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Research article

Strategy selection of logistics services and live-streaming formats in the fresh agri-food supply chain

Chun-Yi Liu[1], **Jie-Lin Hu**[1] **and Li Liu**[2,*]

[1] School of Economics and Management, Yanshan University, Qinhuangdao, 066004, Hebei, China
[2] School of Maritime Economics and Management, Dalian Maritime University, Dalian, 116026, Liaoning, China

* **Correspondence:** Email: liuli@dlmu.edu.cn.

Abstract: Live-streaming can boost agricultural sales and increase farmers' income, yet the perishability of fresh produce generates high logistics costs and spoilage compensation expenses. Responsibility for these costs varies across different live-streaming formats. This paper develops a game-theoretic framework under three scenarios—supplier self-broadcasting (S), key opinion leader(KOL)-assisted agency sales (KA), and KOL-resale (KR)—to examine optimal logistics and live-streaming strategies in fresh agri-food supply chains. The results reveal that (1) the allocation of rights and responsibilities across live-streaming formats critically shapes supply chain members' optimal responses and profit outcomes. Member behaviors largely align in Scenarios S and KR but diverge in Scenario KA; (2) although higher KOL traffic expands market demand, it does not necessarily improve profitability for supply chain members, particularly under the KA model; and (3) the KR model achieves a win–win–win outcome when both the initial spoilage rate and compensation price are high and KOL traffic is at a moderate level. In other cases, while 3PLs and suppliers maintain aligned incentives, KOL preferences differ.

Keywords: fresh agri-food supply chain; live-streaming; logistics services; strategies selection
Mathematics Subject Classification: 9110, 91A05

1. Introduction

In recent years, live-streaming sales have become a major marketing tactic, drawing a large number of consumers to buy products through live-streaming platforms [1]. According to the report from China International Electronic Commerce Center Research Institute [2], China's live-streaming e-commerce market size hit about 5.8 trillion yuan in 2024, with an expected compound annual growth rate (CAGR) of 18.0% from 2024 to 2026. Globally, the live-streaming e-commerce market size in 2024 is estimated at \$1.49–2.0 billion USD, and it is expected to grow to roughly \$25.876 billion USD by 2034, with a CAGR of approximately 33.0% [3]. The benefit of live-streaming sales is that it allows consumers to see the products' quality and manufacturing processes, which increases their confidence in buying. This feature shows strong potential for live-streaming sales of agricultural products. A multitude of data substantiate this trend. "The Power of Produce 2025" states that 36% of shoppers find new fruits and vegetables through online channels [4]. Between September 2024 and September 2025, Douyin E-commerce recorded total sales of 10.2 billion orders for agricultural products [5].

Fresh agri-food is highly perishable and prone to damage during transportation, requiring specialized logistics. For example, aquatic products like crabs and lobsters need cold chain logistics to prevent death, while fruits such as strawberries and cherries need shock-absorbing packaging to prevent spoilage. In the United States, 41% of consumers have experienced quality or safety issues with perishable items upon delivery [6]. Logistics losses greatly affect the fresh agricultural food supply, with spoilage rates reaching 33% annually, leading to millions of dollars in waste [7]. China's fresh agricultural product loss rate is about 10% to 15%, with logistics costs making up 30% to 40% of total expenses. Ensuring proper temperature and appropriate packaging is essential for maintaining freshness, but this also increases the logistics costs far beyond those for regular goods [8].

High spoilage rates not only increase the logistics costs but also lead to high consumer returns, which is particularly pronounced in the online sales of fresh agri-foods. Consumers purchasing fresh agri-foods on platforms such as Taobao, Douyin, and Pinduoduo can seek reimbursement from sellers for damaged items, with reimbursement proportional to the amount of the damage. To address these return and logistics risks, suppliers must consider the entities responsible for cold chain transportation services and cargo damage risks under different live-streaming formats when formulating sales strategies. To mitigate return and logistics risks, fresh agri-product suppliers must evaluate the transportation services and shipment damage while developing live-streaming plans.

There are primarily two types of live-streaming formats: Supplier self-broadcasting (S) and key opinion leader (KOL)-based live-streaming. Under the Scenario S, suppliers bear the risks of logistics-related spoilage of fresh agri-foods. Such suppliers typically have well-known owners or loyal consumers and established long-term collaborations with logistics firms, yet they lack the financial resources to employ professional streamers. An example is "Nana's family in the countryside", a couple of rural lifestyle micro-influencers who share their entrepreneurial life in the countryside and use their influence to sell fresh agri-foods via live-streaming. In contrast, KOL-based live-streaming can be divided into two scenarios. The first scenario is the agency sale (KA), wherein KOLs serve as the middlemen to market the supplier's items during live-streams, while the supplier manages the delivery. In this case, suppliers set the product prices and bear the cold chain logistics and transportation risks. This is a prevalent collaboration concept in live-streaming sales. The second scenario is resale (KR), where KOLs resell purchased products to consumers under their own branding. In this case, the suppliers are often small-to-medium-sized farmers lacking famous managers and stable logistics channels. Examples include Simba Selection and Eastbuy.

Under different online live-streaming formats, the logistics services and spoilage costs for fresh agri-foods are paid by various entities. Since differences in live-streaming formats not only affect the logistics service levels and product freshness but also impact firms' profit performance across the supply chain, this paper analyzes a supply chain system that includes a supplier of fresh agri-foods, a KOL host, and a cold chain logistics service provider. It examines the equilibrium decision-making mechanisms among these three parties under self-broadcasting (S), KOL-assisted agency sales (KA), and KOL-resale (KR) formats. Specifically, we focus on the following three research questions.

(1) How do the supplier, KOL, and third-party logistics (3PL) interactively determine optimal operational strategies (including pricing, live-streaming efforts, and logistics service levels) across different live-streaming formats?

(2) Under what conditions should supply chain members choose the S, KA, or KR formats, and how do KOL traffic and product spoilage rates influence live-streaming format selection strategies?

(3) Is there a “win–win–win” format that achieves Pareto improvement for all stakeholders and the entire system?

To answer these questions, we set three game models to capture the interaction between firms under scenarios S, KA, and KR. In Scenario S, the supplier manages the live-streaming sales, handles return losses, and covers logistics costs. In Scenario KA, the KOL handles the live-streaming sales, while the supplier handles the return losses and the logistics costs. In Scenario KR, the KOL oversees the live-streaming sales and handles both the return losses and logistics costs. We solved the equilibrium solutions for all three models. We then analyzed the influence of significant parameters that the on the outcomes, specifically examining the impact of return losses on pricing strategies and profitability across various live-streaming formats. Finally, we compared equilibrium outcomes across the three scenarios, guiding the choice of the optimal live-streaming format from both the supplier’s and KOL’s perspectives.

In this paper, we make the following contributions. First, this study extends the existing literature on live-streaming sales of agricultural products by explicitly incorporating the high logistics and spoilage compensation costs arising from the perishability of fresh agri-foods, as well as the allocation of these costs among different supply chain members under various live-streaming formats. Second, unlike prior research that primarily assumes higher preservation efforts for agri-foods expand market demand, this study emphasizes the role of such efforts in reducing firms’ compensation costs through spoilage mitigation, thereby providing a more realistic representation of supply chain operations. Third, the study demonstrates that although KOLs’ traffic can stimulate market demand, it does not necessarily benefit all supply chain participants, including the KOLs themselves. Specifically, under the KA model, internal slot payments tied to traffic can create profit conflicts within the supply chain. Finally, the study identifies conditions for selecting the optimal live-streaming format from multiple perspectives and delineates circumstances under which a win–win outcome for 3PL providers, suppliers, and KOLs can be achieved. It further examines how the compensation price, initial the spoilage rate, and KOL traffic influence the choice of live-streaming format. The results reveal that the interaction among traffic advantage, spoilage-related cost exposure, and pricing authority generates nonmonotonic preferences across alternative live-streaming structures.

The remainder of this paper is organized as follows. We review the relevant literature in Section 2 and describe the model setting in Section 3. In Section 4, we derive the equilibrium of the three main models. Then, in Section 5, we explore the strategy selection of live-streaming formats. Finally, in Section 7, we summarize the essential findings and the managerial implications.

2. Literature review

2.1. Fresh agri-food supply chain

Fresh agri-foods possess inherent characteristics such as high perishability, susceptibility to damage, and short shelf life, which make their production, transportation, and sales processes substantially different from those of durable goods [9]. These features impose stringent requirements on logistics timeliness and freshness preservation throughout the supply chain. To mitigate quality deterioration during transportation, firms typically use specialized packaging, temperature-controlled logistics, and expedited delivery. Existing studies show that the "freshness efforts" undertaken by logistics service providers—including packaging, temperature control, and delivery speed—can effectively slow spoilage and stimulate market demand [10]. However, such efforts also entail considerable logistics costs, compelling supply chain members to balance freshness maintenance against the associated expenditures. Consequently, a stream of research has examined decision optimization across various operational dimensions of fresh produce supply chains based on the cost–benefit trade-offs of freshness investments, including pricing strategies [11], procurement strategies [12], inventory strategies [13, 14], and government subsidy policies [15].

Moreover, some studies suggest that logistics service providers' freshness preservation efforts not only expand demand but also alleviate sellers' cost burdens by reducing spoilage rates [16]. This effect is particularly salient under compensation mechanisms. On major e-commerce platforms (e.g., JD.com, Pinduoduo, Amazon), firms commonly offer services such as "badfruit compensation". When consumers receive spoiled items, sellers must provide compensation either proportionally or on a per-item basis. Under such mechanisms, freshness levels directly affect the final quantity of spoiled goods and therefore the magnitude of the sellers' compensation payments, which, in turn, shape their operational decisions and profitability.

Although prior studies have extensively examined freshness preservation, spoilage reduction, and compensation mechanisms in fresh agri-food supply chains, most of them focus on traditional offline methods. In these settings, consumers can often directly assess products' freshness before purchase, and spoilage risks can be mitigated through spot-market replenishment [16]. However, such assumptions may not hold in live-streaming commerce, where consumers make purchasing decisions without directly observing products' freshness and may request compensation only after receiving spoiled products. Therefore, analyzing fresh agri-food supply chains in the context of live-streaming requires explicit consideration of perishability and the associated compensation mechanisms.

Moreover, existing studies rarely examine how logistics preservation efforts, spoilage compensation mechanisms, and live-streaming operations jointly affect supply chain decisions. In particular, little attention has been paid to how different live-streaming formats allocate product ownership, pricing authority, and compensation responsibilities among suppliers, KOLs, and logistics service providers. To address these gaps, this study incorporates freshness preservation efforts and badfruit compensation mechanisms into a live-streaming supply chain framework and investigates how these factors influence operational decisions and live-streaming format selection.

2.2. *Live-streaming commerce in operations management*

Currently, live-streaming commerce has become a popular business model, attracting many scholars to research it within operations management. Some studies examined whether companies should adopt live-streaming channels [17]. Zhang et al. [18] showed that adding a live-streaming channel can increase sales; meanwhile, Li et al. [19] argued that although live-streaming can improve consumers' perception of the product value, firms do not necessarily profit more from this channel. Gong et al. [20] stated that including live-streaming channels reduces firms' profits when selling highly personalized goods. Pan et al. [21] and Du et al. [22] found that live-streaming benefits firms only if the streamers have strong sales skills. Li et al. [23] suggested that high supply volatility encourages firms to adopt live-streaming channels. Additionally, Zhang et al. [17] noted that when revenue-sharing ratios and contract fees are reasonable, the manufacturer can adopt live-streaming to improve the system's overall efficiency and benefit consumers. In competitive markets, companies' strategies for adopting live-streaming vary [24]. Huang et al. [25] analyzed two competing retailers and found that those selling high-fit products are more likely to use live-streaming; retailers with low-fit products only consider it when streamer commissions are low and consumer matching costs are high. Lu and Duan [26] argued that when live-streaming's information flow is limited and streamers lack influence, competitors should avoid using this strategy, regardless of whether their rivals do.

Some scholars have investigated the impact of the attributes of live-streaming on corporate operational decisions. For example, Zhang et al. [27] noted that firms tend to lower commissions for low-influence streamers while offering larger price discounts under conditions of information asymmetry. Liu et al. [28] investigated the effect of anticipated consumer regret, revealing that streamers respond by lowering product prices. Additionally, Xie et al. [29] examined the impact of channel free-riding under both limited and unlimited live-streaming resource scenarios. Lastly, Liu et al. [30] analyzed the impact of misleading product information in live-stream shopping within competitive markets, finding that high-value firms can benefit from the misleading behaviors of low-value firms.

