to TPLSP service providers, which plays a significant role in improving the freshness of fresh agricultural products, the profits of fresh agricultural enterprises and the overall performance of the fresh agricultural product supply chain. Therefore, Cai [23] analyzed the profit of the three-level supply chain system through centralized and decentralized decision-making. Zhang [24] used non cooperative games, and Ma [25] achieved Pareto improvement in the three-tier supply chain system through revenue sharing and cost-sharing contracts. Chen [26], Gu [27] and Ma [28] all introduced 3PL to provide fresh-keeping services, the maintenance of freshness levels of fresh agricultural products, and the promotion of further research on the manufacturer retailer 3PL three-tier supply chain.

2.2. Studies on Carbon Emission Reduction and Low-Carbon Advertising in Supply Chain

With the gradual development of a low-carbon economy, enterprises are required to develop and adopt carbon emission reduction technologies to deal with the environmental crisis [29–31] and to solve the problem of how to further improve the developmental potential and space of enterprises under the guidance of new policies [32–39]. However, few carbon emission reduction policies have been applied to the fresh agricultural products industry, thus, it is of far-reaching significance to analyze the carbon emission reduction strategies of the fresh agricultural products industry. The application of carbon emission reduction technology will increase the production cost and difficulty of commodity sales, but advertising is an effective way to improve sales, thus, how to make optimal carbon emission reduction and advertising decisions has become one of the main research focuses. Liu [40] analyzed the impact of targeted advertising on low-carbon supply chain revenue and carbon emission reduction decisions. Zhang [41] analyzed the carbon emission reduction and advertising decisions of products in consideration of the two factors of consumers' environmental awareness and carbon emission reduction rate. With the increase in deterioration rate, supply chain members will reduce the sales price and increase advertising investment, while the increase in carbon emission price will reduce the level of advertising investment [42]. Tatyana et al. [43] and Li et al. [44] studied three advertising cooperation

models, respectively, and established a linear demand function to propose innovative conclusions for advertising investment and supply chain profit enhancement.

2.3. Research Gap

The scenarios in the related literature are summarized in Table 1. In general, the current fresh agricultural product industry has conducted research on carbon emission reduction decision-making and advertising, and reached relevant conclusions [21,23,35,42]. However, the research on carbon emission reduction and low-carbon advertising in the fresh agricultural product industry is still in its infancy, and there is a lack of research that considers the impact of carbon emission reduction and advertising on the sales of fresh agricultural products at the same time. In addition, most existing research is based on a two-level chain, not a three-level chain [21]. There are a few significant contributions in this work that contrast with the preceding literature. In view of the fact that low-carbon production has become the trend of future development, this paper takes the three-level fresh agricultural product supply chain system composed of a manufacturer, a retailer and a third-party logistics service provider TPLSP as the research object. According to consumers' low-carbon preference and the national low-carbon emission reduction call, manufacturers adopt carbon emission reduction technology to launch low-carbon fresh agricultural products and study the impact of advertising on the sales of low-carbon fresh agricultural products after adopting carbon emission reduction technology, the supplier's carbon emission reduction decision, and the optimal advertising decision. This study contributes to the existing literature by analyzing the impact of carbon emission reduction and low-carbon advertising on the supply chain of fresh agricultural products.

Table 1. Summary of the scenarios in the related literature.

Authors	Supply Chain System	Carbon Emission Reduction	Advertising
Ma [21]	Two-echelon cold chain system	Y	N
Cai [23]	Three-level green supply chain system	N	N
Ji [35]	Retail-/dual-channel supply chain	Y	N
Pan [42]	Multi-stage sustainable supply chain	N	Y
This paper	Three-level cold chain system	Y	Y

N indicates not available. Y indicates available.

This paper proposed a three-level fresh agricultural product supply chain system model composed of manufacturers, retailers and third-party logistics service providers TPLSP as the research object. The innovations of the model proposed in this paper include the innovative introduction of low-carbon advertising into the supply chain of fresh agricultural products. It innovatively analyzes the promotion of low-carbon advertisements in the proposed model under three different advertising contract modes that can directly increase the income of participants in the supply chain of low-carbon fresh agricultural products.

3. Problems and Symbols

A three-tier low-carbon fresh agricultural product supply chain system consisting of a manufacturer (represented by M), a TPLSP service provider (represented by T) and a retailer (represented by R) are studied in this paper. In the three-level supply chain system, the manufacturer, TPLSP and retailer have a Stackberg game relationship. The specific decision-making process is shown in Figure 1: First, TPLSP provides fresh-keeping services, and the fresh-keeping service price per unit product is positively related to the fresh-keeping degree of the product, that is $p_t = a_1\eta$, and the fresh-keeping cost per unit product is $c_t = a_2\eta^2$; Second, the manufacturer shall decide the level of fresh-keeping service to purchase according to the price of fresh-keeping services provided by TPLSP. At the same time, the manufacturer shall decide the low carbon level of products, the

advertising and marketing level of low carbon products, and the wholesale price ω, in which the low carbon cost per unit product is $a_3\sigma^2$ and the advertising expense [43] is $a_4\mu^2$; Third, the retailer decides the sales price of the product according to the market demand function and the wholesale price.

