Received: 4 November 2021 | Revised: 25 April 2022 | Accepted: 30 April 2022

DOI: 10.1002/mde.3639

RESEARCH ARTICLE

WILEY

# Research on optimization of food supply chain considering product traceability recall and safety investment

Junhai Ma | Jiecai Chen | Yuxin Liu

College of Management and Economics, Tianjin University, Tianjin, China

**Correspondence**
Yuxin Liu, College of Management and Economics, Tianjin University, Tianjin 300072, China.
Email: liuyuxinm@126.com

Strict food regulations, high-quality product demand, and fierce market competition urge food enterprises to focus on the optimization strategy of product safety and traceability recall in the food chain. To better meet customers' safety and quality expectations and reduce the loss of problematic products that fail to be recalled in time, the paper establishes a two-level food supply chain consisting of a single manufacturer and supplier, uses the Stackelberg game to explore the interaction between traceability recall and product safety optimization in the food chain, and finds the best food safety investment and product traceability recall strategy. And we consider the case of the former investing in the latter's product safety efforts. The results show that the food safety premium sharing rate determines the optimal decision of manufacturers and suppliers when each member is faced with the difference between the loss cost of unrecalled food per unit and the traceable recall cost coefficient. In addition, the higher safety investment cost factor increases the burden on the entire supply chain and reduces the safety benefits of the food chain. Moreover, higher security investment cost factors increase the burden on the entire supply chain and reduce the safety benefits of the food chain. Interestingly, suppliers can take advantage of the increased cost per unit of unrecalled products to obtain higher safety investments when manufacturers implement recall measures for problematic foods. We also introduced blockchain technology and discovered Pareto optima for food safety. When the supplier bears part of the problem of food loss, food safety, quality, and investment are high. The conclusions show that product traceability recall is beneficial to the overall welfare of the food chain.

## 1 | INTRODUCTION

China's economic development has brought new challenges in food safety and quality to companies and policymakers. The scale and complexity of supply and production chains are growing, and rising consumer incomes mean that consumer demand is upgrading and diversifying. At the same time, social media has also increased the public's attention to food safety issues. However, food safety incidents continue to occur, causing public anxiety. According to statistics from the World Health Organization, more than 400,000 people die from contaminated objects each year, and about 10% of the population suffers from diseases due to food safety issues (Xu et al., 2022). On the other hand, various food scandals exposed by the media, such as the milk incident in China, the Listeria contaminated cantaloupe in the United States, the outbreak of *Escherichia coli* in Germany, and the "food theft" scandal in India, have greatly endangered the health of the general population. Enhance consumers' confidence in food safety and quality. Most of these incidents are caused by human factors, such as insufficient training, lack of technical knowledge and standard knowledge, or fraud and violations for financial gain. The challenge for corporate executives and regulators comes from the highly fragmented nature of the food industry-small pastures; farms and companies occupy the main part of China's food production, processing, wholesale, and trade (Niu et al., 2016).

  

As Chinese consumers pay more attention to their health, they are paying attention to the ingredients and sources of the food they buy. More consumers are loyal to brands they trust and willing to pay more for safer, better food. The government is aware of the importance of integrity in the food industry. The new national food safety regulations will impose new food safety regulations on manufacturers, distributors, retailers, and even online stores. The law will increase fines for violations and require a food traceability system.

Consumers and national attention to green health food and the food market of iteration constantly improve food safety in the form of began to separate from traditional food supply chain members, driven by now in the food market competition, many members of the food chain choose vertical coordination patterns, such as production contract and agriculture. This is because upstream farmers or suppliers tend to be smaller, with less efficient production and management technologies and less developed infrastructure such as transport, cold storage, and information channels (Wang et al., 2014). By signing contracts with stronger downstream processors or producers, suppliers gain access to better technology and inputs from larger companies, improving their productivity and product quality. For example, poultry growers in India, Indonesia, and Bangladesh receive feed and veterinary assistance provided by downstream procurement companies, and Indian dairy growers can obtain high-quality raw materials, seeds, equipment, and chemicals provided by large downstream manufacturers under technical standards imposed by them (Dai et al., 2017). The latter also provided technical training and other consulting services as part of the contract (Niu et al., 2016). Therefore, signing contracts with large processors or manufacturers is one of the ways to enter the high-end market and obtain higher returns to improve their welfare (Bellemare, 2012). In addition, contracts provide a stable and consistent supply for downstream food processors and consumers, giving processors more control and food traceability and reducing losses from problematic food. The purchase contract enables the party with advanced economic strength or technology to actively provide safety investment support for the party with weak conditions and resources, while also being able to obtain products with a higher degree of safety, and to obtain product premiums paid by consumers who prefer food safety.

From a practical point of view, the supply chain of the food industry is relatively complex. The sources of food safety risks at the production end include smallholder operations, lack of agricultural technical knowledge, contaminated soil and water, and excessive pesticide use and residues. In addition, food recalls are caused by a lack of safety and quality assurance during production and processing by one or more supply chain partners and may affect a large number of long-manufactured products (Chao et al., 2009). In a recent Ford report, 76% of a company's quality problems came from its tier-one supplier (Sun & Wang, 2019). Therefore, food safety incidents and product recall caused by products with low safety and quality will cause unnecessary costs, sales decline, reputation loss, and litigation disputes for enterprises (Dai et al., 2017; Thirumalai & Sinha, 2011). At the same time, the cost and scale of problematic food recalls require a deeper understanding of how to manage safety improvement incentives for supply chain partners to ensure higher food health. Therefore, downstream enterprises will sign purchase contracts with upstream suppliers whose own economic, technical, and management problems make it difficult to improve the safety of food raw materials. The latter will receive subsidies for food safety investment from the former to obtain higher quality food and consumer product premium. However, the impact of the sharing of safety premiums on the decision-making of the upstream and downstream sides of the food supply chain and how to obtain the optimal supply chain benefits and social benefits are also the focus of this paper, which has great practical significance.