In addition, some studies have focused on the selection of live-streaming modes. Numerous of them have explored whether firms should conduct self-broadcasting or rely on KOL streamers. Wang and Wang [31] argued that firms should opt for self-broadcasting when KOLs have low sales capabilities and consumers face low hassle costs for participating in live-streaming, while Xu et al. [32] pointed out that the selection primarily depends on the promotional costs of self-broadcasting. Zhang et al. [18] found that KOL streamers often prefer hybrid live-streaming when price competition is intense. Chen et al. [33] proposed that e-commerce platforms should fully rely on KOLs during the initial phase of live-streaming, gradually shift toward self-broadcasting during the growth stage, and revert to partially relying on KOLs during the mature stage. Other scholars have further investigated alternative forms of live-streaming. For example, supplier-hosted versus e-commerce platform-hosted live-streaming [34, 35], platform-enabled mode versus platform-agency mode [32], and e-commerce platform-based live-streaming (such as Taobao) versus dedicated live-streaming platforms [36]. Some scholars have examined corporate selection strategies for streamer types. For instance, Gu et al. [37] found that when companies collaborate with both top-tier and mid-tier KOLs simultaneously, mid-tier KOLs tend to diminish the promotional effectiveness of their top-tier counterparts. Wei and Xi [38] demonstrated that chief executive officer (CEO) streamers enhance engagement by boosting consumers' cognitive trust, while KOL streamers primarily achieve the same effect by establishing consumers' emotional trust.

Despite the burgeoning research on live-streaming commerce, the critical roles of logistics preservation, spoilage risks, and compensation mechanisms in fresh agri-food chains remain relatively underexplored. Furthermore, although some studies investigate different live-streaming formats, they generally do not consider how these formats alter the allocation of product ownership, logistics responsibilities, and compensation costs among suppliers, KOLs, and third-party logistics providers. As a result, the interaction between logistics service decisions and live-streaming format selection remains insufficiently explored. To bridge these gaps, this study develops a fresh agri-food live-streaming supply chain model that explicitly incorporates perishability, preservation efforts, and badfruit compensation mechanisms under different live-streaming formats. By comparing supplier self-streaming, KOL reselling, and KOL agency-selling formats, this study reveals how logistics decisions and responsibility allocation jointly shape operational strategies and format preferences.

3. Model setting

3.1. Firm profits

We consider a live-streaming e-commerce supply chain consisting of a fresh agri-food supplier, a KOL, and a 3PL provider. The supplier can either sell products through self-broadcasting or collaborate with a KOL. The 3PL is responsible for the preservation and transportation of fresh agri-foods. The structure of the supply chain is illustrated in Figure 1. Due to the highly perishable nature of fresh agri-foods, they are particularly vulnerable to spoilage during transportation. On the one hand, it may result in compensation claims for damaged goods; on the other hand, it relies on cold chain logistics and specialized packaging, which increases the logistics costs. In practice, fresh agri-foods are considered to be special goods. As long as the delivery is made on time, the logistics service provider is not liable for any compensation [39]. Typically, the seller (either the supplier or the KOL) compensates consumers proportionally according to the quantity of spoiled products. Regarding the logistics service costs, they are usually borne by the party responsible for shipping.

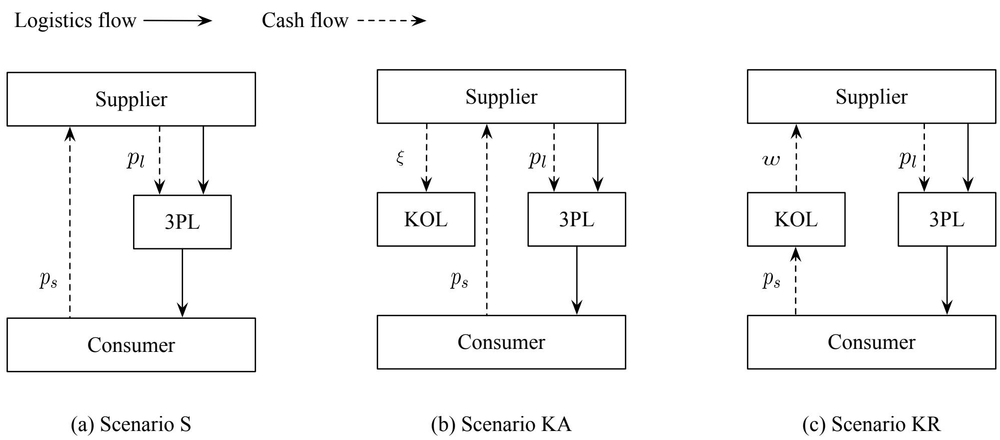

Figure 1. The structure of the supply chain.

Under the supplier self-broadcasting mode (Scenario S), the supplier is responsible for the logistics services and bears the risk of product spoilage or damage during transportation. When collaborating with a KOL, there are two distinct scenarios. In the KOL agency case (Scenario KA), the KOL conducts live-streaming to promote and sell the products, while the supplier remains responsible for product pricing, logistics services, and transportation risks. In the KOL resale case (Scenario KR), the KOL buys products wholesale from the supplier and resells them to consumers, taking charge of live-streaming as well as the logistics services and transportation risks. Table 1 lists three potential decision scenarios. Table 2 lists the basic notation used in this paper.

Table 1. Potential decision scenarios.

Live-streaming sales format	Bear the logistics service cost	Bear the compensation for product spoilage
Supplier self-broadcasting (S)	Supplier	Supplier
KOL-assisted agency sales (KA)	Supplier	Supplier
KOL-resale (KR)	KOL	KOL

Table 2. Notations.

Notation	Definition
Decision variables	
e	Preservation effort of agricultural products
k	Live-streaming effort
p_l	Logistics service price of unit products
p_s	Retail price of a product unit
w	Wholesale price of a product unit
x	Commission fee of a product unit in Scenario KR
Auxiliary variables	
u_i	Consumer i's expected net utility from purchasing
D	Market demand
π_j	Profit function of j, in which $j = L, S, K$ represents the 3PL, supplier, and KOL, respectively
Parameters	
v	Consumer's valuation of the product, $v \sim U[0, 1]$
θ	Consumer's acceptance of live-streaming sales, $\theta \in (0, 1)$
β	Consumer's price sensitivity, $\beta > 0$
f	KOL's traffic
ϕ	Conversion rate of KOL's traffic
T	KOL's basic slotting fee coefficient
ξ	Commission rate paid the supplier to KOL in Scenario KA, $\xi \in (0, 1)$
r	Initial spoilage rate for fresh agri-foods, $r \in (0, 1)$
c_l	Logistic cost per product unit
c_m	Production cost per product unit
p_c	Compensation price for spoiled product
γ	Preservation effort cost coefficient
λ	Live-streaming effort cost coefficient

3.1.1. Scenario S

The supplier sells products directly to consumers through self-broadcasting and bears the logistics costs for fresh agri-foods her/himself. Let the retail price of the product be p_s, the unit production cost be c_m, and the logistics service price be p_l. Then the supplier's unit sales revenue is $p_s - p_l - c_m$, and the total sales revenue is $(p_s - p_l - c_m)D$. To achieve live-streaming effort level k, the supplier incurs live-streaming costs of $\frac{1}{2}\lambda k^2$. This paper uses a quadratic cost function to capture the diminishing marginal utility characteristic of live-streaming effort. A larger λ indicates that improving live-streaming effort becomes more difficult and costly. Such quadratic cost functions are widely used to model diminishing marginal utility scenarios involving live-streaming effort improvement [40], service improvement [41, 42], audit rate improvement [43], etc.

Products may incur losses during transportation. Let the initial loss rate without enhanced logistics service be $r \in (0, 1)$, and the 3PL's preservation effort level be e, and the compensation price per spoiled product delivered to consumers be p_c [44]. Given the perishable nature of fresh agri-foods, a certain degree of natural loss during transportation is unavoidable. As improving the preservation levels cannot completely eliminate spoilage, we assume $e \in (0, 1)$. Then the actual quantity of product loss can be expressed as $r(1 - e)D$, resulting in the loss cost $p_c r(1 - e)D$. Thus, the supplier's profit function can be expressed as in Eq (3.1).

$$\pi_S(p_s, k) = (p_s - p_l - c_m)D - \frac{1}{2}\lambda k^2 - p_c r(1 - e)D. \tag{3.1}$$

When providing logistics services, the 3PL incurs a unit of logistics service cost of c_l per product. The unit revenue generated from providing logistics services is $p_l - c_l$, yielding a total revenue of $(p_l - c_l)D$. To achieve the preservation effort level e, the 3PL must incur a cost of $\frac{1}{2}\gamma e^2$. Similarly, a quadratic cost function is used to characterize the diminishing marginal utility of preservation efforts. Thus, the 3PL's profit function can be expressed as Eq (3.2).

$$\pi_L(p_l, e) = (p_l - c_l)D - \frac{1}{2}\gamma e^2. \tag{3.2}$$

3.1.2. Scenario KA

The supplier sells products to consumers through the KOL live-streaming, sharing a proportion ξ of sales revenue with the KOL, and paying a slotting fee Tf. The higher the KOL's traffic level f, the greater the slotting fee received. The basic slotting fee coefficient T reflects the heterogeneity of traffic monetization across different domains. Even with an identical traffic volume, slotting fees exhibit significant variance across sectors due to disparities in profit margins, average order value, and the niche expertise of the KOL, e.g., beauty vs. daily groceries [45]. The supplier is responsible for the logistics service cost $p_l D$ associated with fresh agri-foods, in addition to the spoilage loss cost $p_c r(1 - e)D$. To achieve live-streaming effort level k, the KOL incurs costs of $\frac{1}{2}\lambda k^2$. Consequently, the profit functions for the supplier and KOL are given by Eqs (3.3) and (3.4), respectively, while the 3PL's profit function remains as given by Eq (3.2).

$$\pi_S(p_s) = (p_s - p_l - c_m)D - \xi p_s D - Tf - p_c r(1 - e)D. \tag{3.3}$$

$$\pi_K(k) = \xi p_s D + Tf - \frac{1}{2}\lambda k^2. \tag{3.4}$$

3.1.3. Scenario KR

The KOL buys products at a wholesale price w from the supplier, adds a commission fee x, and resells them to consumers via live-streaming at a price p_s ($p_s = w + x$). In addition, the KOL pays a logistics service fee p_lD to the 3PL and bears the spoilage loss costs $p_cr(1-e)D$ and the live-streaming costs $\frac{1}{2}\lambda k^2$. Consequently, the profit functions for the supplier and KOL are given by Eqs (3.5) and (3.6), respectively, while the 3PL's profit function remains as given by Eq (3.2).

$$\pi_S(w) = (w - c_m)D. \tag{3.5}$$

$$\pi_K(x,k) = (x - p_l)D - \frac{1}{2}\lambda k^2 - p_c r(1-e)D. \tag{3.6}$$

Furthermore, to guarantee the existence of interior solutions for all three models, the cost coefficients for product preservation and live-streaming efforts are assumed to be sufficiently large, i.e., $\lambda > \max\left\{\frac{1}{2\beta\theta}, \frac{\xi}{\beta\theta}\right\}$ and $\gamma > \max\left\{\frac{\beta^2\lambda r^2 p_c^2}{2(2\beta\theta\lambda-1)}, \frac{r^2 p_c^2(\beta\theta\lambda-\xi)}{4\theta^2\lambda(1-\xi)}\right\}$. This assumption guarantees that the profit functions are concave, thereby ensuring a unique optimal solution for all three models. In addition, it captures the practical challenges of maintaining the freshness of perishable agricultural products and organizing live-streaming sales.

3.2. Consumer utility

The consumer valuation v of a product follows a uniform distribution over the interval $(0,1)$. Let θ denote the consumer's acceptance level for live-streaming. The academic perspectives diverge on θ: Some scholars contend that the consumers' perception of the products' value in live-streaming is identical to that in traditional online sales [23]; others argue that live-streaming enables more intuitive and vivid demonstrations of products' functions and features, thereby enhancing consumers' purchasing utility in live-streaming [46]; while others contend that consumers' acceptance of live-streaming is lower than that of traditional online sales [47]. We adopt the latter assumption: Consumer's acceptance of live-stream shopping $\theta \in (0,1)$. This is primarily based on two considerations: First, as an emerging sales format, live-stream shopping has not yet been universally accepted by all consumers; second, live-stream shopping involves fixed schedules, requires entering the live-stream channel, and may even involve flash sales, making the process more complex than traditional online shopping.

Consumers' purchasing decisions in live-streaming are influenced not only by the product price p_s but also by the streamer's (the supplier or KOL) effort k. Higher streamer effort, such as providing more detailed product presentations or fostering a positive atmosphere, increases consumers' perceived utility. Furthermore, unlike supplier self-broadcasting, KOLs typically possess large fan bases and strong celebrity effects, whose traffic can enhance consumers' purchase intent to some extent. The greater the KOL's traffic, the more potential consumers they can attract. Therefore, following Liu et al. [30] and Xiang et al. [40] the consumers' expected net utility in the supplier self-broadcasting scenario is represented by $u = \theta v - \beta p_s + k$, and in the KOL live-streaming scenario, it is represented by $u = \theta v - \beta p_s + k + \phi f$. The consumers buy the product only if their expected net utility is positive. Consequently, the demand functions for supplier self-broadcasting and KOL live-streaming are formulated as Eqs (3.7) and (3.8), respectively.

$$D = \frac{\theta - \beta p_s + k}{\theta} \tag{3.7}$$

$$D = \frac{\theta - \beta p_s + k + f\phi}{\theta} \tag{3.8}$$

3.3. Events sequence

Cold chain logistics decisions, particularly investments in preservation efforts (e.g., refrigeration equipment and refrigerated delivery vehicles), usually involve longer planning cycles and higher capital commitments than the supplier's pricing decisions and the streamer's commission decisions. In addition, the 3PL's preservation effort directly affects the product loss rate and the effective market supply, while logistics service prices are typically determined prior to the transactions and are difficult to adjust in the short term. Therefore, following Yu et al. [16], we assume that the 3PL acts as the Stackelberg leader, whereas the supplier and the KOL act as followers. Figure 2 illustrates the sequence of events as follows.