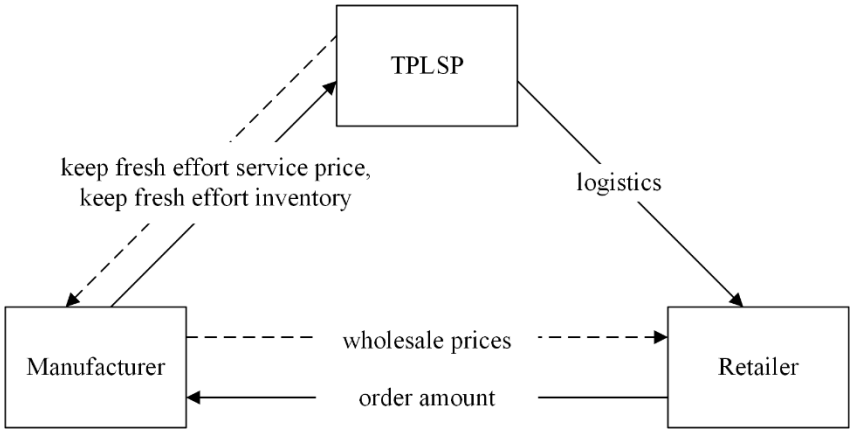


Figure 1. Game sequence of fresh agricultural product supply chain.

Some assumptions are made for the proposed model.

Assumption 1. *The manufacturer launched a low-carbon product against the background of consumers' awareness of low-carbon preference and increased the sales of low-carbon fresh agricultural products through advertising.*

Assumption 2. *TPLSP provided fresh-keeping services, and the price of fresh-keeping services was in direct proportion to the fresh-keeping level.*

Assumption 3. *In this paper, inspired by reference [23], we used the market demand function in the form of a multiplier, with the market demand D being affected by freshness η, advertising level μ, product low carbon level σ, and product sales price P_r at the same time, thus, the market demand function of fresh agricultural products is*:

$$D(p, \eta(\tau)) = y_0\eta(\tau)\mu\sigma p_r^{-k} \quad (1)$$

Equation (1) means that the market demand mainly depends on the freshness of the product when it reaches the market, the level of advertising, the low carbon level of the product and the sales price set by the retailer. The higher the selling price, the less demand there will be in the market. The higher the freshness, the higher the market demand. This is in line with market demand for fresh produce.

The relevant parameters and symbols in this paper are shown in Table 2.

Table 2. Description of relevant parameters and symbols.

Symbols	Illustrate
y_0	Potential market size
η	Product freshness
p_t	Fresh keeping service price per unit product
c_t	Fresh keeping cost per unit product
w	Wholesale price set by manufacturer
c_m	Manufacturer's unit manufacturing cost
σ	Low carbon level of products
μ	Advertising level
p_r	Product sales price

Table 2. *Cont.*

Symbols	Illustrate
c_r	Retailer's unit cost of sales
k	Elasticity coefficient of product demand price
a_1	Fresh keeping price coefficient
a_2	Fresh keeping cost coefficient
a_3	Low carbon cost coefficient
a_4	Advertising cost coefficient
θ	Proportion of advertising cost
π_T	TPLSP income function
π_M	Manufacturer income function
π_R	Retailer income function
D	Market demand
μ_1^*	Optimal advertising level in case of MI
μ_2^*	Optimal advertising level in case of RI
μ_3^*	Optimal advertising level in case of CI
σ^*	Optimal carbon emission reduction level
$\eta*$	Optimal fresh-keeping service level purchased
p_r^*	Optimal selling price

We research a three-echelon supply chain system, including three types of agents: manufacturer, TPLSP and retailer. The timeline of events in the model is shown in Figure 2. TPLSP provides fresh-keeping services to manufacturers. First, TPLSP determines the fresh-keeping services efforts and prices of the product units. Secondly, according to the decision of TPLSP, the manufacturer predicts the quantity of products to be retained by choosing TPLSP, and, at the same time, decides the low-carbon level of the product and the level of advertising and marketing of low-carbon products, setting the wholesale price. When demand arises, retailers will buy products from TPLSP and set selling prices based on freshness and wholesale prices.

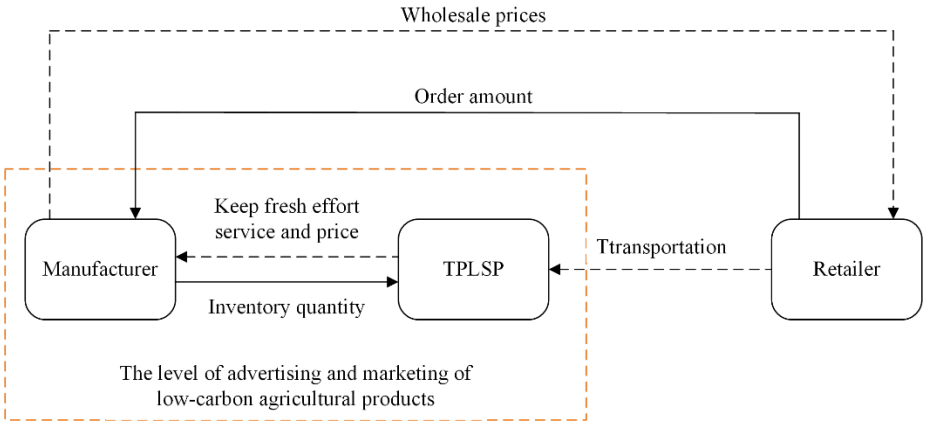


Figure 2. Timeline of events in the proposed model.