For manufacturers, in addition to continuously improving the safety of upstream products in food production, they also need to invest in food traceability throughout the supply chain to reduce the loss of goodwill and policy penalties caused by problematic products on the market. Although it is the optimal strategy to sell safer foods to customers in a food supply chain (FSC) with a high level of traceability, considering the improvement and improvement of product safety and supply chain traceability level, both of them pose great challenges to enterprises' economic investment ability and scientific and technological support and breakthrough. Therefore, in real life, it is difficult to have both. Manufacturers need to rationally allocate resources for food safety investment and supply chain traceability under the constraints of their resource limits and investment capacity and strategically formulate the optimal strategy between high-quality food premiums and low recall product losses. Especially when the market environment and its conditions change, how food manufacturers will choose between the benefits of the two has very important research significance and management innovation.

From a theoretical perspective, most of the current literature related to food quality management and traceability focuses on product quality testing and management (Yao & Zhu, 2020), production efforts (Bondareva & Pinker, 2019), and quality improvement (Zhu et al., 2007) and traceability tracking and product recall cost-sharing (Dai et al., 2021). Further discussed in this article, from the perspective of the vertical coordination of the food supply chain, the cooperation model is formed by considering the mutual capacity limitations between the upstream and the downstream; the latter invests in the safety of the former to help the latter improve the safety and quality of food. The innovations of this article have not yet been studied in most of the literature. At the same time, we inherited the traditional literature on traceability recall in the food supply chain. From the perspective of safety investment, how to coordinate the distribution of traceability and food safety in the supply chain is also an interesting topic. Finally, the optimal decision scheme of each member of the food chain is analyzed from multiple perspectives, which provides some reference significance for the risk management and quality management of the food supply chain in the future.

In this paper, the supplier's safety improvement work is affected by moral hazard and does not participate in the financial burden of the loss of recall of problematic food. The leading manufacturer of the entire supply chain shall be responsible for the loss of food recall and non-recall caused by food safety events caused by food safety and quality. Considering the food supply chain structure of a single supplier and a single manufacturer, and based on the premium sharing ratio of the purchase contract, we propose the following research questions for the best effort decision made by the two in the food supply chain:

1. How can food producers balance the relationship between safety investment and traceability recall to achieve the optimal food safety strategy when there is resource upper limit constraint.
2. What degree of safety efforts will upstream suppliers make between the share ratio of product safety premium agreed in the procurement contract and the manufacturer's safety investment?
3. When the loss cost of unrecalled food varies with the policy and market environment, has the entire food supply chain's approach to improving product safety changed? Is it more inclined to trace or improve food quality?
4. In the face of the current problems facing the food chain, how can companies and governments deal with them to more effectively improve the status quo of the food supply chain and welcome a healthy future?

In the next section, we will introduce the innovations and contributions of this article in the context of existing supply chain literature on quality management and risk management. We then introduced the basic modeling framework and assumptions of our model in Section 3. Section 4 analyzes the safety investment and traceable recall strategy that this article focuses on in detail. We presented an extensive numerical study in Section 5, which examined the equilibrium thresholds for the efforts and benefits of manufacturers and suppliers. Section 6 extends the sharing of recall costs. And Section 7 outlines our findings and future research directions.

## 2 | LITERATURE REVIEW

Aiming at the interaction between traceability in food supply chain quality management and product safety investment optimization, our paper involves the following three research directions: (i) food supply chain, (ii) traceability or recall capability, and (iii) supply chain coordination management.

### 2.1 | Food supply chain

Food safety is a pervasive issue that challenges regulatory agencies, the food industry, and consumers around the world. Managing food safety risks is particularly difficult because of the size, complexity, and opacity of the food supply chain. Food safety incidents happen every day around the world. Therefore, a large number of scholars put forward their own opinions on the product quality and safety of food safety incidents. Levi et al. (2020) analyzed how quality uncertainty, supply chain dispersion, and detection sensitivity jointly affect the activity of speculation in the production of low-quality food on farms and developed a model framework to examine its risk to reduce the possibility of foodborne diseases. Through the food safety risk test of aquatic products, Jin et al. (2021) evaluated the distribution of regulatory resources in the food supply chain to achieve the goal of managing food safety and adulteration risks. On the other hand, due to the double moral hazard problem of food safety often occurs, Mu et al. (2016) use the competitive power between milk stations to solve the deliberate adulteration and free-riding behavior of dairy farmers and convert the harmful effects (quality reduction) caused by competition into beneficial effects (quality improvement). Considering the linear market demand, Liu et al. (2012) showed that both manufacturers and suppliers could improve product quality through efforts and proved the existence of Nash optimal equilibrium solution of the decentralized supply chain by using the upper mode game theory. Zhu et al. (2007) also believes that when different members of the supply chain invest in improving quality, the revenue of the entire supply chain will be most affected. In addition, Cao et al. (2020) coordinated the optimal green agricultural product effort decisions jointly determined by cooperatives and enterprises through cost-sharing contracts and buy-back contracts. Therefore, internal integration and supplier integration of the agricultural supply chain becomes the key to improving product quality (Wang et al., 2021).

The above literature explored the sources and improvement approaches to food quality problems from different perspectives such as detection and supervision and sought the optimal quality balance solution from the perspective of the overall benefits of the supply chain. Our work has supplemented the relevant literature on the food supply chain from two aspects. First, based on the food safety issues mentioned above and the cooperative relationship among the members of the supply chain, a model has been proposed in which one party can improve the safety and quality of products in the food chain, while the other party has the willingness to invest in the safety of the former. This is a very interesting and novel exploration, and it is also different from the research mentioned above that both sides have the same way to improve quality. Then, we combine the traceability recall with the safest investment of the food supply chain to explore the optimal balance between the two, which also has great practical and research significance.

