Fresh Produce Supply Chain Preservation Technology Input Strategy Considering Competition

Yuxiang Li*, Gengjun Gao
Institute of logistics science and engineering, Shanghai Maritime University, Shanghai, China.
**Corresponding author*

Abstract: A competitive two-tier supply chain game model is constructed, comprising two oligopolistic suppliers and a single retailer. By analyzing different scenarios of preservation technology investment and applying Stackelberg game theory, the study explores investment strategies in competitive fresh product supply chains. The findings reveal the following:When competition is relatively mild, the optimal strategy is not to invest in preservation technology. As competition intensifies, unilateral investment becomes the preferred option. When consumers' preference for freshness is low and preservation costs are high, the optimal strategy is to avoid investment. In cases where consumer preference for freshness is moderate and preservation costs are low, unilateral investment yields the best results. When both consumer preference for freshness and preservation costs are high, bilateral investment emerges as the optimal strategy.

Keywords: Fresh Produce Supply Chain; Freshness Technology Inputs; Duopoly Competition; Stackelberg Game

1. Introduction

In the modern fresh supply chain, consumers' preference for freshness continues to strengthen, and driving suppliers' fresh-keeping technology investment has become a key decision variable. However, the vertically and horizontally staggered benefit competition structure among supply chain members makes the technology input decision-making significantly complex. This paper constructs a competitive two-level supply chain model, focusing on the game strategy of suppliers' technology input and its performance impact: in the vertical dimension, the two suppliers as leaders first decide the wholesale price and technology input strategy, and the retailers as followers set the retail price; In the horizontal dimension, suppliers determine the technology investment strategy and pricing scheme through Nash game. The research introduces a four scenario analysis framework to systematically investigate the mechanism of technology input on supply chain profit distribution, and focuses on the interaction of key parameters such as technology cost coefficient, competition intensity and freshness preference. Through the theoretical model deduction, this paper aims to clarify the game effect of technology investment on the allocation of pricing power, the optimization of fresh-keeping level and profit distribution, and provide theoretical support and practical reference for the collaborative management of fresh supply chain.

2. Literature Review

Existing studies demonstrate the critical role of freshness technology in perishable supply chains. Hsu[1]pioneered the theoretical linkage between preservation inputs and supply chain efficiency. Dye[2] developed a spoilage-rate functional model, quantifying the profit optimization effects of preservation technology. Regarding coordination mechanisms, Zhang et al.[3] verified the Pareto improvement through supplier-retailer co-investment, while Yu et al[4]] established a third-party logistics coordination framework using Stackelberg game theory. Notably, Deng et al.[5] revealed the divergent impacts of horizontal versus vertical competition on preservation efficacy. However, dynamic optimization under the coupling effects of competition intensity, consumer preferences, and technological costs remains unexplored, creating the research gap addressed in this study.

3. Modelling and Analysis of Input Strategies for Preservation Technologies

3.1 Description of the Problem

In this paper, we consider a two-tier supply chain consisting of two competitive suppliers of the same type of fresh produce and one retailer. In the vertical structure , its two suppliers i and j act as leaders in the Stackelberg game, with $i \in \{1,2\}, j = 3-i$. In this supply chain game, the retailer acts as the follower who sets retail prices after suppliers determine wholesale prices. Two homogeneous suppliers (with identical unit cost) engage simultaneously decide wholesale prices and freshness technology investments. This generates four scenarios:(1) NN: No preservation investment;(2)YN: Only Supplier 1 invests;(3)NY: Only Supplier 2 invests;(4)YY: Both suppliers invests.

We analytically derive equilibrium decisions under these scenarios, with key notations summarized in Table 1.

Table 1. Model Parameter Settings

Notation	Description of definitions
w_i^x	The wholesale price of the supplier
p_i^x	Retailer's retail price for products from two suppliers
c	Unit cost of supply of products from supplier 1 and supplier 2
λ	Consumer preference for freshness of fresh produce
θ	Initial freshness of fresh produce
e_i^x	product freshness due to preservation technology inputs
β	Competition coefficient
μ	Coefficient of freshness on the cost of preservation
a	Size of market demand
π_i^x	Profit of the supplier
π_R^x	The retailer's profit

3.2 Basic Assumptions

Based on the model description, the following assumptions are made for the model in order to conform to reality and draw effective conclusions:

(1) Both suppliers start with identical base preservation levels.