4. Model Construction

Since the promotion of low-carbon products can help improve the sales of low-carbon products and directly increase the income of participants in the supply chain of low-carbon fresh agricultural products, this paper uses the research method of literature [43] to divide the investment model of advertising into three situations: MI contract (manufacturer as advertising investor), RI contract (retailer as advertising investor) and CI contract (manufacturer and retailer cooperate in advertising investment). Under the three advertising investment models, we maximize the benefits for all participants in the agricultural product supply chain.

4.1. The Manufacturer Shall Bear the Advertising Expenses Alone (MI)

In this investment mode, the manufacturer bears the advertising cost alone. According to the above questions and symbols, the profit functions of TPLSP, the manufacturer and the retailer are expressed in this section.

The TPLSP profit function is as follows:

$$\begin{aligned} \pi_T &= (p_t - c_t)D \\ &= a_1\eta^2 * \mu * \sigma * p_r^{-k} - a_2\eta^3 * \mu * \sigma * p_r^{-k} \end{aligned} \tag{2}$$

Manufacturer's profit function is as follows:

$$\begin{aligned} \pi_M &= (w - c_m - p_t - a_3\sigma^2) * D - a_4\mu^2 \\ &= (w - c_m - a_1\eta - a_3\sigma^2) * y_0 * \eta * \mu * \sigma * p_r^{-k} - a_4\mu^2 \end{aligned} \tag{3}$$

Retailer profit function is as follows:

$$\begin{aligned} \pi_R &= (p_r - w - c_r) * D \\ &= (p_r - w - c_r) * y_0 * \eta * \mu * \sigma * p_r^{-k} \end{aligned} \tag{4}$$

According to the profit functions of all parties in the supply chain system and the Stark game order, Theorem 1 and Inference 1 can be obtained.

Theorem 1. *Under the condition that the manufacturer alone bears the advertising costs, the manufacturer chooses the optimal advertising level as* $\mu_1^* = \frac{(w-c_m)*d*\sqrt{\frac{5(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*p_r^{-k}}{5a_4}$*, the optimal carbon emission reduction level as* $\sigma^* = \sqrt{\frac{(w-c_m)}{5a_3}}$*, and the optimal fresh-keeping service level purchased as* $\eta* = \frac{2(w-c_m)}{5a_1}$*. The retailer's optimal selling price is:* $p_r^* = \frac{2k(w+c_r)}{(2k-1)}$.

It is proven that the second order partial derivative of product freshness η, advertising level μ and low carbon level σ can be obtained through the manufacturer's profit function:

$$\frac{\partial^2\pi_M}{\partial\mu^2} = -2a_4 < 0 \tag{5}$$

$$\frac{\partial^2\pi_M}{\partial\sigma^2} = -6a_3\sigma * y_0 * \eta * \mu * p_r^{-k} < 0 \tag{6}$$

$$\frac{\partial^2\pi_M}{\partial\eta^2} = -2a_1 * y_0 * \mu * \sigma * p_r^{-k} < 0 \tag{7}$$

Then, by setting $\frac{\partial\pi_M}{\partial\mu}$, $\frac{\partial\pi_M}{\partial\sigma}$, and $\frac{\partial\pi_M}{\partial\eta}$ equal to 0, respectively, we can derive:

$$\begin{cases} (w - c_m - a_1\eta - a_3\sigma^2) * y_0 * \eta * \sigma * p_r^{-k} - 2a_4\mu = 0 \\ (w - c_m - a_1\eta - 3a_3\sigma^2) * y_0 * \eta * \mu * p_r^{-k} = 0 \\ (w - c_m - 2a_1\eta - a_3\sigma^2) * y_0 * \mu * \sigma * p_r^{-k} = 0 \end{cases} \tag{8}$$

By solving the equations above, it can be calculated that the manufacturer's optimal advertising level is $\mu_1^* = \frac{(w-c_m)*d*\sqrt{\frac{5(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*p_r^{-k}}{5a_4}$, the optimal carbon emission reduction level is $\sigma^* = \sqrt{\frac{(w-c_m)}{5a_3}}$, and the optimal fresh-keeping service level purchased is $\eta* = \frac{2(w-c_m)}{5a_1}$.

Order $A = (w - c_m) * d * \sqrt{\frac{5(w-c_m)}{5a_3}} * \frac{2(w-c_m)}{5a_1}/5a_4$ and substitute μ_1^*, σ^*, $\eta*$ into π_r to obtain:

$$\begin{aligned} &\frac{\partial \pi_R}{\partial p_r} = \frac{p_r^{2k} - 2k(p_r - c_r - w)p_r^{2k-1}}{(p_r^{2k})^2} * y_0 * \eta^* * A * \sigma^* \\ &= \frac{(p_r + 2k*w + 2k*c_r - 2k*p_r)p_r^{2k-1}}{(p_r^{2k})} * y_0 * \eta^* * A * \sigma^* \\ &= \frac{[2k(w+c_r) - (2k-1)p_r]p_r}{(p_r^{2k})} * y_0 * \eta^* * A * \sigma^* \end{aligned} \tag{9}$$

Order $\frac{\partial \pi_R}{\partial p_r} = 0$, available: $p_r^* = \frac{2k(w+c_r)}{(2k-1)} = \frac{(w+c_r)}{(1-\frac{1}{2k})}$.