Mode selection: The supplier first decides between self-broadcasting and KOL live-streaming.

Case 1. Self-broadcasting is selected.

1. The 3PL sets the logistics service price (p_l) and the preservation effort level (e).
2. The supplier determines the retail price (p_s) and the live-streaming effort (k).

Case 2. KOL live-streaming is selected.

The supplier further chooses between the agency sale and resale models.

Subcase 2.1. The supplier chooses the agency sale model.

1. The 3PL sets the logistics service price (p_l) and the preservation effort level (e).
2. The supplier sets the retail price (p_s).
3. The KOL determines the live-streaming effort (k).

Subcase 2.2. The supplier chooses the resale model.

1. The 3PL sets the logistics service price (p_l) and the preservation effort level (e).
2. The supplier sets the wholesale price (w).
3. The KOL determines the commission fee (x) and the live-streaming effort (k).

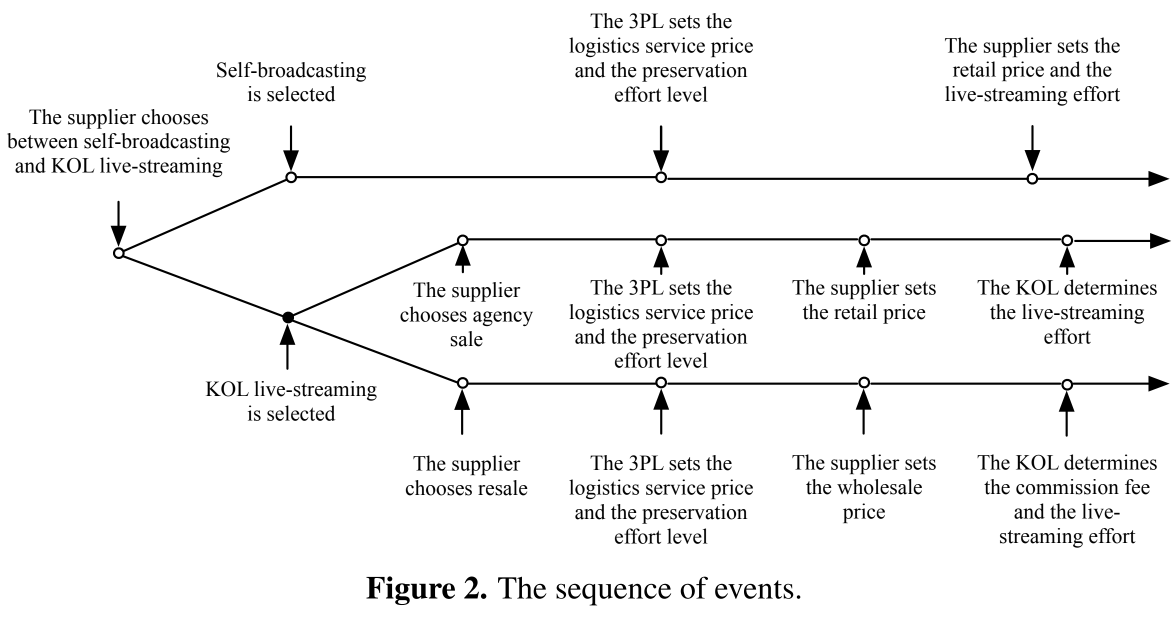

Figure 2. The sequence of events.

4. Equilibrium analysis

This section derives the equilibrium solutions for the model under Scenarios S, KA, and KR, respectively, and examines the impact of key parameter variations on the equilibrium outcomes.

4.1. Scenario S

In Scenario S, the 3PL acts as the Stackelberg leader, setting the logistics service price (p_l) and the preservation effort level (e) first. Then the supplier sets the retail price (p_s) and the live-streaming effort (k) based on p_l and e. This assumption corresponds with practical situations. In real operations, 3PLs usually establish and disclose the logistics pricing beforehand, with the rates typically remaining consistent over a designated timeframe. Concurrently, the standard of logistics service is also pre-established.

By using backward induction, the equilibrium of Scenario S is presented in Theorem 4.2. Lemma 4.1 summarizes the impact of the 3PL's decisions on the supplier's optimal responses. All mathematical proofs presented in this paper can be found in Appendix A.

Lemma 4.1. *For any given logistics service price p_l and preservation effort e, the supplier's optimal response $k^*(p_l, e)$ and $p_s^*(p_l, e)$ satisfy the following:*
(1) $k^*(p_l, e)$ is strictly increasing in e and decreasing in p_l.
(2) If $\theta > \frac{1}{\beta\lambda}$, then $p_s^*(p_l, e)$ decreases with e but increases with p_l; whereas if $\theta < \frac{1}{\beta\lambda}$, then $p_s^*(p_l, e)$ increases with e but decreases with p_l.

Lemma 4.1-(1) shows that the supplier increases the live-streaming effort k when the 3PL enhances the preservation effort e or reduces the logistics service price p_l. The underlying mechanism is that both higher preservation effort and lower logistics service prices reduce the supplier's effective operating costs by decreasing product losses and logistics expenditures, respectively. Consequently, the supplier has a stronger incentive to stimulate market demand through greater live-streaming efforts.

However, Lemma 4.1-(2) indicates that the supplier's pricing decision is additionally affected by consumers' acceptance of live-streaming. If consumer acceptance is high, when the 3PLs enhance efforts to preserve the freshness of agricultural products or reduce logistics service prices, the supplier reduces the retail price to expand sales volume and increase market share. Conversely, when consumer acceptance is low, the supplier tends to raise retail prices. The fundamental reason lies in the fact that consumers' acceptance of live-streaming determines the potential market size for live-stream sales. When the potential market size is small, the stimulus effect of price changes on sales volume is limited. In such circumstances, even if the supplier's logistics spoilage costs and logistics service costs decrease, the supplier prefers to stimulate market demand by adjusting their live-streaming effort rather than altering the retail price. Consequently, the supplier increases the retail price to secure higher profit margins.

Theorem 4.2. *Under Scenario S, the optimal strategies of the supplier and the 3PL are given as follows:*

$$\begin{cases} p_s^{S*} = \dfrac{3\beta\gamma\theta^2\lambda + \beta\gamma(\beta\theta\lambda - 1)(c_l + c_m) + \beta^2\theta\lambda r p_c(\gamma - r p_c) - \gamma(\beta r p_c + \theta)}{\beta(2\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)}; \\ k^{S*} = \dfrac{\gamma(\theta - \beta c_l - \beta c_m - \beta r p_c)}{2\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2}; \\ p_l^{S*} = \dfrac{\gamma(2\beta\theta\lambda - 1)(\theta + \beta c_l - \beta c_m - \beta r p_c) - \beta^3\lambda r^2 c_l p_c^2}{\beta(2\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)}; \\ e^{S*} = \dfrac{\beta\lambda r p_c(\theta - \beta c_l - \beta c_m - \beta r p_c)}{2\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2}. \end{cases}$$

Substituting Theorem 4.2 into Eqs (3.7), (3.1), and (3.2), the optimal demand and the corresponding profits for the supplier and the 3PL can be obtained.

$$D^{S*} = \frac{\beta\gamma\lambda(\theta - \beta c_l - \beta c_m - \beta r p_c)}{2\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2}$$

$$\pi_S^{S*} = \frac{\gamma^2\lambda(2\beta\theta\lambda - 1)(\theta - \beta c_l - \beta c_m - \beta r p_c)^2}{2(2\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)^2}$$

$$\pi_L^{S*} = \frac{\gamma\lambda(\theta - \beta c_l - \beta c_m - \beta r p_c)^2}{2(2\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)}$$

Proposition 4.3 summarizes the impact of the compensation price for spoiled products p_c on the equilibrium strategies of the 3PL and the supplier in Scenario S. All threshold values (such as γ_1, γ_2, γ_3, etc.) used in this paper are presented in Appendix B.

Proposition 4.3. *The impact of the compensation price p_c on the optimal strategies of the 3PL and the supplier is characterized as follows.*
(1) The 3PL's optimal strategies: (i) The optimal logistics service price p_l^{S*} decreases with p_c if $\gamma > \gamma_1$ and increases otherwise. (ii) The optimal preservation effort e^{S*} decreases with p_c if $r > r_1, \gamma > \gamma_2$ or $r < r_1, \gamma < \gamma_2$; otherwise, it increases with p_c.
(2) The supplier's optimal strategies: Both the optimal retail price p_s^{S*} and the live-streaming effort k^{S*} decrease with p_c if $\gamma > \gamma_1$ and increase otherwise.

Proposition 4.3 indicates that the impacts of the compensation price for spoiled products p_c on the equilibrium strategies of the 3PL and the supplier mainly depend on the preservation effort cost coefficient γ. When γ is high, preservation improvement becomes costly and inefficient. In this case, an increase in the compensation price intensifies the 3PL's expected compensation burden, but further preservation investment cannot effectively offset the additional cost pressure. As a result, the 3PL strategically lowers the logistics service price to maintain downstream demand and reduce the risk of demand loss caused by higher circulation costs. Facing weaker market demand and lower profitability, the supplier correspondingly reduces both the retail price and the live-streaming effort.

In contrast, when γ is low, preservation effort becomes more cost-effective. Under this condition, a higher compensation price strengthens the 3PL's incentive to improve logistics service quality because spoilage reduction can effectively reduce the expected compensation losses. The resulting improvement in product quality enhances the supplier's sales incentives, leading to higher retail prices and greater live-streaming effort.

Moreover, the 3PL's decision regarding preservation effort is also influenced by the initial spoilage rate of fresh agri-foods. Specifically, the 3PL reduces the preservation effort level only when both the initial spoilage rate and the preservation cost coefficient are either high or low. This is because the optimal preservation effort is not necessarily maximized; rather, it is determined by the balance between preservation costs and the loss reduction achieved by mitigating spoilage. When both the initial spoilage rate and the preservation cost coefficient are high, additional preservation effort yields limited improvements in product quality, causing the marginal cost of preservation to exceed the marginal benefit. Conversely, when both are low, the risk of deterioration during transportation is already minimal, making the additional preservation effort neither necessary nor economically beneficial. Consequently, in both cases, the marginal return of preservation effort declines, leading the 3PL to reduce preservation investment.

Corollary 4.4. *The impact of the compensation price p_c on the equilibrium demand and the profits of the 3PL and the supplier is characterized as follows.*
(1) Both the optimal demand D^{S*} and the supplier's profit π_S^{S*} decrease with p_c if $\gamma > \gamma_1$ and increase otherwise.
(2) The 3PL's optimal profit π_L^{S*} decreases with p_c if $\gamma > \gamma_3$ and increases otherwise.

Corollary 4.4 further summarizes the impact of the compensation price for spoiled products p_c on the demand and profits of the 3PL and the supplier. When the preservation cost coefficient is high, as the compensation price for spoiled products rises, the 3PL and the supplier get less demand and profits. Conversely, when the preservation cost coefficient is low, both their demand and profits increase. This outcome arises from the combined effects of pricing decisions and live-streaming efforts, among which the latter plays a dominant role. When the cost coefficient is relatively high, a reduction in live-streaming efforts offsets the stimulating effect of lower retail prices, leading to a decline in market demand and, consequently, lower supplier profits. For the 3PL, the decline in demand, coupled with the reduction in the marginal profit from logistics services caused by the decrease in logistics service prices, ultimately reduces its overall profitability.

4.2. Scenario KA

In Scenario KA, the 3PL acts as the Stackelberg leader, setting the logistics service price (p_l) and the preservation effort level (e) first. Then the supplier sets the retail price (p_s) based on p_l and e. Finally, the KOL sets the live-streaming effort (k) based on p_l, e, and p_s.

By using backward induction, the equilibrium of Scenario KA is presented in Theorem 4.6. Lemma 4.5 summarizes the impact of 3PL's decisions on the supplier's and KOL's optimal responses.

Lemma 4.5. *For any given logistics service price p_l and preservation effort e, both the KOL's optimal response $k^*(p_l, e)$ and the supplier's optimal response $p_s^*(p_l, e)$ are monotonically decreasing in e and increasing in p_l.*

Lemma 4.5 indicates that when the 3PL enhances the preservation effort e or reduces the logistics service price p_l, the supplier's effective unit cost decreases due to lower spoilage losses and logistics expenditures. This cost reduction intensifies price competition pressure and leads the supplier to adjust the retail price downward in order to expand demand.