### 2.2 | Traceable recall supply chain

The agri-food regulations provide traceability throughout the supply chain to ensure consumer safety and product quality. This has prompted producers and retailers to consider opportunities to improve company reputation and consumer confidence by implementing traceability systems that are not only designed to meet legal requirements but also track product quality by optimizing the supply chain. Aiello et al. (2015) evaluate and summarize traceability and implementation methods of food supply chain and processing stage based on recall effect, traceable resource unit, and comprehensive granularity. By conducting regression analysis and testing of model construction on the Italian fishery supply chain, Asioli et al. (2014)

explored the relationship between traceability level and expected and actual traceability costs and benefits. Sun and Wang (2019) use a joint contract approach to address information asymmetry in purchasing decisions in the food supply chain, enabling buyers to obtain a higher level of traceability from suppliers. Moreover, traceability elements used in products can also improve the trust index of consumers (Matzembacher et al., 2018). In addition, traceability is a tracking capability used to identify the source of many quality problems. It is a powerful solution to food safety issues (Sun & Wang, 2019); improving the traceability of the food supply chain to deal with potential food security incidents is very important. Product recalls, for example, have become an important feature of the supply chain. Based on the accuracy of pollution source identification in the traceable supply chain, Piramuthu et al. (2013) identified the appropriate level of visibility and recall strategy, taking into account the allocation of responsibilities between the different players in the perishable goods supply network. Thirumalai and Sinha (2011) evaluated the financial consequences of product scope, sales, growth prospects and capital structure of enterprises from recalls related to medical devices and persistent quality problems, and explored and found by analyzing the sources of device recalls that the more comprehensive the product portfolio focused on R&D and development, the more likely the company is to recall devices. Blockchain technology is an emerging technology developed in recent years, with a powerful information traceability function. This technology plays an important role in monitoring product quality and dealing with product safety issues. Fan, Wu, et al. (2020) explored the adoption of blockchain traceability in the supply chain, based on consumers' awareness of traceability and the technical cost of using blockchain. Hastig and Sodhi (2020) said that traceability systems under blockchain can deter illegal activities, improve sustainability performance and operational efficiency, and enhance supply chain coordination.

However, compared with the existing retrospective literature, our work has a different purpose: As traceability becomes a key element in supply chain management, we are interested especially in safety-sensitive sectors such as food and pharmaceuticals, and consumers also place high expectations on the safety of the food supply chain (FSC) (Casino et al., 2020). Exploring the interaction between traceability and product safety investment optimization in the food supply chain is of great practical significance, and we further analyze the optimal balanced recall strategy and safety efforts of each member of the food chain from the perspective of a collaborative supply chain.

## 2.3 | Supply chain coordination management

In supply chain relationships, collaborative arrangements become an important way for various internal and external stakeholders to improve organizationally and supply chain performance and to improve the sustainability of the food supply chain (Krishnan et al., 2021). Through the acceptance sampling test model under the condition of uncertain product quality, Chen et al. (2014) proved that a decentralized supply chain structure may lead to distortion of product quality and that different pricing and regulatory options under vertical control can affect product quality and distribution of total profit of supply chain. When contract farming agreements become an important driving force, it is an important driving force to improve farmers' production efforts (such as purchasing agricultural machinery or using new farming techniques). Niu et al. (2016) examined how different types of cooperation affect the effort and utility coordination of channel members and enable farmers to achieve systematic optimal production efforts. Ma et al. (2021) studies the design of price coordination mechanism of automobile manufacturers under the condition of government intervention and finds that appropriate government intervention can maximize social welfare. In addition, Zhu et al. (2007) believe that the fact that manufacturers and suppliers share warranty costs when selling substandard products is conducive to encouraging both sides to invest in product quality improvement. In the face of product recall events with quality problems, Zhang et al. (2020) found that quality management cooperation and supplier qualification were positively correlated with product recall ability by combining case study and quantitative investigation. Dai et al. (2020) indicate that both suppliers and manufacturers can reduce the probability of recall events through recall efforts, and the degree of both parties' efforts is related to the initial expected unit recall cost and the potential market size. Fan, Ni, et al. (2020) reveals the impact of product liability cost allocation and channel leadership structure on the quality decisions of supply chain members and the corresponding profitability of each member and the entire supply chain. Lee et al. (2013), however, fully harmonized the supply chain through quality compensation contracts, which compensate manufacturers for faulty products that retailers inadvertently sold to consumers. Bhaskaran and Krishnan (2009) studied the subtle interaction between the cost investment and effort sharing mechanism of two different enterprises jointly developing new products the degree of revenue sharing and the type of projects between companies. Ziggers and Trienekens (1999) believe that the specific market and production characteristics of the food supply chain are the motivation for vertical coordination to obtain competitive advantages. The quality assurance system can only play a promoting role, and its actual competitiveness will depend on the ability to develop successful partnerships. Xie et al. (2020) study the coordination of two-level supply chain. The results show that the buyback contract is sufficient to coordinate the supply chain when the seller has high bargaining power and can control uncertain returns. Ma and Sun (2018) study nonlinear mixed oligopolies game based on Production Cooperation. The results show that system uncertainty will affect the profit of cooperation. Bao et al. (2020) studied the game behavior of duopoly automakers producing pure electric vehicles and fuel vehicles. Considering consumers' low-carbon preferences and government subsidy schemes, the optimal decisions under three game strategies of supply chain coordination, namely, non-cooperative game, cooperative game, and cost sharing contract, are compared and analyzed. The study found that the price of electric vehicles is more dependent on reducing carbon emissions and government subsidies than electric vehicles.

A two-level supply chain in which upstream manufacturer and downstream retailer share product liability costs caused by quality defects is studied. Study found that when product liability cost share by the retailer to the manufacturer, when the manufacturer is in the lead, manufacturers can not improve the quality of products, with higher wholesale prices will increase the cost of product liability all transferred to the retailer, but when the manufacturer is in the lead, retailers will reduce the retail margin to encourage manufacturers to improve product quality (Fan, Ni, et al., 2020).

Fan, Wu, et al. (2020) study the three-level supply chain composed of suppliers, manufacturers and retailers, and studied the optimal pricing strategy of the supply chain in two cases considering consumers' traceability awareness. The results show that there are conditions for the adoption of blockchain technology in the supply chain, which are related to the traceability awareness of consumers, the production costs of suppliers and manufacturers, and the costs of using blockchain technology.

However, when the upstream and downstream members of the food supply chain cooperate, one party accepts the safety investment of the other party to improve product safety and quality and shares the benefits of safety premium, while the latter not only gains profits but also reduces the liability cost of defective products. This is something the aforementioned competitive food recall efforts and production efforts did not involve in the supply chain. And how traceability in the food chain is affected by cooperation between upstream and downstream has not received much attention so far. We also consider the impact of non-recall liability cost and safety premium sharing ratio on safety efforts and recall strategies throughout the food supply chain.