Certificate completion.

According to the results of the optimal decisions of manufacturers and retailers, the impact of the main parameters on their optimal decisions can be analyzed, as shown in Inference 1.

Inference 1

(1) With the increase in the manufacturer's wholesale price, or the reduction in production cost, the optimal product preservation service level, the optimal advertising level, and the optimal low carbon level selected by the manufacturer are all improved. With the increase in potential market size and retail price, the manufacturer's optimal advertising level also increases, while the increase in the price elasticity coefficient, fresh-keeping price coefficient, low carbon cost coefficient and advertising cost coefficient will lead to the decrease in the manufacturer's optimal advertising level. The coefficient of preservation price was negatively correlated with the optimal preservation level selected by the manufacturer. When the preservation price coefficient increases, the optimal preservation level selected by the manufacturer will decline. The increase in low carbon cost coefficient also reduces the optimal low carbon level of manufacturers.

(2) When the manufacturer's wholesale price and the retailer's selling cost increase, the retailer's optimal retail price will also increase. With the increase in the price elasticity coefficient, the optimal selling price of retailers will decrease.

4.2. Retailers Bear Advertising Expenses Alone (RI)

At this point, the retailer bears the advertising cost alone. The profit functions of TPLSP, the manufacturer and the retailer are listed are presented in this section.

The TPLSP profit function is as follows:

$$\begin{aligned} &\pi_T = (p_t - c_t)q \\ &= a_1\eta^2 * \mu * \sigma * p_r^{-k} - a_2\eta^3 * \mu * \sigma * p_r^{-k} \end{aligned} \tag{10}$$

The manufacturer's profit function is as follows:

$$\begin{aligned} &\pi_M = (w - c_m - p_t - a_3\sigma^2) * q \\ &= (w - c_m - a_1\eta - a_3\sigma^2) * d * \eta * \mu * \sigma * p_r^{-k} \end{aligned} \tag{11}$$

The retailer profit function is as follows:

$$\begin{aligned} &\pi_R = (p_r - w - c_r) * q - a_4\mu^2 \\ &= (p_r - w - c_r) * d * \eta * \mu * \sigma * p_r^{-k} - a_4\mu^2 \end{aligned} \tag{12}$$

According to the profit functions of all parties in the supply chain system and the Stark game order, Theorem 2 and Inference 2 can be obtained.

Theorem 2. *Under the condition that retailers bear advertising costs alone, the optimal carbon emission reduction level* $\sigma^* = \sqrt{\frac{(w-c_m)}{5a_3}}$ *selected by manufacturers is the optimal fresh-keeping*

service level purchased $\eta* = \frac{2(w-c_m)}{5a_1}$. *The optimal selling price* $p_r^* = \frac{k(w+c_r)}{(k-1)}$ *and advertising level of retailers is* $\mu_2^* = \frac{d*\sqrt{\frac{(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*[\frac{k(w+c_r)}{(k-1)}]^{1-k}}{2a_4k}$.

In the process of proving reference Theorem 1, similarly to Theorem 2, the influence of main parameters on the optimal decision of manufacturers and retailers can be analyzed.

Inference 2

(1) With the increase in the manufacturer's wholesale price or the decrease in the production cost, the optimal product freshness and the optimal low carbon level selected by the manufacturer have shown an upward trend. The fresh-keeping price coefficient is negatively related to the optimal fresh-keeping level selected by the manufacturer, and the low carbon cost coefficient is negatively related to the optimal low carbon level selected by the manufacturer.

(2) With the increase in the manufacturer's wholesale price and retailer's selling cost, the retailer's optimal retail price will increase. The increase in the price elasticity coefficient will reduce the optimal selling price of retailers.

(3) With the increase in potential market size, wholesale price and sales cost, the optimal advertising level selected by retailers will increase. If the preservation price coefficient, low carbon cost coefficient, advertising cost coefficient and price elasticity coefficient increase, the optimal advertising level selected by retailers will decrease.

To prove the influence of main parameters on the optimal decision, we can observe the expression in Theorem 2. For the influence of price elasticity coefficient on the retailer's optimal advertising level, the specific solution process is listed in this section.

First simplify $\mu*$,

$$\begin{aligned}\mu* &= \frac{d*\sqrt{\frac{(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*[\frac{k(w+c_r)}{(k-1)}]^{1-k}}{2a_4k} \\ &= \frac{d*\sqrt{\frac{(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*(p_r^*)}{2a_4k(p_r^*)^k}\end{aligned} \tag{13}$$

The above formula $\frac{d*\sqrt{\frac{(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}}{2a_4} = A$ can be changed into:

$$\mu* = \frac{\mathrm{A}*(p_r^*)}{k(p_r^*)^k} \tag{14}$$

The partial derivative of the above formula $\mu*$ to the price elasticity coefficient k is obtained with:

$$\begin{aligned}\frac{\partial\mu*}{\partial k} &= A*\frac{\frac{\partial p_r^*}{\partial k}(p_r^*)^k k-\left(p_r^*\right)[(p_r^*)^k+k*k(p_r^*)^{k-1}\frac{\partial p_r^*}{\partial k}]}{[k(p_r^*)^k]^2} \\ &= A*\frac{\frac{\partial p_r^*}{\partial k}(p_r^*)^k k(1-k)-(p_r^*)^{k+1}}{[k(p_r^*)^k]^2}\end{aligned} \tag{15}$$

Because $k > 1$, it is $\frac{\partial\mu*}{\partial k} < 0$. Therefore, with the increase in price elasticity coefficient, the optimal advertising level selected by retailers decreases.