(2) Suppliers can choose to invest in the use of preservation technology for high-intensity preservation to increase freshness , and the cost of preservation technology is positively correlated with freshness, assuming that the cost of preservation technology to be paid is $C^e = \frac{1}{2}\mu e^2$, The freshness function of fresh agricultural products is $\theta(e) = \lambda(\theta + e)$.

(3) Demand functions follow the classical competition model:

$$d_i = a - p_i + \beta p_j + \theta(e) \tag{1}$$

(4) All supply chain members are risk-neutral and engage in Stackelberg-Nash game following profit maximization principles.

3.3 Modelling under Different Preservation Technology Input Scenarios

3.3.1 No preservation investment (NN)

The payoff functions for the two suppliers and the retailer in this scenario are

$$\pi_i^{NN} = (w_i^{NN} - c)d_i^{NN} - C(e) \tag{2}$$

$$\pi_R^{NN} = \sum (p_i^{NN} - w_i^{NN})d_i^{NN} \tag{3}$$

The optimal equilibrium solutions, supply chain members' profits in the NN case are as follows:

Table 2. Optimal Equilibrium Solutions of Supply Chain Members' Profits in the NN Case

w_i^{NN}	$\frac{a+c+\theta\lambda}{2-\beta}$
p_i^{NN}	$\frac{3a+c-2a\beta-c\beta+3\theta\lambda-2\beta\theta\lambda}{4-6\beta+2\beta^2}$
π_i^{NN}	$\frac{\left(a+c(-1+\beta)+\theta\lambda\right)^2}{2(-2+\beta)^2}$
π_R^{NN}	$-\frac{\left(a+c(-1+\beta)+\theta\lambda\right)^2}{2(-2+\beta)^2(-1+\beta)}$

Proposition 1: In the NN scenario, where neither fresh produce supplier invests in preservation technology, wholesale prices for both supplier 1 and supplier 2 tend to increase as consumer sensitivity to freshness increases, and decrease as the intensity of competition increases. Correspondingly, the retail price set by retailers for both types of products increases with consumer sensitivity to freshness and decreases with the intensity of competition.

Proof:

$$\frac{\partial w_1^{NN}}{\partial \lambda} > 0;\quad \frac{\partial w_1^{NN}}{\partial \beta} < 0;\quad \frac{\partial w_2^{NN}}{\partial \lambda} > 0;\quad \frac{\partial w_2^{NN}}{\partial \beta} < 0$$

$$\frac{\partial p_1^{NN}}{\partial \lambda} > 0;\quad \frac{\partial p_1^{NN}}{\partial \beta} < 0;\quad \frac{\partial p_2^{NN}}{\partial \lambda} > 0;\quad \frac{\partial p_2^{NN}}{\partial \beta} < 0$$

3.3.2 Only Supplier 1 invests (YN)

The payoff functions for the two suppliers and the retailer in this scenario are.

$$\pi_i^{YN} = (w_i^{YN} - c)d_i^{YN} - C(e) \tag{4}$$

$$\pi_R^{YN} = \sum (p_i^{YN} - w_i^{YN})d_i^{YN} \tag{5}$$

The optimal equilibrium solutions, supply chain members' profits in the NN case are as follows:

Table 3. Optimal Equilibrium Solutions of Supply Chain Members' Profits in the NN Case

w_1^{YN}	$\frac{c\gamma^2\lambda^2-(2+\beta)(a+c+\theta\lambda)\mu}{\gamma^2\lambda^2+(-4+\beta^2)\mu}$
e_i^{YN}	$-\frac{(2+\beta)\gamma\lambda(a+c(-1+\beta)+\theta\lambda)}{2(\gamma^2\lambda^2+(-4+\beta^2)\mu)}$
w_2^{YN}	$\frac{\gamma^2\lambda^2(a+c+c\beta+\theta\lambda)-2(2+\beta)(a+c+\theta\lambda)\mu}{2\gamma^2\lambda^2+2(-4+\beta^2)\mu}$
p_1^{YN}	$\frac{c(-1+\beta)((4+3\beta)\gamma^2\lambda^2-2(1+\beta)(2+\beta)\mu)-(a+\theta\lambda)(\beta\gamma^2\lambda^2+2(1+\beta)(2+\beta)(-3+2\beta)\mu)}{4(-1+\beta^2)(\gamma^2\lambda^2+(-4+\beta^2)\mu)}$
p_2^{YN}	$\frac{-\lambda^2(c+c\beta(6+7\beta)+a(3+\beta(6+\beta))+(3+\beta(6+\beta))\theta\lambda)+2(2+\beta(7+6\beta))(c(1+\beta)+a(3+\beta)+(3+\beta)\theta\lambda)\mu}{4(1+2\beta)(-((1+\beta)\lambda^2)+(2+\beta)(2+3\beta)\mu)}$
π_1^{YN}	$-\frac{(2+\beta)^2(a+c(-1+\beta)+\theta\lambda)^2(\gamma^2\lambda^2-4\mu)\mu}{8(\gamma^2\lambda^2+(-4+\beta^2)\mu)^2}$
π_2^{YN}	$\frac{(a+c(-1+\beta)+\theta\lambda)^2(\gamma^2\lambda^2-2(2+\beta)\mu)^2}{8(\gamma^2\lambda^2+(-4+\beta^2)\mu)^2}$
π_R^{YN}	$\frac{(a+c(-1+\beta)+\theta\lambda)^2(-\gamma^4\lambda^4+4(1+\beta)(2+\beta)\gamma^2\lambda^2\mu-8(1+\beta)(2+\beta)^2\mu^2)}{16(-1+\beta^2)(\gamma^2\lambda^2+(-4+\beta^2)\mu)^2}$

Proposition 2: Under the YN scenario, Supplier 1 exhibits positive correlations between wholesale/retail prices/freshness levels and consumer freshness sensitivity, but negative correlations with competition intensity.

Proof:

$$\frac{\partial w_1^{YN}}{\partial\lambda}>0;\quad \frac{\partial w_1^{YN}}{\partial\beta}<0;\quad \frac{\partial w_1^{YN}}{\partial\beta}<0$$

$$\frac{\partial p_1^{YN}}{\partial\lambda}>0;\quad \frac{\partial e_1^{YN}}{\partial\lambda}>0;\quad \frac{\partial e_2^{YN}}{\partial\beta}<0$$

3.3.3 Only Supplier 2 invests (NY)

The payoff functions for the two suppliers and the retailer in this scenario are:

$$\pi_i^{NY}=(w_i^{NY}-c)d_i^{NY}-C(e) \tag{6}$$

$$\pi_R^{\mathrm{NY}}=\sum(p_i^{\mathrm{NY}}-w_i^{\mathrm{NY}})d_i^{\mathrm{NY}} \tag{7}$$

The optimal equilibrium solution, member profits in the supply chain in the NN case are as follows:

Table 4. Optimal Equilibrium Solution of Member Profits in the Supply Chain in the NN Case