Zhao et al. (2021) study the impact of agricultural supply chain integration on agricultural product quality and financial performance. The results show that internal integration and supplier integration are the key factors to improve product quality in agricultural supply chain. In addition, product quality plays a completely mediating role between internal integration and financial performance, and between supplier integration and financial performance.

Throughout the existing literature, existing articles discuss the impact of traceability technology investment on upstream and downstream enterprises in the food supply chain system. Traceability technology can help improve the safety of food raw materials, meet consumers' demand for safe food, and reduce the negative impact of food safety uncertainty on food manufacturers in the food supply chain, however, investment in traceability technology may lead to conflict of interest between suppliers and manufacturers in the supply chain; how to coordinate the conflicts between the two is an essential problem. Reasonable distribution of the costs and benefits brought by traceability technology is also the top priority to ensure the maximum benefits of traceability technology. Therefore, this paper innovatively discusses the impact of traceability technology investment on upstream and downstream enterprises in the supply chain and considers the two coordination mechanisms of cost sharing and revenue sharing are established to promote the win-win situation of the supply chain system. At the same time, this paper also innovatively considers the impact of blockchain technology on the backtracking of agricultural supply chain.

# 3 | MODEL

## 3.1 | Model description

We have constructed a two-level food sales supply chain composed of a single supplier and a single manufacturer. Under the purchase contract signed between the two, the leading producer will purchase all the food raw materials of $q$ output provided by the upstream food supplier, produce and process them into food, and sell them to retailers or consumers in the market. Here, we collectively refer to them as buyers. As consumers pay more and more attention to food safety, buyers tend to have a higher preference for the safety and traceability of the food they buy. In reality, many large manufacturers or retailers take the initiative to provide food safety investment assistance to partners with weak resources to better meet consumers' food safety needs and improve the market share of their products. On the other hand, to prevent the production of inferior food and the sale of contaminated food, manufacturers choose to establish a food traceability recall system between the upstream and downstream of the supply chain, timely detection of problems, and the maximum number of recalls of problematic food. Under the safety investment of the manufacturer, the upstream suppliers make $e$ safety efforts of the purchased food raw materials to reduce the probability of safety incidents in the food supply chain and improve the safety utility of consumers for food to obtain higher income. Therefore, according to Liu et al. (2018), we establish inverse demand function $p = A - q + \alpha e$, where $A$ represents the current market size of food sales, $q$ represents the food output sold, $\alpha e$ represents the product premium paid by consumers to the food safety efforts made by suppliers, and $\alpha$ represents the perceived strength of consumers to food safety efforts. Based on the existing reality, this paper focuses on how manufacturers invest in suppliers to improve the safety level of the food supply chain and improve the traceability ability to reduce the cost of loss caused by problematic products. Therefore, similar to Chao et al. (2009), this paper assumes that regardless of inventory and out-of-stock costs, the food output $q$ provided by upstream suppliers is fixed, and the food price sold in the market can be simplified as $p = p_0 + \alpha e$, where $p_0 = A - q$.

Figure 1 displays the structure of the secondary food supply chain with a single supplier and single producer, the manufacturer's decision variable is the optimal level of traceability for constructing the food supply chain and the optimal level of investment in upstream suppliers' safety efforts, and the supplier's decision variable is the optimal level of food safety efforts based on the safety investment provided by the manufacturer.

Figure 2 shows the event sequence, the cooperative parties first sign a food purchase contract through negotiation, and the manufacturer purchases all the food with fixed output $q$ from the supplier and produces the food at the wholesale price $w_0 + (1-\theta)\alpha e$ throughout

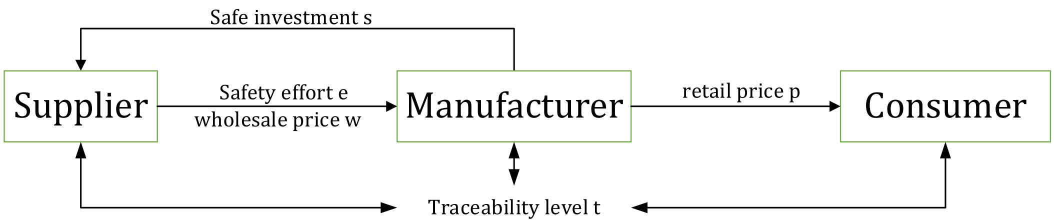


FIGURE 1 Structure of the secondary food supply chain with a single supplier and single producer [Color figure can be viewed at wileyonlinelibrary.com]

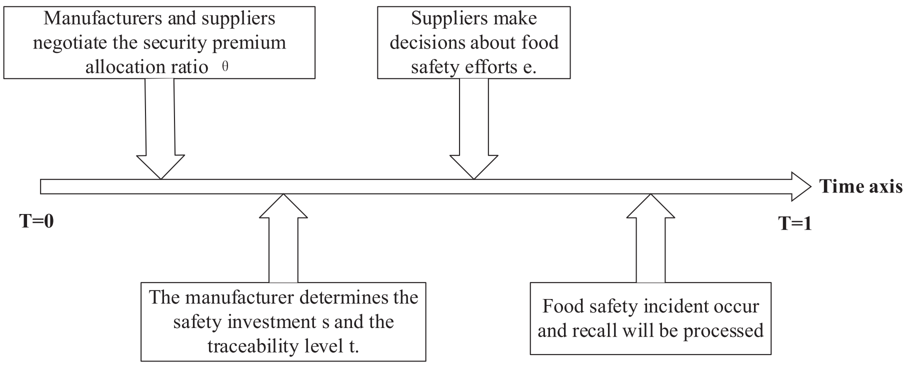


FIGURE 2 Event sequence diagram

the whole cycle, where $w_0$ represents the wholesale purchase price agreed by both parties without the support of safety investment by the manufacturer and $(1-\theta)$ is the share of premium income paid by the consumer for food safety that the supplier can obtain when safety effort is e. A higher value of $\theta$ indicates that the consumer premium earned by safety efforts in the food supply chain is owned by the manufacturer in a higher proportion. Afterward, according to their interests, both parties will make expensive efforts to improve the food safety level and traceability level to reduce the losses caused by food safety incidents. After the manufacturer determines the upstream food safety investments and the traceability recall level $t$ of the whole food supply chain, the supplier decides the safety effort level $e$ of the raw material products based on the safety investment intensity of the manufacturer. Similar to Chao et al. (2009), the measurement of effort in modeling research assumes that it conforms to the quantitative expression of the interval [0, 1].