However, different from Scenario S, the KOL reduces the live-streaming effort k in Scenario KA. This is because when the retail price is lowered, it simultaneously reduces the KOLs' marginal earnings from live-streaming and decreases demand's reliance on live-streaming efforts. Consequently, the KOL optimal strategy is to lower the live-streaming effort.

Therefore, improved logistics conditions reduce both the supplier's pricing level and the KOL's effort level, but through distinct channels: Cost-driven pricing adjustment on the supplier side and diminished marginal effort return on the KOL side.

Theorem 4.6. *Under Scenario KA, the optimal strategies of the supplier, the KOL, and the 3PL are given as follows:*

$$\begin{cases} p_s^{KA*} = \dfrac{\theta\lambda\left((\beta\theta\lambda-\xi)\left(\gamma\theta\,(c_l+c_m+rp_c)-r^2p_c^2(f\phi+\theta)\right)+3\gamma\theta^2\lambda(1-\xi)(f\phi+\theta)\right)}{(\beta\theta\lambda-\xi)\,(4\gamma\theta^2\lambda(1-\xi)-r^2p_c^2(\beta\theta\lambda-\xi))}; \\ k^{KA*} = \dfrac{\xi\left((\beta\theta\lambda-\xi)\left(\gamma\theta\,(c_l+c_m+rp_c)-r^2p_c^2(f\phi+\theta)\right)+3\gamma\theta^2\lambda(1-\xi)(f\phi+\theta)\right)}{(\beta\theta\lambda-\xi)\,(4\gamma\theta^2\lambda(1-\xi)-r^2p_c^2(\beta\theta\lambda-\xi))}; \\ p_l^{KA*} = \dfrac{2\gamma\theta^2\lambda(1-\xi)\,((\beta\theta\lambda-\xi)\,(c_l-c_m-rp_c)+\theta\lambda(1-\xi)(f\phi+\theta))-r^2c_lp_c^2(\beta\theta\lambda-\xi)^2}{(\beta\theta\lambda-\xi)\,(4\gamma\theta^2\lambda(1-\xi)-r^2p_c^2(\beta\theta\lambda-\xi))}; \\ e^{KA*} = \dfrac{rp_c\,(\theta\lambda(1-\xi)(f\phi+\theta)-(\beta\theta\lambda-\xi)\,(c_l+c_m+rp_c))}{4\gamma\theta^2\lambda(1-\xi)-r^2p_c^2(\beta\theta\lambda-\xi)}. \end{cases}$$

By substituting Theorem 4.6 into Eqs (3.8), (3.2), (3.3), and (3.4), the optimal demand and the corresponding profits for the 3PL, the supplier, and the KOL can be obtained.

$$D^{KA*} = \frac{\gamma\,(\theta\lambda(1-\xi)(f\phi+\theta)-(\beta\theta\lambda-\xi)\,(c_l+c_m+rp_c))}{4\gamma\theta^2\lambda(1-\xi)-r^2p_c^2(\beta\theta\lambda-\xi)}$$

$$\pi_L^{KA*} = \frac{\gamma\,(\theta\lambda(1-\xi)(f\phi+\theta)-(\beta\theta\lambda-\xi)\,(c_l+c_m+rp_c))^2}{2(\beta\theta\lambda-\xi)\,(4\gamma\theta^2\lambda(1-\xi)-r^2p_c^2(\beta\theta\lambda-\xi))}$$

$$\pi_S^{KA*} = \frac{\gamma^2\theta^2\lambda(1-\xi)\,(\theta\lambda(1-\xi)(f\phi+\theta)-(\beta\theta\lambda-\xi)\,(c_l+c_m+rp_c))^2}{(\beta\theta\lambda-\xi)\,(4\gamma\theta^2\lambda(1-\xi)-r^2p_c^2(\beta\theta\lambda-\xi))^2} - fT$$

$$\pi_K^{KA*} = \frac{\lambda\xi\left((\beta\theta\lambda-\xi)\left(\gamma\theta\,(c_l+c_m+rp_c)-r^2p_c^2(f\phi+\theta)\right)+3\gamma\theta^2\lambda(1-\xi)(f\phi+\theta)\right)\Omega}{2(\beta\theta\lambda-\xi)^2\,(4\gamma\theta^2\lambda(1-\xi)-r^2p_c^2(\beta\theta\lambda-\xi))^2} + fT$$

Proposition 4.7 summarizes the impact of the KOL's traffic f on the equilibrium strategies of the 3PL, the supplier, and the KOL in Scenario KA.

Proposition 4.7. *The impact of the KOL's traffic f on the optimal strategies of the 3PL, the supplier, and the KOL is characterized as follows.*
(1) The 3PL's optimal strategies: Both the optimal logistics service price p_l^{KA*} and the preservation effort e^{KA*} increase with the KOL's traffic f.
(2) The supplier's optimal strategies: The optimal retail price p_s^{KA*} increases with traffic f if $r < r_2$ and decreases otherwise.
(3) The KOL's optimal strategies: The optimal live-streaming effort k^{KA*} increases with traffic f if $r < r_2$ and decreases otherwise.

Proposition 4.7 highlights how the KOL's traffic reshapes the operational decision of the live-streaming supply chain through its dual role in expanding demand and amplifying spoilage-related risk.

On the 3PL's side, higher traffic directly increases expected transaction volume and therefore raises the marginal return to logistics service quality. This strengthens the 3PL's incentive to invest in preservation efforts, which, in turn, justifies a higher logistics service price as the market becomes more valuable.

For the supplier and the KOL, the effects of traffic depend crucially on the initial spoilage rate r, which determines whether demand expansion or compensation losses dominate the decision trade-off. When r is low, spoilage risk is limited and the system primarily benefits from demand expansion. In this case, higher KOL traffic increases the effective market size, allowing the supplier to raise the retail price to extract surplus, while the KOL further increases his/her live-streaming effort to capitalize on the enlarged demand base. In contrast, when r is high, increased traffic not only expands demand but also enlarges the scale of potential spoilage losses, thereby intensifying expected compensation and operational risk. Under this condition, the supplier responds by lowering the retail price to mitigate loss exposure and stabilize demand, and the KOL reduces his/her live-streaming effort accordingly.

Corollary 4.8. *The impact of the KOL's traffic f on the equilibrium demand and the profits of the 3PL, the supplier, and the KOL is characterized as follows.*
(1) The optimal demand D^{KA*} is strictly increasing in f.
(2) The optimal profits of both the 3PL and the supplier increase with f if $r < r_3$ and decrease otherwise.
(3) The KOL's optimal profit increases with f if $T > T_1$ and decreases otherwise.

Corollary 4.8 further summarizes the impact of f on firms' profits. It suggests that traffic is not always beneficial in live-streaming supply chains, and the economic value depends on the trade-off between market expansion and spoilage-related costs. Specifically, although increasing the KOL's traffic can stimulate market demand, it does not necessarily translate into higher profits for the 3PL, the supplier, or the KOL. The key reason is that traffic growth not only increases sales opportunities but also amplifies spoilage-related operational risks in the live-streaming supply chain.

For the 3PL and the supplier, an increase in the KOL's traffic enhances profitability only when the products exhibit a low initial spoilage rate. In this case, the demand expansion effect dominates, allowing both parties to benefit from larger sales volume. However, when the spoilage rate is high, traffic-driven demand growth simultaneously increases compensation losses and preservation costs. As a result, the additional operational burden outweighs the revenue gains from higher demand, leading to lower profits for both the supplier and the 3PL.

For the KOL, the dominant factor influencing profit changes is the basic slotting fee. When the base slotting fee is sufficiently high, higher traffic increases the total revenue generated from slotting fees, thereby improving the KOL's profit. Otherwise, the marginal revenue generated by additional traffic is insufficient to offset the associated effort cost, causing the KOL's profit to decline.

Proposition 4.9. *The impact of the compensation price p_c on the optimal strategies of the 3PL, the supplier, and the KOL is characterized as follows:*
(1) The 3PL's optimal strategies: (i) The optimal logistics service price p_l^{KA*} decreases with p_c if $\gamma > \gamma_4$ and increases otherwise. (ii) The optimal preservation effort e^{KA*} decreases with p_c if $r > r_4$ and $\gamma > \gamma_5$, or if $r < r_4$ and $\gamma < \gamma_5$ and increases otherwise.
(2) The supplier's optimal strategies: The optimal retail price p_s^{KA*} increases with p_c if $\gamma > \gamma_4$, and decreases otherwise.
(3) The KOL's optimal strategies: The optimal live-streaming effort k^{KA*} increases with p_c if $\gamma > \gamma_4$, and decreases otherwise.

Proposition 4.9 demonstrates that the impact of p_c on the 3PL's equilibrium decision under Scenario KA is similar to what is observed under Scenario S. Specifically, when the preservation cost coefficient γ is high, higher compensation prices increase the 3PL's cost pressure but improving preservation becomes relatively inefficient. As a result, the 3PL lowers the logistics service price to alleviate downstream operational pressure. In contrast, when γ is low, preservation effort is more cost-effective, motivating the 3PL to increase both logistics service prices and preservation effort in response to higher compensation risk. Moreover, when both the preservation cost coefficient γ and the initial spoilage rate r are either relatively large or small, an increase in p_c leads the 3PL to decrease the preservation effort level. The underlying mechanism of this result has been discussed in Proposition 4.3 and is therefore not restated here.

Compared with Scenario S, Proposition 4.9 indicates that the pricing and live-streaming effort decisions exhibit opposite tendencies in Scenario KA. This divergence arises because, under Scenario KA, pricing and live-streaming decisions are made independently by suppliers and KOLs. When the preservation cost coefficient γ is high, the decline in logistics service prices p_l^{KA*} lowers suppliers' logistics expenditures. Although the compensation price p_c increases, the cost-saving effect dominates, motivating suppliers to raise retail prices to enhance marginal profits. Observing the price increase, KOLs respond by exerting greater live-streaming efforts to maintain sales conversion rates. By contrast, when the preservation cost coefficient γ is low, the increase in compensation prices p_c prompts 3PLs to raise logistics service prices, thereby elevating the supplier's costs. Since the supplier cannot directly stimulate demand through live-streaming effort adjustments, he/she lowers retail prices to attract more consumers. KOLs, perceiving the supplier's price reduction, in turn, reduce their live-streaming efforts to mitigate potential income losses.

Therefore, under the KA mechanism, compensation risk not only affects logistics decisions but also reshapes the strategic interaction between supplier pricing and the KOL's effort decisions.

Corollary 4.10. *The impact of the compensation price p_c on the equilibrium demand and the profits of the 3PL, the supplier, and the KOL is characterized as follows.*
(1) The optimal market demand D^{KA*} decreases with p_c if $\gamma > \gamma_4$ and increases otherwise.
(2) The 3PL's profit π_L^{KA*} increases with p_c if $r > r_3$ or if $r < r_3$ and $\gamma < \gamma_6$. Conversely, it decreases with p_c if $r < r_3$ and $\gamma > \gamma_6$.
(3) The supplier's profit π_S^{KA*} increases with p_c if $r > r_3$ or if $r < r_3$ and $\gamma < \gamma_4$. Otherwise, it decreases with p_c when $r < r_3$ and $\gamma > \gamma_4$.
(4) The KOL's optimal profit π_K^{KA*} increases with p_c if $\gamma \in (\gamma_6, \gamma_7)$. Otherwise, it decreases with p_c if $\gamma > \gamma_7$ or $\gamma < \gamma_6$.

Corollary 4.10 reveals that when the preservation cost coefficient γ is high, a higher compensation price p_c motivates KOLs to exert greater live-streaming effort; however, this positive effect is offset as the supplier raises the retail price. Consequently, overall demand declines.

Interestingly, this does not necessarily erode the profits of the 3PL and the supplier. When the initial spoilage rate exceeds a certain threshold ($r > r_3$), their profits increase even under high preservation costs. This occurs because the 3PL reduces preservation efforts to minimize costs, while the supplier raises product prices to capture additional revenue. In contrast, for the KOL, the profitability effect mainly depends on whether the increased retail price can generate sufficient commission revenue to compensate for the demand reduction.

In summary, Corollary 4.10 suggests that higher compensation may shift firms' strategies from market expansion toward profit-margin protection in live-streaming supply chains.

4.3. Scenario KR

In Scenario KR, the 3PL acts as the Stackelberg leader, setting the logistics service price (p_l) and the preservation effort level (e) first. Then the supplier sets the wholesale price (w) based on p_l and e. Finally, the KOL sets the commission fee (x) and the live-streaming effort (k) based on p_l, e, and w.

By using backward induction, the equilibrium of Scenario KR is presented in Theorem 4.12. Lemma 4.11 summarizes the impact of the 3PL's decisions on the supplier's and KOL's optimal responses.