w_2^{NY}	$\frac{c\gamma^2\lambda^2-(2+\beta)(a+c+\theta\lambda)\mu}{\gamma^2\lambda^2+(-4+\beta^2)\mu}$
e_i^{NY}	$-\frac{(2+\beta)\gamma\lambda(a+c(-1+\beta)+\theta\lambda)}{2(\gamma^2\lambda^2+(-4+\beta^2)\mu)}$
w_1^{NY}	$\frac{\gamma^2\lambda^2(a+c+c\beta+\theta\lambda)-2(2+\beta)(a+c+\theta\lambda)\mu}{2\gamma^2\lambda^2+2(-4+\beta^2)\mu}$
p_i^{NY}	$\frac{c(-1+\beta)((4+3\beta)\gamma^2\lambda^2-2(1+\beta)(2+\beta)\mu)-(a+\theta\lambda)(\beta\gamma^2\lambda^2+2(1+\beta)(2+\beta)(-3+2\beta)\mu)}{4(-1+\beta^2)(\gamma^2\lambda^2+(-4+\beta^2)\mu)}$
π_1^{NY}	$-\frac{(2+\beta)^2(a+c(-1+\beta)+\theta\lambda)^2(\gamma^2\lambda^2-4\mu)\mu}{8(\gamma^2\lambda^2+(-4+\beta^2)\mu)^2}$
π_2^{NY}	$\frac{(a+c(-1+\beta)+\theta\lambda)^2(\gamma^2\lambda^2-2(2+\beta)\mu)^2}{8(\gamma^2\lambda^2+(-4+\beta^2)\mu)^2}$
π_R^{NY}	$\frac{(a+c(-1+\beta)+\theta\lambda)^2(-\gamma^4\lambda^4+4(1+\beta)(2+\beta)\gamma^2\lambda^2\mu-8(1+\beta)(2+\beta)^2\mu^2)}{16(-1+\beta^2)(\gamma^2\lambda^2+(-4+\beta^2)\mu)^2}$

Proposition 3: In the NY scenario, Supplier 2's investment decisions exhibit symmetric patterns to YN, structurally consistent with Proposition 2.

Proof:

$$\frac{\partial w_1^{NY}}{\partial\lambda}>0;\quad \frac{\partial w_1^{NY}}{\partial\beta}<0;\quad \frac{\partial e_1^{NY}}{\partial\lambda}>0$$

$$\frac{\partial e_2^{NY}}{\partial\beta}<0;\quad \frac{\partial p_1^{NY}}{\partial\lambda}>0$$

3.4 Both suppliers invests (YY)

The demand function at this point is

$$d_i=a-p_i+\beta p_j+\theta(e)-\beta\left(e_i-e_j\right) \tag{8}$$

The payoff functions for the two suppliers and the retailer in this scenario are

$$\pi_i^{YY}=(w_i^{YY}-c)d_i^{YY}-C(e) \tag{9}$$

$$\pi_R^{YY}=\sum(p_i^{YY}-w_i^{YY})d_i^{YY} \tag{10}$$

The optimal equilibrium solution, member profits in the supply chain in the NN case are as follows:

Table 5. Optimal Equilibrium Solution, Member Profits in the Supply Chain in the NN Case

w_i^{YY}	$\frac{c\gamma^2\lambda^2-2(a+c+\theta\lambda)\mu}{\gamma^2\lambda^2+2(-2+\beta)\mu}$
e_i^{YY}	$-\frac{\gamma\lambda(a+c(-1+\beta)+\theta\lambda)}{\gamma^2\lambda^2+2(-2+\beta)\mu}$
p_i^{YY}	$\frac{c(-1+\beta)(\gamma^2\lambda^2-\mu)-(-3+2\beta)(a+\theta\lambda)\mu}{(-1+\beta)(\gamma^2\lambda^2+2(-2+\beta)\mu)}$
π_1^{YY}	$-\frac{(a+c(-1+\beta)+\theta\lambda)^2(\gamma^2\lambda^2-4\mu)\mu}{2(\gamma^2\lambda^2+2(-2+\beta)\mu)^2}$
π_2^{YY}	$-\frac{(a+c(-1+\beta)+\theta\lambda)^2(\gamma^2\lambda^2-4\mu)\mu}{2(\gamma^2\lambda^2+2(-2+\beta)\mu)^2}$
π_R^{YY}	$-\frac{2(a+c(-1+\beta)+\theta\lambda)^2\mu^2}{(-1+\beta)(\gamma^2\lambda^2+2(-2+\beta)\mu)^2}$

Proposition 4: In the case of YY, the wholesale price and retail price of supplier 1 and supplier 2 both decrease with the increase of competition intensity. In addition, the product freshness level of supplier 1 and supplier 2 also decreases with the increase of competition intensity.