Certificate completion.

4.3. Shared Advertising Expenses (CI)

When the manufacturer and retailer share the advertising cost, assuming that the proportion of advertising cost borne by the manufacturer is θ, the profit functions of TPLSP, the manufacturer and the retailer are listed in this section.

TPLSP profit function is as follows:

$$\begin{aligned}\pi_T &= (p_t - c_t)q \\ &= a_1\eta^2*\mu*\sigma*p_r^{-k} - a_2\eta^3*\mu*\sigma*p_r^{-k}\end{aligned} \tag{16}$$

Manufacturer's profit function is as follows:

$$\begin{aligned}\pi_T &= (w - c_m - p_t - a_3\sigma^2) * q - \theta a_4\mu^2 \\ &= (w - c_m - a_1\eta - a_3\sigma^2) * d * \eta * \mu * \sigma * p_r^{-k} - \theta a_4\mu^2\end{aligned} \tag{17}$$

Retailer profit function is as follows:

$$\begin{aligned}\pi_R &= (p_r - w - c_r) * q - (1-\theta)a_4\mu^2 \\ &= (p_r - w - c_r) * d * \eta * \mu * \sigma * p_r^{-k} - (1-\theta)a_4\mu^2\end{aligned} \tag{18}$$

According to the above profit functions of all parties in the supply chain system and the Stark game order, Theorem 3 and Inference 3 can be obtained.

Theorem 3. *Under the condition that the manufacturer and retailer jointly bear the advertising expenses, the manufacturer selects the optimal advertising level as* $\mu_3^* = \frac{(w-c_m)*d*\sqrt{\frac{5(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*p_r^{-k}}{5\theta a_4}$, *the optimal carbon emission reduction level as* $\sigma^* = \sqrt{\frac{(w-c_m)}{5a_3}}$, *and the optimal fresh-keeping service level as* $\eta* = \frac{2(w-c_m)}{5a_1}$. *The retailer's optimal selling price is* $p_r^* = \frac{2k(w+c_r)}{(2k-1)}$.

The process of proving reference Theorem 1.

By comparing MI contract (manufacturer as advertising investor), RI contract (retailer as advertising investor) and CI contract (manufacturer and retailer cooperate in advertising investment), we can draw the following conclusions:

Inference 3

(1) By the comparison of μ_1^* and μ_3^*, it can be seen that the joint assumption of advertising costs by manufacturers and retailers will promote manufacturers to improve their advertising level.

(2) By the comparison of μ_1^* and μ_2^*, we can see that at that time of $\frac{2}{5}(k-1) > \frac{w+c_r}{w-c_m}$, the advertising level under the MI investment mode was higher than that under the RI investment mode. At the time of $\frac{2}{5}(k-1) < \frac{w+c_r}{w-c_m}$, the advertising level under the MI investment mode was lower than that under the RI investment mode. At that time of $\frac{2}{5}(k-1) = \frac{w+c_r}{w-c_m}$, the MI investment model and the RI investment model had the same level of advertising.

(3) Under the MI investment mode, the optimal selling price of retailers is less than that under the RI investment mode.

Prove that subtracting μ_3^* and μ_1^* yields:

$$\begin{aligned}\mu_3^* - \mu_1^* &= \frac{(w-c_m)*d*\sqrt{\frac{5(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*p_r^{-k}}{5\theta a_4} - \frac{(w-c_s)*d*\sqrt{\frac{5(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*p_r^{-k}}{5a_4} \\ &= (\tfrac{1}{\theta} - 1) * \frac{(w-c_m)*d*\sqrt{\frac{5(w-c_m)}{5a_3}}*\frac{2(w-c_m)}{5a_1}*p_r^{-k}}{5a_4}\end{aligned} \tag{19}$$

Because $\theta < 1$, therefore $\frac{1}{\theta} - 1 > 0$, therefore $\mu_3^* - \mu_1^* > 0$, and the Inference (2) and (3) can be proved similarly.

5. Results Analysis

On the basis of theoretical analysis, this section constructs relevant calculation examples by assigning relevant parameters to further verify the correctness and applicability of the theoretical model in this paper. Based on the relevant assumptions above, the initial values of relevant parameters in this example are shown in Table 3.

Table 3. Design of relevant parameters.

d	w	c_m	c_r	k	a_1	a_2	a_3	a_4	θ
10,000	70	20	15	1.4	30	20	1.3	2	0.5

According to the parameter settings in the above table, the following data analysis diagram can be obtained. Figure 3 shows the impact of the fresh-keeping service price coefficient and the wholesale price on the optimal fresh-keeping service level selected by manufacturers. According to Figure 3, when the price coefficient of the fresh-keeping service is lower or the wholesale price of products is higher, the optimal fresh-keeping service level selected by the manufacturer is higher; on the contrary, the fresh-keeping service level selected by the manufacturer is lower. This is because the increase in the price coefficient of fresh-keeping services will increase the production costs of manufacturers and reduce their investment in fresh-keeping services. The increase in wholesale prices will help manufacturers invest more money in fresh-keeping services, and better fresh-keeping services will bring more product sales, forming a virtuous circle.