Below, we introduce the basic structure of our model:

**Hypothesis H1.** We assume that the food raw materials produced by $q$ are provided by the supplier to the manufacturer for production and processing. When food safety incidents such as food problems or food contamination, the latter will recall the food in time and bear the responsibility for losses caused by the recall and the defective products.

**Hypothesis H2.** We will only consider the cost of loss caused by each unit of food that cannot be recalled and ignore the cost of food recalls that can be implemented by recall measures, such as transportation and inventory costs. This is mainly due to the unique attributes of the food supply chain. Compared with the defective food that can be recalled, the unrecalled part will cause more serious damage to the goodwill of the enterprise, the reduction of product market share, and the punishment of food health-related policies (Dai et al., 2021).

In the food supply chain, there are often loopholes and uncertainties in the detection system of natural factors, food contamination, quality and safety problems, and recall events. According to the traceability recall level $t \in (0,1)$, the quantity range of recalled products in food safety incidents is modeled as a function of the traceability recall level of the food supply chain. According to Dai et al. (2021), define $f(t)$ as the scale of problematic products that can be recalled in a food safety incident, $f(0)=1$, $f(1)=0$ and $f'(t)<0$, $f''(t)<0$. When $t=0$, it means that the manufacturer has not performed food traceability, which means that the manufacturer is responsible for any goodwill or penalties caused by all possible bad foods in the market. $f'(t)<0$ means that the higher traceability level leads to more recalls of defective products and thus reduces further losses. This assumption is reasonable and realistic. In $f(e)=1-(1-f(e))$, it is found that $e$ and $1-f(e)$ have a one-to-one enantiomer relationship. For simplification, we assume that $f(e)=1-e$ and the above parameter design has been referred to in the literature.

Based on the effort level $e \in (0,1)$ of suppliers, the probability of food safety events that may occur in the process of processing, production, and sales of the supply chain is modeled as a function of food safety effort level by referring to Chao et al. (2009). Manufacturers can reduce the probability of recall events by reducing the initial value of $1-e^{-\lambda}$ to $1-e^{-\lambda(1-e)}$ by investing in suppliers. Note that in practice, $\lambda$ is usually very small, and therefore, according to Taylor's formula, $1-e^{-\lambda(1-e)}$ is approximately equal to $\lambda(1-e)$. This paper focuses on the decision-making of safety efforts. Because the value of $\lambda$ is robust, it is not involved in the analysis in the formula below. In practice, when food safety causes serious consequences to consumers, delaying the decision of recall will bring a high risk of safety responsibility to the manufacturer, so we assume that the manufacturer immediately takes action to initiate a recall when a food safety incident occurs.

## 3.2 | Parameter interpretation

Table 1 lists the parameters related to model establishment and the meaning of symbols.

## 3.3 | Model building

In our model, the manufacturer and the supplier sign a purchase contract at the agreed wholesale price and security premium sharing ratio. Among them, the former provides sufficient incentives for the latter, such as the investment support for suppliers on the safety level of food raw materials and the sharing of premiums paid by consumers due to the improvement of safety efforts at the end of the sale. Therefore, suppliers have the motivation to improve food safety efforts, while producers can obtain premium income from consumers for high safety and quality food, reduce the probability of food safety incidents, and reduce the compensation losses caused by problematic foods. For this purpose, we respectively formulate the best-effort strategy for the two in pursuit of maximizing returns.

$$\underset{s,t}{\text{Max}}\pi_m = (p-w)q-(1-e)qtC_1-(1-e)q(1-t)C_2-C_t(t)-C_s(s). \quad (1)$$

**TABLE 1** Symbol and meaning

| Symbol | Meaning |
|---|---|
| $s$ | Manufacturers' investment in upstream safety |
| $t$ | The manufacturer's traceability recall level |
| $e$ | Supplier's safety effort level |
| $C$ | Loss cost per unit of unrecalled food |
| $\alpha$ | Consumer perception of food safety efforts |
| $\eta$ | Safety effort cost coefficient of agricultural products |
| $h$ | Cost coefficient for manufacturer's traceability level |
| $k$ | The cost factor of the manufacturer's safety investment |
| $\theta$ | The share of the security premium paid by consumers |
| $r$ | The proportion of non-recall food cost-sharing |
| $w_0$ | Wholesale product price |
| $u$ | Cost of raw material |
| $\pi_s$ | profit of supplier |
| $\pi_m$ | profit of producer |

In reality, the occurrence of food safety problems will lead to a decrease in the performance of the whole supply chain, and the profits of each member of the chain will be affected to varying degrees due to food issues. Due to asymmetric information between channels, low information transparency, imperfect traceability system, and management problems, the responsibility of food events cannot be fairly distributed, making the large producers or processing retailers of production terminals bear all the losses of food events alone. As mentioned above, TESCO's horsemeat scandal and retail giant Wal-Mart bear all the losses of the contaminated product recall. This article, the loss of product recall, waste treatment, customer after-sales compensation, and the cost of food, recalls such as transportation and inventory for recall measures in the process of sales are defined as unit cost $C_1$. However, the negative impact (like brand reputation, consumer market share decline, and safety penalty) caused by the unrecalled food is recorded as $C_2$ and borne by the dominant manufacturer. Due to the unique attributes of the food supply chain, compared with the food that can be recalled with problems, the unrecalled products cause more serious damage to the goodwill of the enterprise, the reduction of the market share, and the punishment of the food health-related policy (Dai et al., 2021). Considering that this paper mainly studies the equilibrium optimization of food safety effort and traceability level, it is robust to ignore the small negative loss cost, and the conclusion of this paper remains unchanged. To simplify the model, we only consider the unrecalled and penalized loss cost, $C_2$, which has a large impact and a wide range of serious losses. Therefore, the revenue function of the producer is updated as

$$\underset{s,t}{\text{Max}}\ \pi_m = (p-w)q-(1-e)q(1-t)C-C_t(t)-C_s(s). \quad (2)$$

The revenue function of the supplier is

$$\underset{e}{\text{Max}}\ \pi_s = (w-u)q-\frac{1}{2}\varphi Z(s)e^2. \quad (3)$$