Lemma 4.11. *For any given logistics service price p_l and preservation effort e, the supplier's optimal response $w^*(p_l, e)$, the KOL's optimal response $x^*(p_l, e)$ and $k^*(p_l, e)$, and the retail price $p_s^*(p_l, e)$ satisfy the following.*
(1) $w(p_l, e)$ and $k(p_l, e)$ and both strictly increasing in e but decreasing in p_l.
(2) If $\theta > \frac{2}{3\beta\lambda}$, then $x(p_l, e)$ decreases with e but increases with p_l; whereas if $\theta < \frac{2}{3\beta\lambda}$, then $x(p_l, e)$ increases with e but decreases with p_l.
(3) If $\theta > \frac{1}{\beta\lambda}$, then $p_s(p_l, e)$ decreases with e but increases with p_l; whereas if $\theta < \frac{1}{\beta\lambda}$, then $p_s(p_l, e)$ increases with e but decreases with p_l.

Lemma 4.11 shows that, different from Scenario KA but similar to Scenario S, in Scenario KR, the KOL raises the live-streaming effort k when the 3PL enhances the preservation effort e or reduces the logistics service price p_l. This is because the KOL directly bears the logistics service costs and spoilage losses under Scenario KR, so improved logistics conditions strengthen the incentive to expand sales through greater live-streaming effort.

From Lemma 4.11, we also find that the KOL's pricing decision on the commission fee x is additionally influenced by consumers' acceptance of live-streaming, thereby impacting the retail price p_s in a similar manner. The fundamental reason behind this is similar to Scenario S: Consumers' acceptance of live-streaming determines the potential market size for live-stream sales. When the potential market size is small, the stimulus effect of price changes on sales volume is limited, leading to the KOL stimulating market demand by adjusting the live-streaming effort rather than the retail price. Consequently, the KOL raises the retail price even if the logistics spoilage costs and logistics service costs decrease. However, since the supplier bears neither the logistics spoilage costs nor the logistics service costs, the wholesale pricing strategies are primarily influenced by market demand. When the 3PL enhances preservation efforts or reduces logistics service prices, the KOLs correspondingly improve the live-streaming effort, thereby expanding market demand. The rightward shift in the demand curve prompts the supplier to raise the wholesale price to maximize profit. This behavior clearly illustrates the bargaining position of the supplier being strengthened within the game's equilibrium.

Theorem 4.12. *Under Scenario KR, the optimal strategies of the supplier, the KOL, and the 3PL are given as follows.*

$$\begin{cases} p_s^{KR*} = \dfrac{\gamma(7\beta\theta\lambda - 3)(f\phi + \theta) - r^2\beta^2\lambda p_c^2(f\phi + \theta) + \beta\gamma(\beta\theta\lambda - 1)(c_l + c_m + rp_c)}{\beta(4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)}; \\ x^{KR*} = \dfrac{\gamma(5\beta\theta\lambda - 2)(\beta(c_l - c_m + rp_c) + f\phi + \theta) - r^2\beta^2\lambda p_c^2(\theta + f\phi - \beta c_m) - 2\beta^2\gamma\theta\lambda(c_l + rp_c)}{\beta(4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)}; \\ w^{KR*} = \dfrac{\gamma(2\beta\theta\lambda - 1)(\theta + f\phi - \beta(c_l - 3c_m + rp_c)) - \beta^3\lambda r^2 c_m p_c^2}{\beta(4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)}; \\ k^{KR*} = \dfrac{\gamma(\theta + f\phi - \beta(c_l + c_m + rp_c))}{4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2}; \\ p_l^{KR*} = \dfrac{2\gamma(2\beta\theta\lambda - 1)(\beta(c_l - c_m - rp_c) + f\phi + \theta) - \beta^3\lambda r^2 c_l p_c^2}{\beta(4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)}; \\ e^{KR*} = \dfrac{\beta\lambda r p_c(\theta + f\phi - \beta(c_l + c_m + rp_c))}{4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2}. \end{cases}$$

Substituting Theorem 4.12 into Eqs (3.8), (3.2), (3.5), and (3.6), the optimal demand and the corresponding profits for the 3PL, the supplier, and the KOL can be obtained.

$$D^{KR*} = \frac{\beta\gamma\lambda(\theta + f\phi - \beta(c_l + c_m + rp_c))}{4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2}$$

$$\pi_L^{KR*} = \frac{\gamma\lambda(\theta + f\phi - \beta(c_l + c_m + rp_c))^2}{2(4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)}$$

$$\pi_S^{KR*} = \frac{\gamma^2\lambda(2\beta\theta\lambda - 1)(\theta + f\phi - \beta(c_l + c_m + rp_c))^2}{(4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)^2}$$

$$\pi_K^{KR*} = \frac{\gamma^2\lambda(2\beta\theta\lambda - 1)(\theta + f\phi - \beta(c_l + c_m + rp_c))^2}{2(4\gamma(2\beta\theta\lambda - 1) - \beta^2\lambda r^2 p_c^2)^2}$$

Proposition 4.13. *The impact of the KOL's traffic f on the optimal strategies of the 3PL, the supplier, and the KOL is characterized as follows.*
(1) The 3PL's optimal strategies: Both the optimal logistics service price p_l^{KR*} and the preservation effort e^{KR*} strictly increase with f.
(2) The supplier's optimal strategies: The optimal wholesale price w^{KR*} strictly increases with f.
(3) The KOL's optimal strategies: (i) The optimal live-streaming effort k^{KR*} strictly increases with f. (ii) The optimal commission fee x^{KR*} increases with f if $r < r_5$ and decreases otherwise.
(4) The optimal retail price p_s^{KR*} increases with f if $r < r_6$ and decreases otherwise.

Proposition 4.13 indicates that under Scenario KR, the effect of the KOL's traffic f on the equilibrium strategy of the 3PL is consistent with that under Scenario KA: Higher KOL traffic strengthens the incentives of the 3PL to improve service. Furthermore, as traffic f increases under Scenario KR, market demand expands, prompting the supplier to raise the wholesale price to capture additional profits, while the KOL enhances the live-streaming efforts.

Different from Scenario KA, under Scenario KR, only the pricing decisions are affected by the initial spoilage rate r. This is because the KOL directly bears the spoilage losses and also possesses partial pricing authority. When the initial spoilage rate r is low, the KOL faces limited compensatory losses. With traffic growth driving demand expansion, he/she increases product prices to secure higher revenue, thereby raising retail prices. Conversely, when the initial spoilage rate r is high, compensatory losses expand with traffic growth. To mitigate these losses, the KOL reduces marginal revenue, thereby lowering retail prices.

Corollary 4.14. *The impact of the KOL's traffc f on the equilibrium demand and the profits of the 3PL, the supplier, and the KOL is characterized as follows.*
(1) The optimal market demand D^{KR*} strictly increases with f.
(2) The optimal profits of the 3PL, the supplier, and the KOL ($\pi_L^{KR*}, \pi_S^{KR*}, \pi_K^{KR*}$) all strictly increase with f.

Corollary 4.14 further highlights the differences between the KR and KA scenarios. Under Scenario KR, increasing the KOL's traffic f drives higher market demand, resulting in increased profits for the 3PL, the supplier, and the KOL. This is because the absence of a slotting fee in KR eliminates a potential source of internal friction. Consequently, the KOL's traffic functions solely as a driver for market expansion rather than a catalyst for profit-sharing disputes between the supplier and the KOL. In contrast, under Scenario KA, the supplier's profitability is constrained, as they bear all the spoilage costs while sharing a portion of the revenue ($\xi p_s D$) with the KOL. In this case, the slotting fee Tf is an additional cost. Ultimately, Scenario KR achieves better incentive alignment, as the KOL internalizes both the spoilage cost and the benefit of traffic.

Proposition 4.15. *The impact of the compensation price p_c on the optimal strategies of the 3PL, the supplier, and the KOL is characterized as follows.*
(1) The 3PL's optimal strategies: (i) The optimal logistics service price p_l^{KR*} increases with p_c if $\gamma < \gamma_8$ and decreases otherwise. (ii) The optimal preservation effort e^{KR*} decreases with p_c if $r > r_7$ and $\gamma > \gamma_9$, or if $r < r_7$ and $\gamma < \gamma_9$, and increases otherwise.
(2) The supplier's optimal strategies: The optimal wholesale price w^{KR*} increases with p_c if $\gamma < \gamma_8$ and decreases otherwise.
(3) The KOL's optimal strategies: (i) The optimal live-streaming effort k^{KR*} increases with p_c if $\gamma < \gamma_8$, and decreases otherwise. (ii) The optimal commission rate x^{KR*} increases with p_c if $\lambda < \frac{2}{3\beta\theta}$ and $\gamma < \gamma_8$, or if $\lambda > \frac{2}{3\beta\theta}$ and $\gamma > \gamma_8$ and decreases otherwise.
(4) The optimal retail price p_s^{KR*} increases with p_c if $\lambda < \frac{1}{\beta\theta}$ and $\gamma < \gamma_8$, or if $\lambda > \frac{1}{\beta\theta}$ and $\gamma > \gamma_8$, and decreases otherwise.

Proposition 4.15 shows that the impact of compensation price on the 3PL's pricing and preservation decisions remains consistent across different live-streaming formats. When the preservation cost coefficient γ is high, additional preservation investment becomes inefficient, leading the 3PL to lower logistics service prices in response to higher compensation pressure. In contrast, when γ is low, improving preservation is more cost-effective, encouraging the 3PL to raise logistics service prices.

Additionally, the effect of the compensation price for spoiled products (p_c) on the pricing strategy of the supplier and live-streaming effort decisions under Scenario KR is consistent with that observed in Scenario S, but differs markedly from that in Scenario KA. This similarity stems from the alignment of decision-making authority and logistics cost responsibility in both scenarios. In Scenario KR, the KOL simultaneously bears the logistics-related costs and controls live-streaming effort. When γ is high, the increase in compensation risk weakens the KOL's incentive to expand sales through costly live-streaming effort, leading to lower effort levels. Anticipating weaker market demand, the supplier correspondingly lowers the wholesale price. In contrast, when γ is low, the KOL has stronger incentives to maintain sales performance through higher effort, which supports higher wholesale pricing.

In addition, the effects of p_c on the commission fee and retail price depend on both the preservation cost coefficient γ and the live-streaming effort cost coefficient λ. When preservation and effort costs are low, the KOL can offset cost pressure through greater sales expansion, making higher commission fees and retail prices sustainable. However, when both costs are high, expanding demand through live-streaming effort becomes less effective, leading the KOL to rely more on higher marginal revenue rather than sales expansion to maintain profitability.

Corollary 4.16. *The impact of the compensation price p_c on the equilibrium demand and the profits of the 3PL, the supplier, and the KOL is characterized as follows.*
(1) The optimal market demand D^{KR*} increases with p_c if $\gamma < \gamma_8$ and decreases otherwise.
(2) The optimal profits of the 3PL, the supplier, and the KOL ($\pi_L^{KR*}, \pi_S^{KR*}, \pi_K^{KR*}$) all increase with p_c if $\gamma < \gamma_8$ and decrease otherwise.

Similar to Scenario S, Corollary 4.16 indicates that whether an increase in the compensation price (p_c) benefits the firms primarily depends on the preservation cost coefficient (γ). When γ is low, a higher compensation price raises demand and profits for the 3PL, the supplier, and the KOL; conversely, when γ is high, it reduces demand and profits for all three parties. The underlying mechanism has been discussed in Corollary 4.4 and will not be repeated here.

5. Live-Streaming strategy

This section compares the equilibrium solutions under Scenarios S, KA, and KR to analyze the strategy selection of the fresh agri-food supply chain for the optimal live-streaming format.

Proposition 5.1. *There are thresholds f_{p_l1}, f_{p_l2}, and f_{p_l3} such that we have the following.*
(1) The optimal logistics service price in Scenario S exceeds that in Scenario KA when $f < f_{p_l1}$ but is lower when $f > f_{p_l1}$.
(2) The optimal logistics service price in Scenario S exceeds that in Scenario KR when $f < f_{p_l2}$ but is lower when $f > f_{p_l2}$.

Proposition 5.1 demonstrates that the relative logistics service pricing across live-streaming formats depends on how the KOL's traffic reshapes the value created in the supply chain. When the KOL's traffic level f is sufficiently high, KOL-based live-streaming significantly expands market demand and increases the dependence of downstream sales on logistics service quality. As a result, the 3PL gains stronger bargaining power in Scenarios KA and KR and sets higher logistics service prices than in Scenario S, correspondingly.

Proposition 5.2. *There are thresholds f_{e1}, f_{e2}, and f_{e3} such that we have the following.*
(1) The optimal preservation effort in Scenario S exceeds that in Scenario KA when $f < f_{e1}$ but is lower when $f > f_{e1}$.
(2) The optimal preservation effort in Scenario S exceeds that in Scenario KR when $f < f_{e2}$ but is lower when $f > f_{e2}$.
(3) The optimal preservation effort in Scenario KA is lower than that in Scenario KR when $f < f_{e3}$ but exceeds it when $f > f_{e3}$.