Figure 4 shows the impact of the low carbon cost coefficient and the wholesale price on the manufacturers' choice of the optimal low carbon level. It can be seen from Figure 4 that with the reduction in the low carbon cost coefficient or the increase in wholesale price of products, the optimal low carbon level selected by manufacturers will increase; otherwise, the low carbon level selected by manufacturers will decrease. Similarly, the lower the low carbon cost coefficient is, the lower the cost for manufacturers to choose low carbon technology is. Manufacturers are more willing to improve the low carbon level of products to increase sales and promote the further development of the carbon emission reduction trend.

Figure 5 shows the changes in the profits of all parties in the supply chain under different advertising cost-sharing models. It can be seen from Figure 5 that the profits under the RI investment model are the highest, because when the retailers bear the advertising costs, they can increase the sales price of the products by increasing the low-carbon publicity of advertising to increase the profits. At the same time, the profits of manufacturers increase because they do not bear the advertising costs. TPLSP has the highest revenue under the condition of sharing advertising, because the relationship between price and advertising is the most stable and balanced (the retailer's pricing is moderate and the level of advertising is high), thus, the sales volume is the highest, which increases TPLSP's profit.

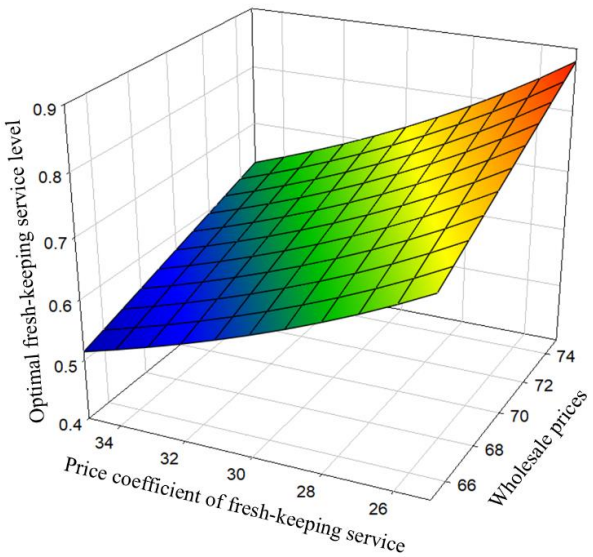


Figure 3. The impact of the fresh-keeping service price coefficient and the wholesale price on the optimal fresh-keeping service level selected by manufacturers.

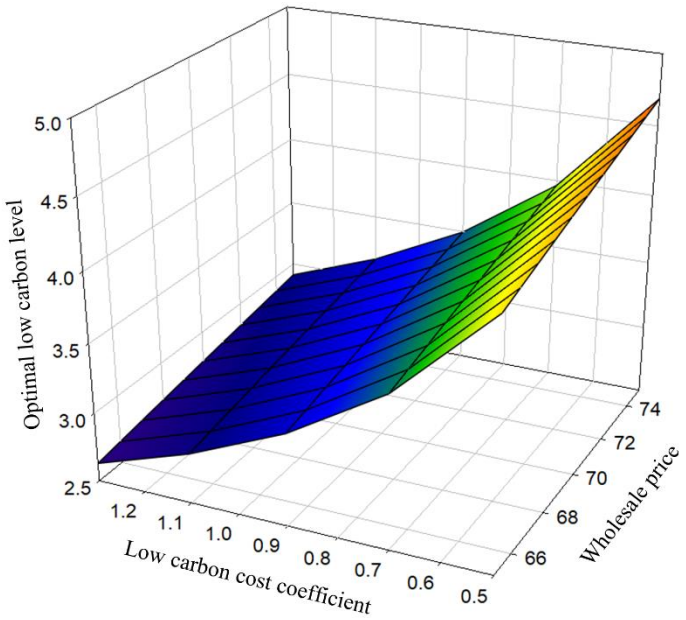


Figure 4. The impact of the low carbon cost coefficient and the wholesale price on manufacturers' choice of optimal low carbon level.