$w-u$ ($w=w_0+(1-\theta)\alpha e$) refers to the unit income of food raw materials provided by the supplier. The safety investment of the manufacturer can help the supplier to realize process and informatization, so the assisted supplier can obtain a higher level of safety by paying the lower cost of safety efforts. For reference (Iida, 2012; Liu et al., 2018; Xie et al., 2016), the influence coefficient of introducing manufacturer investment on suppliers' safety effort cost is $Z(s)=\frac{\phi}{s}$, and the supplier's safety effort cost is $\frac{1}{2}\theta Z(s)e^2$. The smaller the influence coefficient $Z(s)$ is, the smaller the safety effort cost paid by the supplier at the same safety effort level is, simplified to

$$\underset{e}{\text{Max}}\ \pi_s = (w-u)q-\frac{1}{2}\eta\frac{e^2}{s}. \quad (4)$$

On the other hand, we consider that $C_e(e)=\frac{1}{2}\theta Z(s)e^2$, $C_t(t)=\frac{1}{2}ht^2$, and $C_s(s)=\frac{1}{2}ks^2$ are quadratic continuously differentiable at [0, 1]; that is, for the manufacturer and the supplier, their traceability recall level and safety efforts are a convex increasing trend. For

$(e, t) \in (0, 1] \times (0, 1]$, there are $C_e'(e) > 0$ and $C_t'(t) > 0$、$C_e''(e) > 0$ and $C_t''(t) > 0$. To avoid the boundary problem of manufacturer and supplier decision-making, we combined the actual situation in real life, such as considering the limited material, economic strength, and resources of enterprises and relevant literature. We further hypothesized that the cost of obtaining a high level of effort would be prohibitively high. More specific models, by $lim_{e \to 1} C_e(e) = \infty$, $lim_{t \to 1} C_t(t) = \infty$. Similar cost functions are common assumptions of model negotiability and are widely used in economics and operations research literature (Dai et al., 2021; Tang et al., 2014).

The solution sequence in this paper is as follows. We use reverse induction to solve this problem. First, we solve the food supplier's optimal safety effort decision, $e$, and obtain the supplier's response function to the manufacturer's investment. Then, the manufacturer makes a decision based on the supplier's response function and decides its own optimal investment level $s$ and optimal traceability level $t$, to maximize its income. To simplify, let $p_0 = w_0 = 0$. Stackelberg game is widely used in supply chain modeling (Ma et al., 2020; Ma & Xu, 2022).

Among them, we get the Hessian matrix of the profit of the food manufacturer under the food traceability recall level $t$ and the investment $s$ in the supplier s as follows:

$$H = \begin{pmatrix} \frac{\partial^2 \pi_m}{\partial s^2} & \frac{\partial^2 \pi_m}{\partial s \partial t} \\ \frac{\partial^2 \pi_m}{\partial t \partial s} & \frac{\partial^2 \pi_m}{\partial t^2} \end{pmatrix} = \begin{pmatrix} -k & \frac{\alpha(1-\theta)C}{\eta} \\ \frac{\alpha(1-\theta)C}{\eta} & -h \end{pmatrix}, \tag{5}$$

where $|H| = \sqrt{kh} - \alpha(1-\theta)C/\eta > 0$, indicating that the manufacturer has an optimal decision-making solution for the traceability recall and safety investment of the food supply chain. Finally, the optimal decision of the manufacturer is substituted into the reaction function of the supplier, and the optimal decision of the supplier is obtained.

Derivation of Equation 2, by the first-order condition $\frac{\partial \pi_s}{\partial e} = 0$ and $\frac{\partial^2 \pi_m}{\partial e^2} < 0$, there is

$$e^* = \frac{q\alpha(1-\theta)}{\eta} s^*. \tag{6}$$

Substitute $e^*$ in formula 6 into $\pi_s$ to obtain the optimal $s^*$ and $t^*$:

$$s^* = \frac{q^2 \alpha \eta (1-\theta)\left(h(\alpha\theta + C) - C^2\right)}{kh\eta^2 - q^4 C^2 \alpha^2 (1-\theta)^2}, \tag{7}$$

$$t^* = \frac{C\left(kq\eta^2 - q^4 \alpha^2 (1-\theta)^2 (\alpha\theta + C)\right)}{kh\eta^2 - q^4 C^2 \alpha^2 (1-\theta)^2}. \tag{8}$$

Finally, the optimal safety effort level is obtained:

$$e^* = \frac{q^3 \alpha^2 (1-\theta)^2 \left(h(\alpha\theta + C) - qC^2\right)}{kh\eta^2 - q^4 C^2 \alpha^2 (1-\theta)^2}. \tag{9}$$

Manufacturer's profit under optimal safety effort and optimal retrospective recall strategy:

$$\pi_m = \frac{q\left(qC^2\left(k\eta^2 - 2q^3\alpha^3(1-\theta)^2\theta\right) + h\left(q^3\alpha^2(1-\theta)^2(C+\alpha\theta)^2 - 2kC\eta^2\right)\right)}{2\left(kh\eta^2 - q^4C^2\alpha^2(1-\theta)^2\right)}. \tag{10}$$

Supplier's profit:

$$\pi_s = \frac{q^4\alpha^3(1-\theta)^3\left(h(\alpha\theta + C) - qC^2\right)}{2\left(kh\eta^2 - q^4C^2\alpha^2(1-\theta)^2\right)}. \tag{11}$$

## 4 | ANALYSIS

In this section, we attempt to propose an optimal product effort strategy for safety effort and traceability levels in the food supply chain by addressing the producer and retailer issues described in Section 3, where $s^*$, $t^*$, and $e^*$ are, respectively, the optimal investment level, product recall strategy, and safety effort strategy of food manufacturers and suppliers in pursuit of the maximization of their interests. The complex formula in the formula is simplified. Note that $(p - w) - (1 - e)(1 - t)C > 0$, this can be interpreted to mean that the manufacturer's marginal profit is non-negative, even if the manufacturer does not work hard to trace the product. The following theorems illustrate game analysis of safety effort and traceability level strategy in the food supply chain.