Proposition 5.2 shows that the 3PL's preservation effort across different live-streaming formats depends on how the KOL's traffic reshapes spoilage risk. When the KOL's traffic f is low, demand under KOL-based live-streaming is relatively limited, reducing the marginal benefit of preservation investment. As a result, the 3PL allocates more preservation effort to the self-broadcasting Scenario S.

In contrast, when the KOL's traffic is high, KOL-based live-streaming substantially expands market demand and simultaneously amplifies potential spoilage losses. To reduce compensation risk and maintain service quality under larger sales volume, the 3PL increases preservation effort more aggressively in Scenarios KA and KR. Moreover, the stronger preservation effort under Scenario KA reflects the greater operational dependence of suppliers on logistics service quality when suppliers directly bear the spoilage-related losses.

Proposition 5.3. *There are thresholds f_{k1} and f_{k2} such that the following hold.*
(1) The optimal live-streaming effort in Scenario S exceeds that in Scenario KA when $r < r_2$ and $f < f_{k1}$, or when $r > r_2$ and $f > f_{k1}$; otherwise, it is lower.
(2) The optimal live-streaming effort in Scenario S exceeds that in Scenario KR when $f < f_{k2}$ but is lower when $f > f_{k2}$.

Proposition 5.4. *There are thresholds f_{p_s1} and f_{p_s2} such that we have the following.*
(1) The optimal retail price in Scenario S exceeds that in Scenario KA when $r < r_2$ and $f < f_{p_s1}$, or when $r > r_2$ and $f > f_{p_s1}$; otherwise, it is lower.
(2) The optimal retail price in Scenario S exceeds that in Scenario KR when $f < f_{p_s2}$ but is lower when $f > f_{p_s2}$.

Propositions 5.3 and 5.4 show that live-streaming effort and retail pricing across different formats are jointly determined by traffic advantage and spoilage risk. When traffic f is low, the supplier in Scenario S exerts greater live-streaming effort than the KOL in Scenario KR, resulting in stronger demand stimulation and higher retail prices in Scenario S. However, when traffic is high, the KOL's traffic advantage becomes dominant, allowing Scenario KR to sustain higher live-streaming effort and retail prices. The comparison between Scenarios S and KA further depends on the initial spoilage rate r. When both traffic and spoilage risk are simultaneously low or high, the supplier in Scenario S has stronger incentives to increase live-streaming effort, which further supports higher retail prices. Otherwise, the KOL in Scenario KA gains greater advantages in demand expansion.

Propositions 5.1 to 5.4 indicate that KOL-based live-streaming does not always outperform supplier self-broadcasting. Its effectiveness critically depends on whether the traffic advantage is sufficiently strong to offset the operational risks associated with the products' perishability.

Figure 3 further illustrates the results reported in Propositions 5.1 to 5.4. It shows that both the preservation effort (e^*) and the live-streaming effort (k^*) are influenced by the compensation price for spoiled products (p_c). As p_c increases from 0.1 to 0.8, the logistics service prices and product pricing strategies remain largely unchanged. However, in Scenarios KR and KA, the regions where freshness preservation and live-streaming efforts exceed those in Scenario S expand. This suggests that higher compensation pressure amplifies the relative advantages of the KOL to collaborate in live-streaming.

The underlying reason is that higher compensation pressure increases the value of effective demand conversion and spoilage control. Compared with supplier self-broadcasting, KOL-based live-streaming can generate stronger traffic effects and larger market demand, which increases the incentive for firms to invest in preservation and live-streaming efforts to reduce compensation losses and maintain sales performance. Therefore, as the compensation risk increases, the relative operational advantages of KOL collaboration become more pronounced.

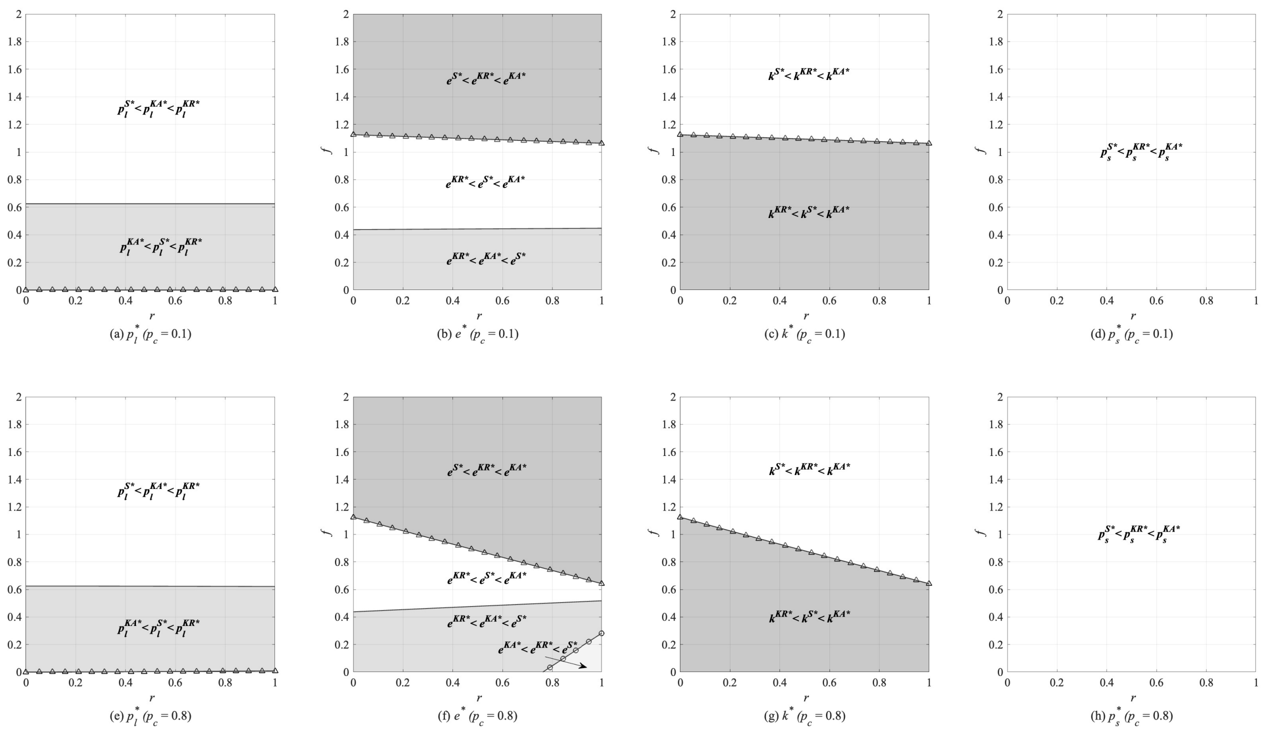

Figure 3. Comparison of optimal decisions under Scenarios S, KA, and KR. $\beta = 0.5$, $\theta = 1$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, and $T = 0.1$.

Proposition 5.5. *There are thresholds f_{D1}, f_{D2}, and f_{D3} such that we have the following.*
(1) The optimal demand in Scenario S exceeds that in Scenario KA when $f < f_{D1}$ but is lower when $f > f_{D1}$.
(2) The optimal demand in Scenario S exceeds that in Scenario KR when $f < f_{D2}$ but is lower when $f > f_{D2}$.
(3) The optimal demand in Scenario KA is lower than that in Scenario KR when $f < f_{D3}$ but exceeds it when $f > f_{D3}$.

Proposition 5.5 and Figure 4 show that the relative demand performance of different live-streaming formats depends on the KOL's traffic advantage. When the KOL has extremely high traffic f, KOL-based live-streaming, particularly with agency sales (KA), generates higher market demand than supplier self-broadcasting (S) because the strong traffic effect substantially enhances demand conversion.

However, as traffic f decreases, the advantage of KOL-based live-streaming gradually weakens. In this case, the additional commission fees and operational costs associated with the KOL's cooperation begin to outweigh the traffic benefits, causing the relative demand advantage to shift toward supplier self-broadcasting. When traffic is very low, supplier self-broadcasting achieves the highest demand because it avoids the extra coordination and pricing distortions introduced by the KOL's participation.

In addition, Scenario KA outperforms Scenario KR when traffic is sufficiently high because the agency-sale structure centralizes retail pricing decisions on the supplier, allowing the supply chain to more effectively exploit the demand expansion generated by the KOL's traffic. In contrast, under Scenario KR, pricing decisions are decentralized between the supplier and the KOL, which weakens the traffic-driven demand expansion effect and reduces overall market demand.

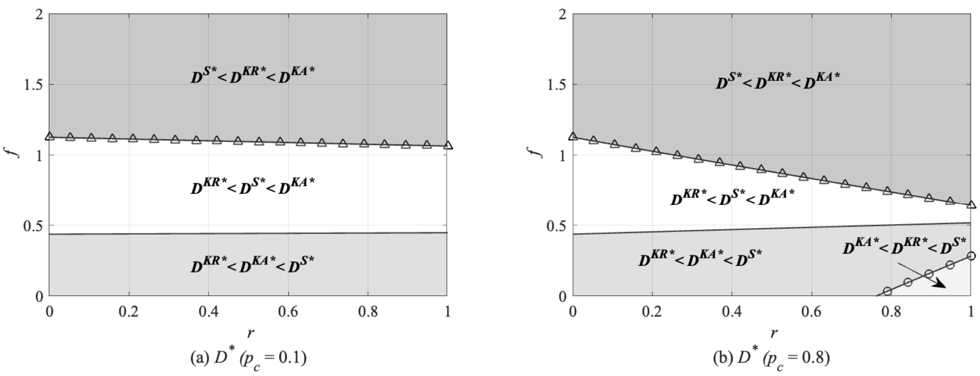

Figure 4. Comparison of optimal demand under Scenarios S, KA, and KR. $\beta = 0.5$, $\theta = 1$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, and $T = 0.1$.

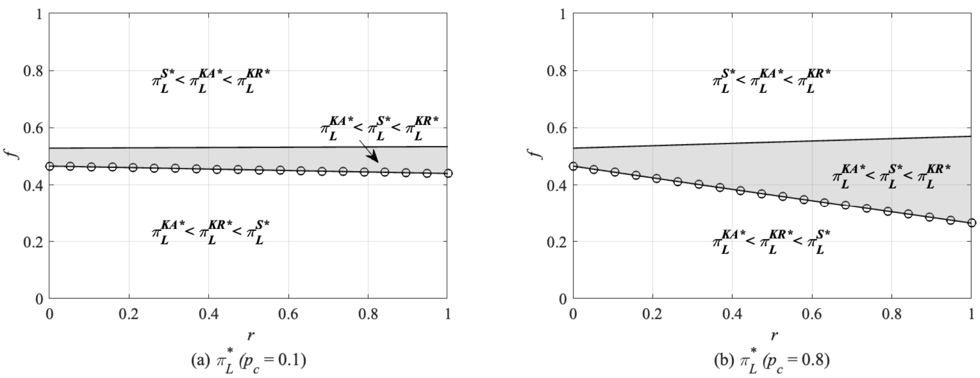

Figure 5. Comparison of optimal 3PL profits under Scenarios S, KA, and KR. $\beta = 0.5$, $\theta = 1$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, and $T = 0.1$.

Moreover, Figure 4 illustrates that as the compensation price p_c increases, supplier self-broadcasting becomes increasingly disadvantaged in stimulating market demand compared with KOL-based live-streamings. The underlying mechanism is that higher compensation prices increase the marginal cost of demand expansion because each additional unit sold also increases potential spoilage compensation losses. Under supplier self-broadcasting, the supplier must bear this risk while relying only on his/her own live-streaming capability, which weakens the incentive to further stimulate demand. In contrast, KOL-based live-streaming provides stronger traffic support and higher demand conversion efficiency, allowing the supply chain to maintain greater market demand even under rising compensation pressure.

Proposition 5.6. *The 3PL's preference among Scenarios S, KA, and KR is not uniquely determined and depends on the KOL's traffic f as follows:*

(1) $\pi_L^{S*} < \pi_L^{KA*}$ for low and high levels of f (i.e., $f < f_{\pi_l 2}$ or $f > f_{\pi_l 1}$), but $\pi_L^{S*} > \pi_L^{KA*}$ for intermediate levels (i.e., $f_{\pi_l 2} < f < f_{\pi_l 1}$).
(2) $\pi_L^{S*} > \pi_L^{KR*}$ when $f < f_{\pi_l 3}$, but $\pi_L^{S*} < \pi_L^{KR*}$ when $f > f_{\pi_l 3}$.

Proposition 5.6 and Figure 5 reveal that when KOL has low traffic f, supplier self-broadcasting generates higher overall demand because it avoids the additional pricing distortion and operational coordination costs introduced by the KOL's participation. As a result, even though logistics service prices are lower in Scenario S, the 3PL still obtains higher profit from the larger logistics volume.