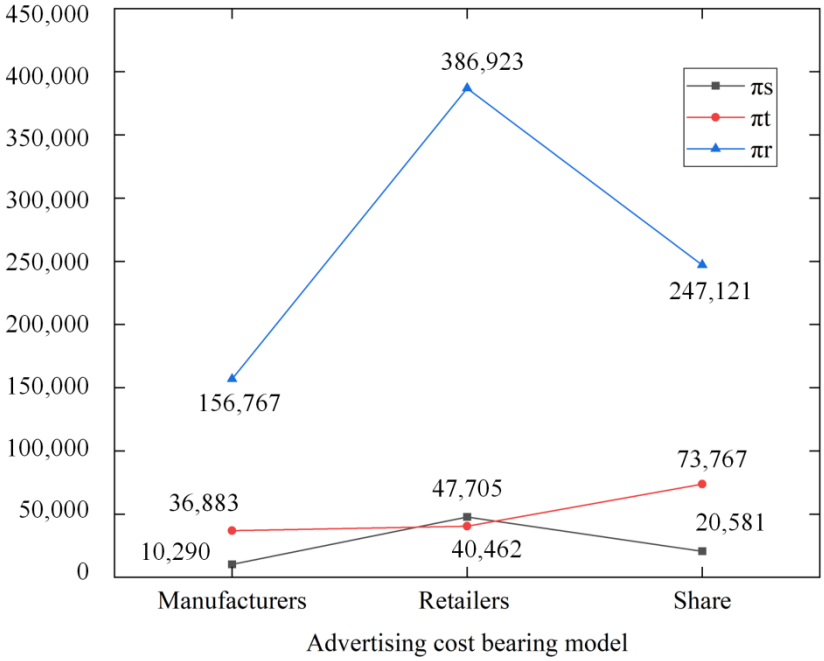


Figure 5. The changes in the profits of all parties in the supply chain under different advertising cost-sharing models.

Figure 6 shows the impact of the manufacturer's advertising cost-sharing ratio on the profits of all parties in the supply chain. According to Figure 6, with the increase in the manufacturer's advertising cost-sharing ratio, the profits of all parties in the supply chain show a downward trend. With the increase in advertising costs borne by manufacturers, their investment in fresh-keeping services and low-carbon technologies will be squeezed, which will directly affect the sales of the product market, leading to a decline in the overall efficiency of the supply chain.

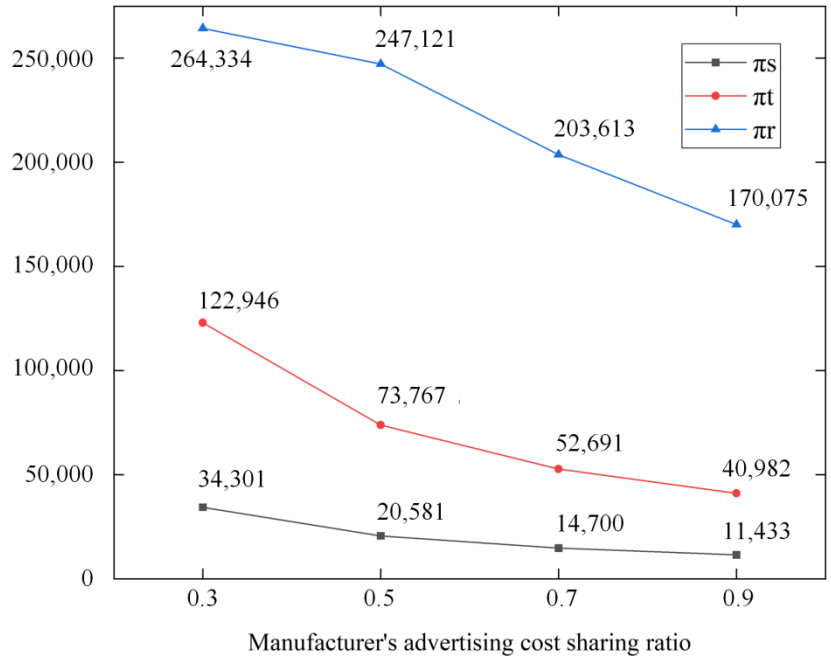


Figure 6. The impact of the manufacturer's advertising cost-sharing ratio on the profits of all parties in the supply chain.

In addition, we perform a sensitivity analysis on the manufacturer's unit manufacturing cost and the fresh-keeping cost coefficient on the profits of all parties in the supply chain.

Figure 7 shows the impact of the manufacturer's unit manufacturing cost on the profits of all parties in the supply chain. According to Figure 6, as the manufacturer's unit manufacturing cost increases, the profits of all parties in the supply chain show a downward trend. As the manufacturer's unit manufacturing cost increases, the investment in advertising and low-carbon technology is reduced, which directly affects the sales of products in the market, resulting in a decline in the overall efficiency of the supply chain.

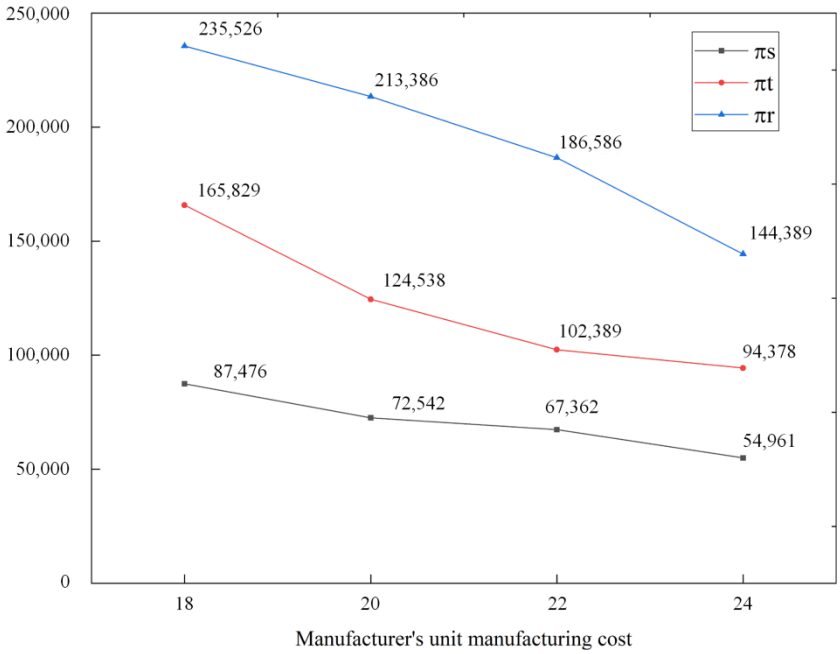


Figure 7. The impact of the manufacturer's unit manufacturing cost on the profits of all parties in the supply chain.