**Corollary 1.1:** If cost coefficient for manufacturer's traceability level is bigger than loss cost per unit of unrecalled food $h > C$, 且$kh\eta^2 < (C\alpha)^2$

1. The relationship between supplier's safety effort level $e$ and the share of the security premium paid by consumers $\theta$.

When $\theta \in \left(0, 1 - \frac{\eta\sqrt{hk}}{q^2 C\alpha}\right)$, $\frac{\partial e}{\partial \theta} > 0$, and $\theta \in \left(1 - \frac{\eta\sqrt{hk}}{q^2 C\alpha}, 1\right)$, $\frac{\partial e}{\partial \theta} < 0$. When $\theta$ is lower than a certain threshold value, the safety effort level of suppliers in the food supply chain increases with the increase of the sharing ratio; otherwise, it decreases with the increase of the sharing ratio when $\theta$ exceeds this threshold value.

2. The relationship between manufacturers' investment in upstream safety $s$ and the share of the security premium paid by consumers $\theta$.

when $\theta \in \left(0, 1 + \frac{kh^2\eta^2}{q^4C^2\alpha\left(qC^2 - h(C+\alpha)\right)}\right)$, $\frac{\partial s}{\partial \theta} > 0$, and $\theta \in \left(1 + \frac{kh^2\eta^2}{q^4C^2\alpha\left(qC^2 - h(C+\alpha)\right)}, 1\right)$, $\frac{\partial s}{\partial \theta} < 0$. The manufacturer's investment in upstream suppliers' safety efforts increases with the increase of $\theta$ values in the early stage and decreases with the increase of $\theta$ values in the later stage.

3. The relationship between the manufacturer's traceability recall level $t$ and the share of the security premium paid by consumers $\theta$.

When $\theta \in \left(0, 1-\frac{\eta\sqrt{hk}}{q^2 w\alpha}\right)$, $\frac{\partial t}{\partial \theta} < 0$, and $\theta \in \left(1-\frac{\eta\sqrt{hk}}{q^2 w\alpha}, 1\right)$, $\frac{\partial t}{\partial \theta} > 0$. The enthusiasm of manufacturers in food traceability recall level will decrease with the increase of the share proportion of safety effort premium; then, it will increase beyond a certain threshold.

Theorem 1 gives a closed-form expression of the optimal food safety effort and recall strategy for both upstream and downstream manufacturers and suppliers in the food supply chain for the problem parameters and obtains the relevant threshold strategy. When the technical cost coefficient of traceability level in the food supply chain is large and higher than the loss cost of unrecalled food per unit, similar trends emerged in best safety efforts and product recall strategies for both manufacturers and suppliers. In other words, as the proportion of consumer premium brought about by safety improvement in the procurement contracts of producers and suppliers in the food supply chain changes, the optimal safety strategies of both parties change from positive (negative) correlation in the early stage to negative (positive) correlation in the later stage, presenting a convex (concave) change form. To reduce the loss of food products purchased and produced from upstream suppliers when they are sold in the market, food manufacturers will establish a product traceability system for the whole food supply chain and try to recall all the problematic products as soon as possible on the largest scale. If the cost coefficient of food traceability level is large and higher than the loss caused by failure to recall defective food in time, the profit-oriented manufacturers will be less enthusiastic in food traceability and more inclined to improve product safety.

After signing the purchase contract with the supplier, the manufacturer will determine the sharing proportion of consumer premium after the improvement of food safety efforts. We can know that if the large manufacturer has a strong voice in the whole food supply chain, it requires a large proportion in revenue sharing. It will reduce the enthusiasm of suppliers in improving the level of food safety so that the food safety degree of the whole supply chain is not high, the probability of selling problematic food is higher, and the safety premium of products will also be reduced. This has further prompted manufacturers to reduce their investment in supplier safety and focus on improving product traceability across the food chain. Conversely, if the giant manufacturer can share the premium benefits of more food safety efforts, the supplier's safety efforts will be more profitable, and the motivation to improve its safety efforts will be stronger, which will lead to higher food safety efforts. It has also encouraged manufacturers to invest in upstream safety and to devote more resources to improving supplier safety rather than the traceability level of recalled food. Therefore, if the share ratio of food safety premium is too high, although it is conducive to the improvement of traceability level, it reduces the enthusiasm of suppliers to improve food safety and fails to improve the health and safety level of the whole food industry.

**Corollary 1.2:** If cost coefficient for manufacturer's traceability level is smaller than loss cost per unit of unrecalled food $h < c$,

1. The relationship between supplier's safety effort level $e$ and the share of the security premium paid by consumers $\theta$.

i. When $\theta \in \left(1-\frac{\eta}{\alpha}, 1-\frac{\eta\sqrt{hk}}{q^2 C\alpha}\right)$, then $\frac{\partial e}{\partial \theta} < 0$, or $\theta \in \left(1-\frac{\eta\sqrt{hk}}{q^2 C\alpha}, \tilde{\theta}\right)$, $\frac{\partial e}{\partial \theta} > 0$.

ii. The relationship between manufacturers' investment in upstream safety $s$ and the share of the security premium paid by consumers $\theta$.

iii. When $\theta \in \left(1-\frac{\eta}{\alpha}, \tilde{\theta}\right)$, there $\frac{\partial s}{\partial \theta} > 0$.

iv. The relationship between the manufacturer's traceability recall level $t$ and the share of the security premium paid by consumers $\theta$.

v. When $\theta \in \left(1-\frac{\eta}{\alpha}, 1-\frac{\eta\sqrt{hk}}{q^2 C\alpha}\right)$, there $\frac{\partial t}{\partial \theta} > 0$; or $\theta \in \left(1-\frac{\eta\sqrt{hk}}{q^2 C\alpha}, \tilde{\theta}\right)$, $\frac{\partial t}{\partial \theta} < 0$.

$$\tilde{\theta} = \min\left(\frac{C}{\alpha}\left(\frac{C}{h}-1\right), \frac{\alpha\eta\left(-w^2+h(w+\alpha)\right)+\sqrt{4hk\eta^2\alpha^2(w^2-h\eta)+\alpha^2\eta\left(-w^2+h(w+\alpha)\right)^2}}{2\alpha^2(w^2-h\eta)}\right).$$