In contrast, when the KOL's traffic is high, the strong traffic effect substantially expands market demand and increases the value of logistics services, making KOL-based live-streaming more profitable for the 3PL, particularly under Scenario KR. Compared with Scenario KA, Scenario KR allows the 3PL to capture more value from traffic-driven demand expansion because the KOL directly bears the logistics-related costs and spoilage risks, which strengthens the dependence of sales performance on logistics service quality.

Moreover, Figure 5 further shows that higher compensation prices strengthen the 3PL's preference for Scenario KR. The underlying reason is that rising compensation pressure increases the economic importance of preservation and logistics service quality, thereby enhancing the value of the risk-sharing structure under Scenario KR.

Proposition 5.7. *The supplier's preference among Scenarios S, KA, and KR is not uniquely determined and depends on the KOL's traffic f as follows:*
(1) $\pi_S^{S*} < \pi_S^{KA*}$ for low and high levels of f (i.e., $f < f_{\pi_s 2}$ or $f > f_{\pi_s 1}$), but $\pi_S^{S*} > \pi_S^{KA*}$ for intermediate levels (i.e., $f_{\pi_s 2} < f < f_{\pi_s 1}$).
(2) $\pi_S^{S*} > \pi_S^{KR*}$ when $f < f_{\pi_s 3}$, but $\pi_S^{S*} < \pi_S^{KR*}$ when $f > f_{\pi_s 3}$.

Proposition 5.7 and Figure 6 show that the supplier's preference for live-streaming formats largely mirrors that of 3PLs. When the KOL's traffic f is low, self-broadcasting generates higher profits because the supplier can avoid KOL commissions and pricing distortions while maintaining relatively stable market demand. Conversely, when the KOL's traffic is high, the strong demand expansion effect generated by the KOLs outweighs these additional costs, making KOL-based live-streaming more profitable for the supplier.

Moreover, Figure 6 reveals that, similar to the 3PL, the supplier favors the resale format (KR) over the agency format (KA) under KOL-based live-streaming. The key reason is that the KR format allows higher retail prices and transfers part of the spoilage-related operational risk to the KOL, thereby improving the supplier's profit margin. As a result, when compensation pressure increases, the supplier's preference for Scenario KR becomes even stronger because the value of risk-sharing becomes more significant under high spoilage compensation costs.

Figure 7 illustrates the KOL's choice of live-streaming format. When the compensation price (p_c) is low, the KOL prefers Scenario KA because the KOL can obtain stable slotting fee income without directly bearing the spoilage-related operational risks. In this case, the traffic advantage of the KOL can be efficiently monetized through agency cooperation with the supplier.

However, when both the compensation price p_c and the initial spoilage rate r are high, the KOL becomes more likely to prefer Scenario KR. The underlying reason is that high spoilage risk weakens the profitability of fixed slotting-fee arrangements under Scenario KA and intensifies the supplier's incentive to transfer the operational pressure through pricing adjustments. In contrast, under Scenario KR, the KOL possesses greater pricing flexibility and can strategically adjust retail prices and live-streaming effort to control demand and mitigate spoilage-related losses. Therefore, higher compensation risk increases the relative value of operational control under the resale format.

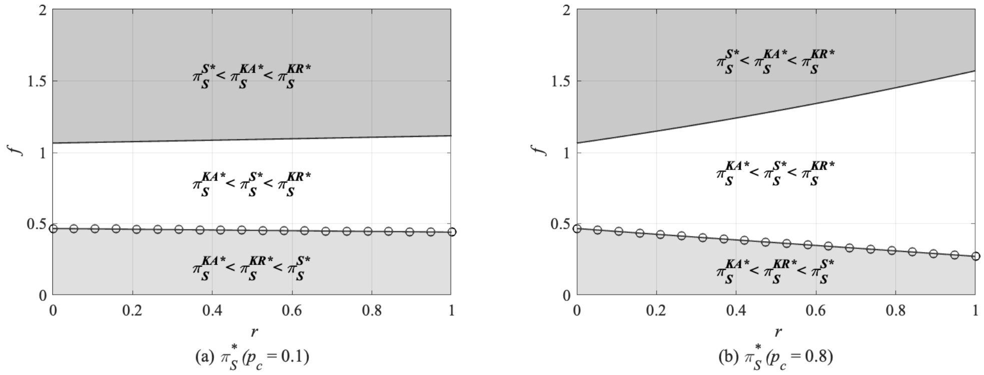

Figure 6. Comparison of optimal supplier profits under Scenarios S, KA, and KR. $\beta = 0.5$, $\theta = 1$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, and $T = 0.1$.

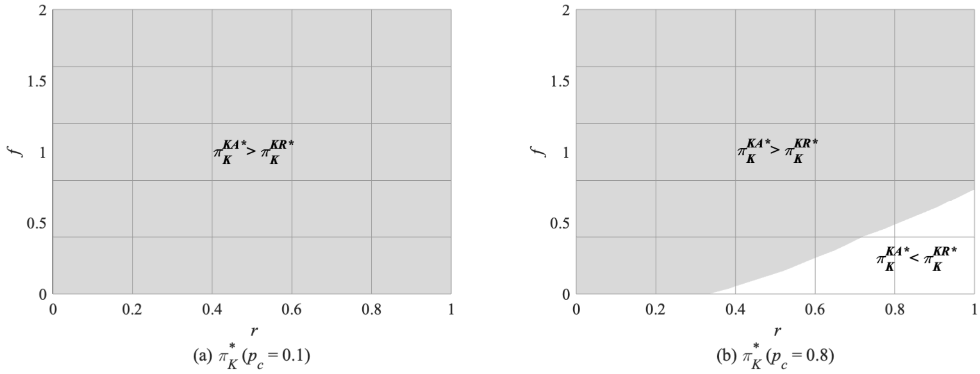

Figure 7. Comparison of optimal KOL profits under Scenarios S, KA, and KR. $\beta = 0.5$, $\theta = 1$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, and $T = 0.1$.

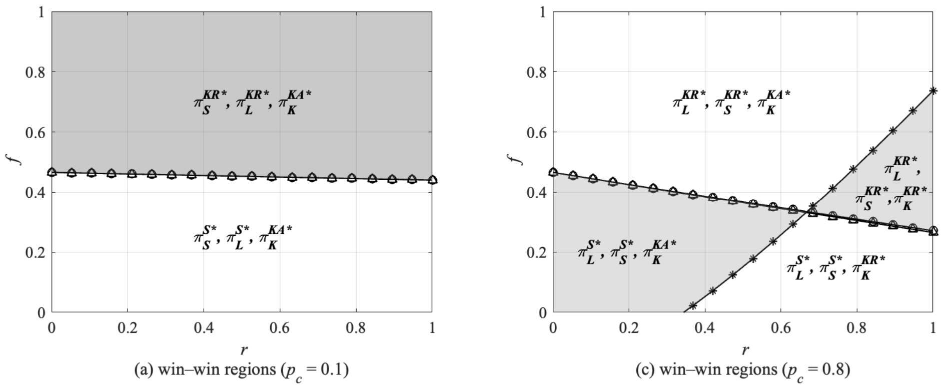

Figure 8. Win–win regions of live-streaming formats among the supplier, 3PL, and KOL. $\beta = 0.5$, $\theta = 1$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, and $T = 0.1$.

Figure 8 illustrates the win–win potential among the 3PL, the supplier, and the KOL. As shown in Figure 8(a), when the compensation price is low ($p_c = 0.1$), a tripartite win–win outcome does not emerge because spoilage-related operational pressure is limited. In this case, the supplier and the 3PL mainly focus on demand expansion and logistics profitability, leading them to prefer KOL-based live-streaming under high traffic and supplier self-broadcasting under low traffic. However, the KOL prefers the agency-sale format (KA), which provides stable slotting-fee income while avoiding direct spoilage risk.

Figure 8(b) further shows that a collective win–win becomes achievable when both the compensation price and the initial spoilage rate are high, while the KOL's traffic remains moderate. Under these conditions, spoilage risk becomes the dominant operational challenge, making the risk-sharing structure of Scenario KR more valuable for all parties. Specifically, the supplier can transfer part of the spoilage-related pressure to the KOL, the KOL gains greater pricing flexibility to manage demand and operational risk, and the 3PL benefits from stronger dependence on preservation and logistics service quality. Therefore, the KR format achieves a better balance between demand expansion and risk control, leading to aligned incentives among all three parties.

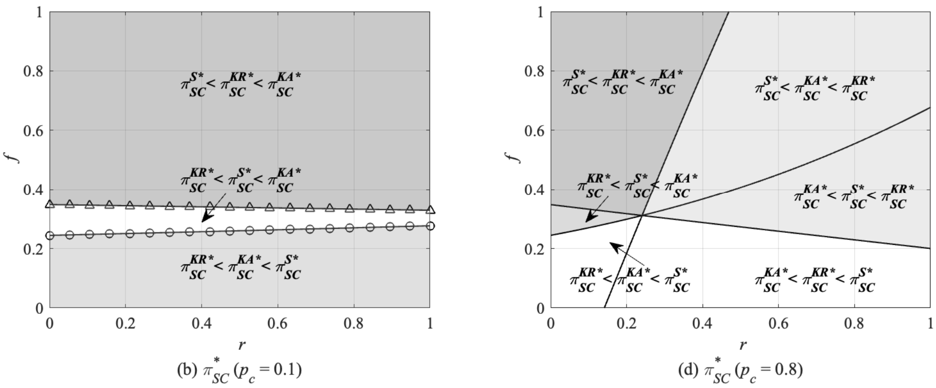

Figure 9. Comparison of optimal supply chain profits under Scenarios S, KA, and KR. $\beta = 0.5$, $\theta = 1$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, and $T = 0.1$.

Figure 9 further depicts the optimal live-streaming format from the supply chain's perspective. As illustrated in Figure 9(a), when the compensation price is low, spoilage-related operational pressure is relatively limited, making demand expansion the dominant factor affecting the total supply chain profit. Under medium to high KOL traffic, the strong traffic advantage of KOL-based live-streaming substantially increases market demand, causing the supply chain to prefer the KA format. In contrast, when traffic is low, the traffic benefit generated by the KOL's cooperation becomes insufficient to offset the additional commissions and coordination costs, making supplier self-broadcasting (S) more efficient for the supply chain.

Figure 9(b) further shows that when the compensation price is high, the supply chain's preferred format depends jointly on the KOL's traffic and the product spoilage risk. When traffic is low, the supply chain still prefers self-broadcasting because the traffic advantage generated by the KOL's cooperation is insufficient to offset the additional operational costs associated with the KOL's participation. However, under high traffic conditions, KOL-based formats become more attractive due to their stronger demand conversion capability. In particular, when both traffic and spoilage risk are high, the supply chain prefers the KR format because the resale structure strikes a balance between sales growth and spoilage control, thereby enhancing the overall supply chain profit. By contrast, when spoilage risk is low, the KA format becomes more efficient, allowing the supply chain to more fully exploit the KOL's traffic advantage to maximize demand.

6. Extended analysis

6.1. Multiplicative demand

To examine the robustness of the main results with respect to the demand specification, we further consider an extended model with a multiplicative demand structure. In particular, we assume that the KOL's traffic and live-streaming effort jointly affect market demand through an interaction effect, reflecting that traffic conversion efficiency may depend on the streamer's effort level. Accordingly, the consumers' expected net utility in the KOL-based live-streaming scenarios is reformulated as $u = \theta v - \beta p_s + fk$. Then the demand functions for KOL live-streaming are formulated as $D = \frac{\theta - \beta p_s + fk}{\theta}$.

Compared with the benchmark additive form, the multiplicative structure captures the complementary relationship between the KOL's traffic and live-streaming effort. Specifically, higher traffic can amplify the effectiveness of live-streaming efforts in stimulating consumer demand, while greater live-streaming efforts can also improve the conversion of traffic into actual purchases.

By solving the model under the multiplicative demand specification and analyzing the impacts of the initial spoilage rate of fresh agri-foods r and the KOL's traffic f on the profits of the 3PL, the supplier, the KOL, and the overall supply chain, the results shown in Figure 10 are obtained.

Figure 10 shows that under the multiplicative demand specification, the KOL's traffic interacts with live-streaming effort. When traffic is low, the interaction effect is weak and the model behaves similarly to the additive case, so the 3PL, the supplier, and the supply chain prefer supplier self-broadcasting (S). In contrast, when traffic is high, the multiplicative structure amplifies the marginal impact of effort on demand, thereby heightening the necessity for coordination and incentive alignment. Under high traffic, the supplier maintains a preference for KR across both specifications, as it effectively eliminates slotting fees. However, the preferences of the 3PL, the KOL, and the supply chain system deviate from those in the additive case: The 3PL shifts toward KA to better secure logistics-related returns amid high transaction volumes, while the KOL and the overall system lean toward KR to fully leverage the amplification effect of high traffic on live-streaming efforts.

Figure 10 demonstrated that although the preferences of the KOL and 3PL between the KA and KR formats may shift under specific multiplicative conditions, the overarching strategic choice between KOL-based broadcasting and supplier self-broadcasting remains consistent. Particularly when traffic is low, the main insights and equilibrium patterns are qualitatively robust.