Proof:

$$\frac{\partial w_1^{YY}}{\partial \beta} < 0; \quad \frac{\partial w_2^{YY}}{\partial \beta} < 0; \quad \frac{\partial p_1^{YY}}{\partial \beta} < 0$$

$$\frac{\partial e_2^{YY}}{\partial \beta} < 0; \quad \frac{\partial p_2^{YY}}{\partial \beta} < 0;$$

3.4 Preservation Technology Investment Game

For Supplier 1, when Supplier 2 chooses strategy Y, if $\pi_1^{YY} > \pi_1^{NY}$, then Supplier 1's optimal response is to choose strategy Y. When Supplier 2 chooses strategy N, if $\pi_1^{YN} > \pi_1^{NN}$, then Supplier 1's optimal response is to choose strategy Y. Similarly, the optimal response strategy of supplier 2 can be analyzed.

Due to the excessive number of parameters, it is difficult to analyze the key conclusions by simply using algebraic expressions, so we set appropriate fixed variable values for visual display. Set $a = 10, c = 2, \theta = 1$:

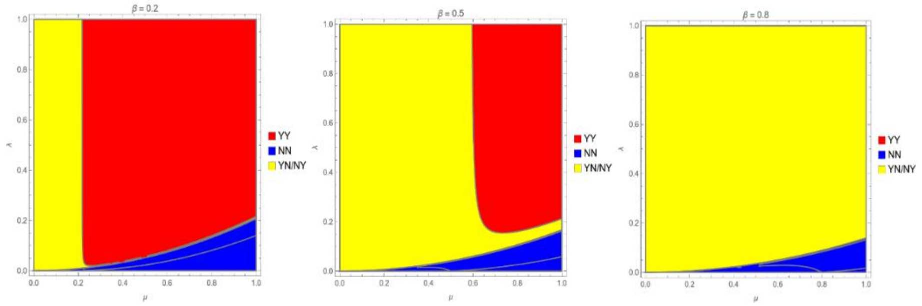

Figure 1. Regional Balance of Investment Strategy Distribution

Analysis of Figure 1 shows that when consumers' preference for freshness is low and the cost of preservation technology is high, NN is the best strategy; When consumers' preference for freshness is moderate and the cost of preservation technology is low, YN/NY is the best strategy; When consumers' preference for freshness is high and the cost of preservation technology is high, YY is the best strategy. As the competition coefficient decreases, the blue area gradually increases, indicating that NN is the best strategy when the competition is small. As the competition coefficient increases, the yellow area gradually engulfs the red area, indicating that YN/NY is the best strategy when the competition is fierce.

4. Conclusions

This study establishes a game theory model to study the investment strategy of fresh-keeping technology in the competitive fresh product supply chain. The results are as follows:

When the competition is small, the optimal strategy is not to invest in fresh-keeping technology. With the intensification of competition, unilateral investment has become the first choice. When consumers' preference for freshness is low and the cost of preservation is high, the optimal strategy is not to invest in preservation technology; For moderate consumer freshness preference and low fresh-keeping cost, unilateral investment is the best; When consumers' freshness preference and fresh-keeping cost become higher, the investment of both parties is the optimal strategy.

References

[1]Hsu P H, Wee H M, Teng H M. Preservation technology investment for deteriorating inventory[J]. International Journal of Production Economics, 2010, 124(2):388-394.

[2]Dye C Y , Hsieh T P . An optimal replenishment policy for deteriorating items with effective investment in preservation technology[J]. European Journal of Operational Research, 2012, 218(1):106-112.

[3]Zhang J, Liu G, Zhang Q, et al. Coordinating a supply chain for deteriorating items with a revenue sharing and cooperative investment contract[J]. Omega: The international journal of management science, 2015,56:37-49.

[4]Yu Yunlong, Xiao Tiaojun. Pricing and cold-chain service level decisions in a fresh agriproducts supply chain with logistics outsourcing[J]. Computers & Industrial Engineer-ing,2017,111:56-66.

[5]Deng, W., Feng, L., Zhao, X., et al. Effects of supply chain competition on firms' product sustainability strategy[J]. Journal of Cleaner Production, 2020, 275(10):124061.