Figure 8 shows the impact of the fresh-keeping cost coefficient on the profits of all parties in the supply chain. Figure 7 shows that with the increase in the fresh-keeping cost coefficient, the profits of all parties in the supply chain show a downward trend. Because with the increase in fresh-keeping cost coefficient, the fresh-keeping cost increases, which in turn reduces the investment in advertising and low-carbon technology, directly affecting the sales of products in the market, and leading to a decline in the overall efficiency of the supply chain.

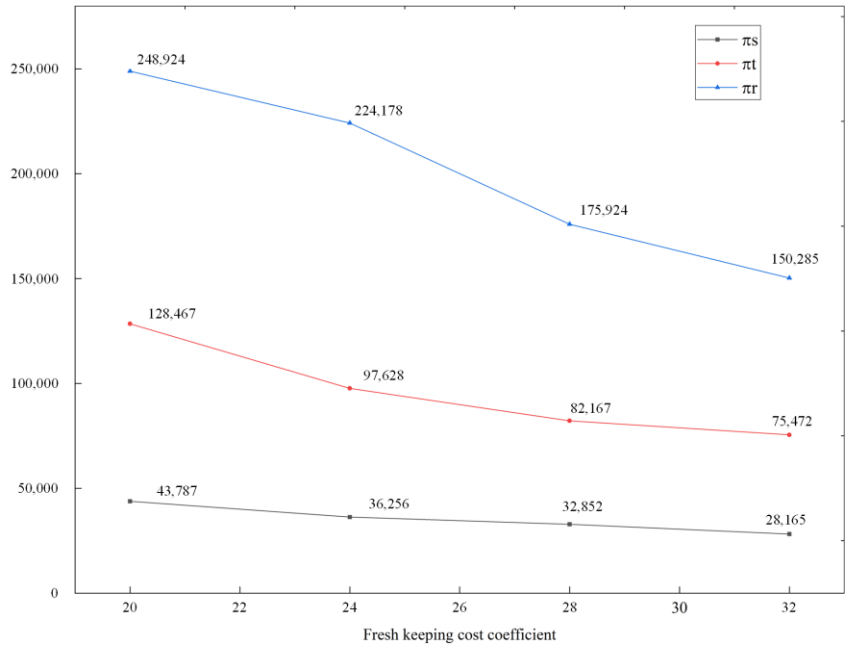


Figure 8. The impact of the fresh-keeping cost coefficient on the profits of all parties in the supply chain.

6. Conclusions

This paper focuses on the three-level supply chain system composed of a manufacturer, a retailer and a third-party logistics service provider TPLSP, and introduces low-carbon fresh agricultural products according to consumer preference awareness and development trends. In order to improve the sales of low-carbon fresh agricultural products, manufacturers and retailers invest in advertising alone or jointly (the three contracts of MI, RI and CI). They also analyze the profit difference of each party under different advertising investment contracts, the impact of market low-carbon preference on manufacturers' willingness to adopt carbon emission reduction technologies, and the impact of advertising low-carbon publicity investment on the market demand for low-carbon products.

Through this study, it is found that under the contract mode of MI and RI, the optimal fresh-keeping service level, the optimal advertising level and the optimal carbon emission reduction level selected by manufacturers will significantly increase with the increase in wholesale prices and the reduction in production costs. The optimal advertising level of manufacturers will increase with the increase in potential market size and retail price. When the price coefficient of fresh-keeping service increases, manufacturers will choose a lower optimal fresh-keeping level. If the low carbon cost coefficient increases, the manufacturer's optimal low carbon level will be reduced, which is not conducive to the development of carbon emission reduction in the fresh agricultural product industry. When a CI contract is implemented, the effect of advertising can be improved if the manufacturer and retailer jointly bear the advertising cost. At that time, the advertising level when the manufacturer alone bears the advertising cost is higher than that when the retailer alone bears the advertising cost. At that time, the advertising level when the manufacturer alone bears the advertising cost is lower than that when the retailer alone bears the advertising cost. At

that time, whether manufacturers or retailers bear advertising costs separately, they choose the same level of advertising. When manufacturers bear advertising costs alone, retailers set lower retail prices. Then, the above conclusions are verified by a numerical analysis.

As fresh agricultural products are perishable, it is necessary to take measures to keep them fresh in picking, production, transportation and sales. However, we should also vigorously develop carbon emission reduction technologies to reduce the carbon emissions generated by the efforts to keep them fresh. In order to improve the sales volume of low carbon fresh agricultural products and the revenue of the three parties in the three-level supply chain system, this study sets up three advertising contract models and analyzes the impact of advertising on product sales decisions. However, this study specifies that the supply chain participants choose carbon emission reduction technologies without joining specific carbon emission reduction policies, thus, the analysis under specific policies is a further research direction. In addition, it is also one of the research directions in the future to join multiple retailers to compete.

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