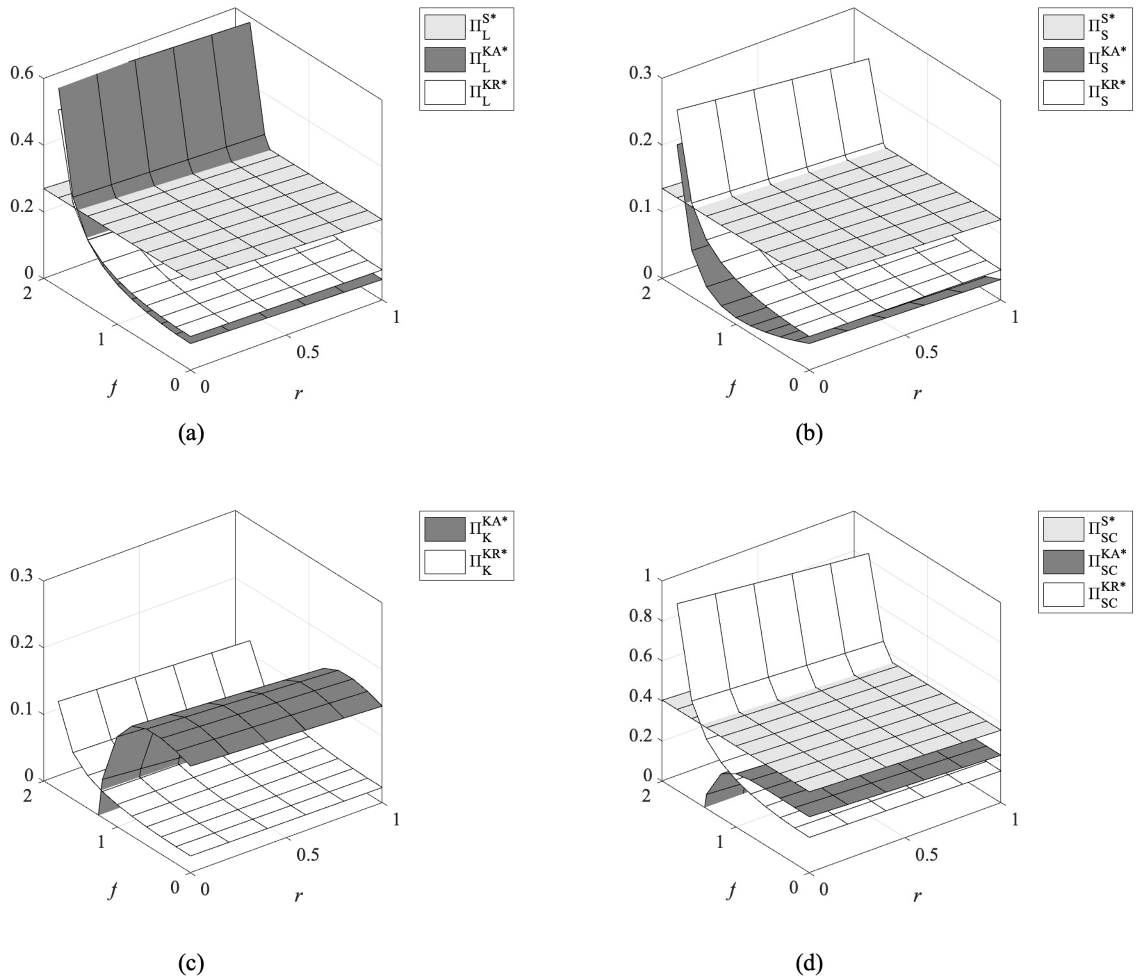

Figure 10. Impact of traffic and spoilage rate on profits under multiplicative demand. $\beta = 0.5$, $\theta = 1$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, and $T = 0.1$.

6.2. High consumer acceptance

In this extended analysis, we consider the case where the consumer acceptance parameter satisfies $\theta \geq 1$, representing a market environment in which live-streaming significantly enhances consumers' perceived valuation of products, for example, due to highly persuasive or charismatic streamers.

To examine the impact of a higher θ on live-streaming format selection, Figure 11 illustrates the corresponding profits of the 3PL, the supplier, the KOL, and the overall supply chain under $\theta = 0.8$ and $\theta = 2$.

Figure 11 shows that a higher θ not only strengthens the profitability advantage of supplier self-broadcasting (S) for the 3PL and the supplier, but also enhances the KOL's profit advantage under the KA format. This is because an increase in θ effectively scales up the baseline market valuation, thereby expanding the total surplus generated from live-streaming sales. Under the S format, the supplier can directly appropriate this expanded demand without incurring coordination frictions, while under the KA format, the KOL benefits from increased slotting-based revenue as higher demand amplifies the value of traffic monetization. By contrast, in KR, decentralized pricing partially dilutes this scaling effect. As a result, a higher θ amplifies the profitability of both S and KA.

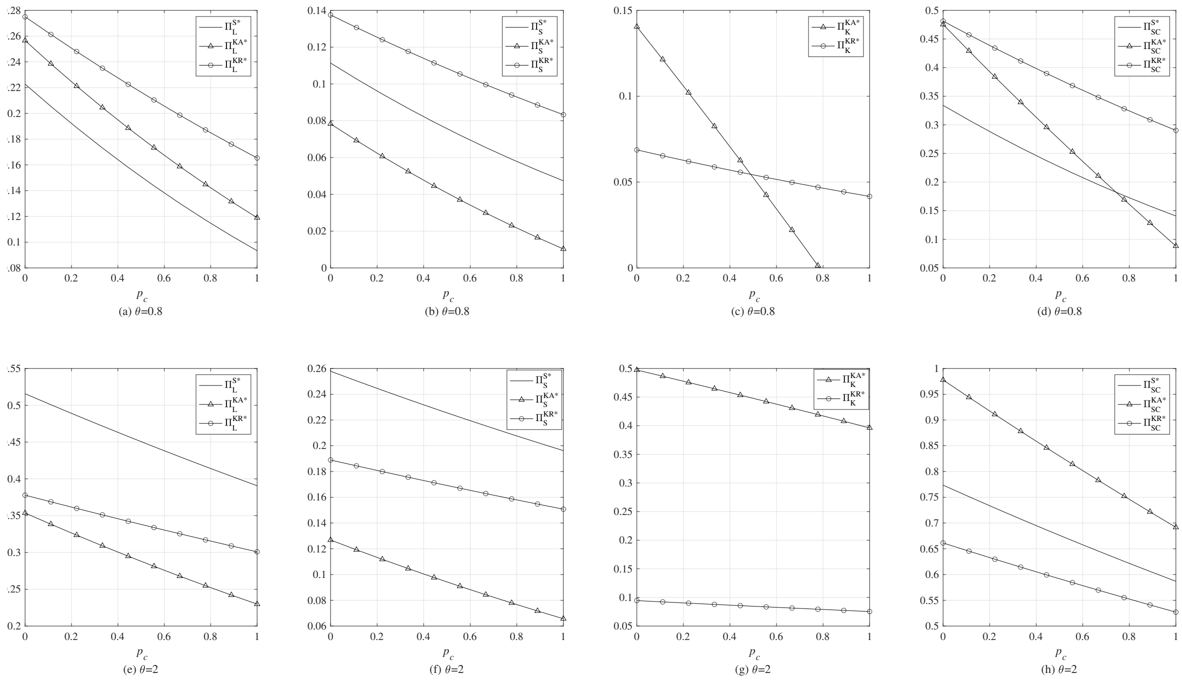

Figure 11. Effect of θ on equilibrium profits and live-streaming format selection. $\beta = 0.5$, $\lambda = 4$, $\gamma = 4$, $\xi = 0.5$, $c_l = 0.1$, $c_m = 0.1$, $\phi = 0.8$, $T = 0.1$, $f = 0.5$, and $r = 0.5$.

7. Conclusions

Live-streaming sales can boost agricultural product sales and increase farmers' income. However, the perishable nature of fresh agri-food leads to high logistics costs and additional compensation for spoilage. Responsibility for these logistics and spoilage costs varies across live-streaming formats. Consequently, consideration of both logistics and compensation is essential when selecting an appropriate live-streaming sales format. In this paper, we develop a game-theoretic model under three scenarios—supplier self-broadcasting (S), KOL-assisted agency sales live-streaming (KA), and KOL-resale live-streaming (KR)—to investigate optimal strategies for selecting logistics services and live-streaming formats within the fresh agri-food supply chain. The main findings of our study are summarized as follows.

(1) The allocation of rights and responsibilities across live-streaming formats substantially shapes the supply chain members' optimal response to 3PL decisions. Suppliers and KOLs exhibit consistent reactions to the 3PL's decisions in Scenarios S and KR, but their responses are opposite in Scenario KA. The underlying reason is that, in Scenarios S and KR, the party bearing the logistics and compensation costs simultaneously holds authority over the pricing and live-streaming effort, allowing coordinated adjustments of price and effort in response to the 3PL's actions. In contrast, Scenario KA allocates these two decision rights separately to the supplier and the KOL, leading to divergent responses.

(2) Live-streaming formats also influence the profit performance of the supply chain members. In Scenarios S and KR, when the preservation cost coefficient is high, increases in compensation prices for spoiled products reduce the profits of the supply chain members. In contrast, in Scenario KA, when the initial spoilage rate exceeds a certain threshold, higher compensation prices enhance the supply chain members' profits, even under high preservation costs.

(3) Increased KOL traffic expands market demand but does not necessarily enhance the profitability of the supply chain members. In the KR scenario, higher traffic benefits all participants. In contrast, under Scenario KA, traffic growth reduces the profits of both the 3PL and the supplier when the initial spoilage rate is high. This is because, unlike in the KR model, traffic in the KA setting not only stimulates market demand but also amplifies the slot-fee transfer payments between the supplier and the KOL, thereby exacerbating profit conflicts within the supply chain.

(4) KOL traffic, initial spoilage rate, and compensation price for spoiled products are critical determinants in selecting the optimal live-streaming format. High KOL traffic leads to the greatest market demand under KA, whereas KR generates higher profits for 3PLs and suppliers. When traffic is low, Scenario S maximizes both demand and profits. From the supply chain's perspective, Scenario S is optimal when traffic is low; Scenario KR is preferred when the compensation prices, traffic, and initial spoilage rates are all high; and Scenario KA is recommended in all other circumstances.

(5) As compensation prices increase, the KR model's advantage in stimulating market demand becomes increasingly pronounced, reinforcing the preference for KR among 3PLs, suppliers, and KOLs. This format further achieves a win–win–win outcome when the initial spoilage rate is high and KOL traffic is moderate. In other scenarios, although 3PLs and suppliers maintain aligned interests, KOLs' preferences diverge.

On the basis of the findings above, the following managerial implications can be derived for suppliers, KOLs, and 3PLs. (1) Suppliers and KOLs should establish robust coordination mechanisms to mitigate conflicts arising from the separation of pricing and cost responsibilities in the KA scenario. (2) Supply chain members should adjust their compensation and preservation strategies according to preservation efficiency, spoilage severity, and live-streaming formats. In the S and KR scenarios, when the preservation cost coefficient is high, firms should avoid raising compensation prices for spoiled products. In contrast, under the KA scenario, when the initial spoilage rate is extremely high, suppliers should increase compensation prices even if preservation costs remain high. (3) Suppliers in the KR scenario can benefit from cooperating with high-traffic KOLs. However, in the KA scenario, suppliers should avoid excessively pursuing high-traffic KOLs without carefully evaluating the associated transfer costs and operational risks. (4) Suppliers should avoid adopting a single fixed live-streaming strategy and instead choose live-streaming formats according to the traffic conditions, spoilage risks, and compensation policies. When KOL traffic is low, the supplier self-streaming format (S) is preferable. When compensation prices, the KOL's traffic, and initial spoilage rates are simultaneously high, the KR format becomes more advantageous. In most other situations, the KA format is recommended.

Several potential extensions of this study merit further investigation. First, this paper focuses on compensating for product spoilage unrelated to the 3PLs, assuming that the sellers bear full responsibility. In practice, however, some spoilage results from inadequate logistics or packaging and should be covered by 3PLs. Therefore, examining the impact of different spoilage types and the allocation of compensation between sellers and 3PLs represents a promising direction for future research. Additionally, all three live-streaming formats analyzed in this paper rely on human hosts, while some firms have begun adopting AI streamers. Given the differences in effectiveness and cost structures between human and AI hosts, examining the choice between these two types of live-streaming formats in fresh agri-food supply chains is of particular interest.

Author contributions

Chun-Yi Liu: Conceptualization, methodology, formal analysis, validation, writing–original draft, writing–review and editing, funding acquisition; Jie-Lin Hu: Formal analysis, writing–original draft; Li Liu: Writing–review and editing, supervision, funding acquisition.

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Use of Generative–AI tools declaration

The authors declare that they did not utilize any artificial intelligence (AI) tools in the creation of this article.

Conflict of interest

There are no conflicts of interest regarding the publication of this paper.

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