When the unit loss cost of unrecalled food was higher than the traceability cost coefficient of the supply chain, what makes us feel interesting is that both sides showed opposite conclusions about the optimal food safety decision and recall strategy. With the increase of the premium proportion of food safety effort shared in the purchase contract between manufacturer and supplier, we have observed that upstream suppliers in the food supply chain are less motivated to pay for product safety efforts. This is because when suppliers get only a fraction of the premium paid by consumers for their food safety efforts, there is no strong will to improve the safety level of their products even if they get the safety investment from downstream producers. It is counter-intuitive that food producers' investment in the safety of their upstream suppliers always increases as the proportion of the consumer premium for safety improvements increases. We can understand that when the sharing ratio of safety premium is low, even if suppliers are not enthusiastic about improving food safety, producers will try their best to improve the food chain in terms of safety investment and food traceability when they are faced with higher cost unrecalled food losses. As producer investment increases gradually and the safety of the upstream exceeds a certain threshold, even when the safety premium sharing ratio is high, the supplier can more efficiently improve food safety and obtain benefits with the help of the downstream, and manufacturers will also reduce the improvement of traceability and further increase their security investment in suppliers.

Consumers and governments of all countries attach great importance to food safety in the market; there will be a more strict policy of food safety, food and health problems of merchants have severe punishment measures, and problems existed in food businesses for its reputation on the market, stock price, and product sales caused extremely serious blow (Hastig & Sodhi, 2020). This has led large downstream manufacturers to both improve their traceability and cooperate with suppliers with higher product safety and quality. And when they find high-quality suppliers, they will invest in food safety upstream as much as possible to improve product safety. Suppliers need to accept a higher share of the security premium too.

**Corollary 2.1**: If cost coefficient for manufacturer's traceability level is bigger than loss cost per unit of unrecalled food $h > c$,

1. The relationship between the profit of supplier $\pi_s$ and the share of the security premium paid by consumers $\theta$.

   If $\theta \in (0, \theta_s^h)$, $\frac{\partial \pi_s}{\partial \theta} > 0$, or $\theta \in (\theta_s^h, 1)$, $\frac{\partial \pi_s}{\partial \theta} < 0$.

2. The relationship between the profit of manufacturer $\pi_m$ and the share of the security premium paid by consumers $\theta$.

   If $\theta \in (0, \theta_m^h)$, $\frac{\partial \pi_m}{\partial \theta} > 0$, or $\theta \in (\theta_m^h, 1)$, $\frac{\partial \pi_m}{\partial \theta} < 0$.[1]

When the traceability cost coefficient of food supply chain is higher than the loss of unrecalled products, it can be found that the share premium ratio $\theta$ of both producers and retailers with safety efforts meets a certain threshold, within which the benefits of both increase with the increase of $\theta$, and then decrease with the increase of $\theta$. Counterintuitively, suppliers' profits did not decrease when the share of the premium for early security efforts increased, but their profits increased. The reason is that although the distribution proportion increases the premium, means that the supplier's security efforts in terms of food safety more share to the downstream producers, but the latter will also give more security investment to help the former and reduce the cost of the former in promoting food safety and technology such as burden to gain higher food safety efforts. High-quality food reduces the probability of food safety incidents and the requirements for the traceability of the food supply chain. Manufacturers can devote more resources from building food traceability capabilities to the safety investment of upstream suppliers. This has played a positive effect in a two-way cycle. The increase in the share of the premium for safety efforts $\theta$ has made the food supply chain appear a win–win situation. But the security premium share ratio of the two sides is a win–win situation with a certain threshold of constraints; when it is more than suppliers within the scope of its power to improve food security, producers of the former investment enthusiasm also reduce and choose to put more resources into food traceability. This behavior of excessive exploitation of win-win benefits brings losses to the interests of both sides and makes the overall supply chain benefit lower than before. It is suggested that the two parties in cooperation should make a reasonable distribution of the gains obtained, to maximize the mutual benefit of both sides.

**Corollary 2.2:** If cost coefficient for manufacturer's traceability level is smaller than loss cost per unit of unrecalled food $h < c$,

1. The relationship between the profit of manufacturer $\pi_m$ and the share of the security premium paid by consumers $\theta$.

   If $\theta \in (0, \theta_m^c)$, then $\frac{\partial \pi_m}{\partial \theta} > 0$, or $\theta \in (\theta_m^c, 1)$, we get $\frac{\partial \pi_m}{\partial \theta} < 0$.

2. The relationship between the profit of supplier $\pi_s$ and the share of the security premium paid by consumers $\theta$.

   If $\theta \in \left(\underline{\theta_s^c}, \overline{\theta_s^c}\right)$, there $\frac{\partial \pi_s}{\partial \theta} < 0$.

If the loss cost of unrecalled defective products is higher than the cost coefficient of the traceability level of the food supply chain consumers or food regulators prefer safe food and have a low tolerance for defective products or food safety incidents cause large losses. It can be observed that the profit function of the manufacturer is the same as when the loss cost of the previous problem product is low. It starts to increase with the increase in the premium ratio of the safety effort within a certain range and then exceeds the critical value; it decreases with the increase of the distribution proportion. However, the supplier's profit will always decrease as the premium distribution ratio increases. This phenomenon is very interesting. How to understand how manufacturers make optimal decisions to recall products when the compensation loss of unrecalled products is high, and why suppliers' profits keep decreasing? We make a deeper analysis of this. When the former bears the higher liability costs caused by the defective products, as the leader of the food supply chain, it tends to take a higher proportion in the premium income of safe food to offset the losses caused by the defective products to maximize their interests. Manufacturers will make more safety investments for the latter to incentivize them to increase the level of food safety efforts. This allows suppliers to obtain higher safety investment and pay more safety efforts; the overall marginal income decreases because the premium sharing ratio of the purchase contract signed by both parties is too low. As the leader, the producer can obtain higher profits from the advantage in the initial premium distribution ratio. The increase in distribution requires the manufacturer to provide higher investment support to upstream suppliers to maintain higher food safety levels. Although the former can save the cost of the retrospective recall and obtain a higher proportion of sharing, the requirement of safety investment is higher at this time. By contrast, the sum of cost-saving and premium income is lower than the expenditure on safety investment, and the total income of the final manufacturer is reduced compared to before. It shows that when the unit does not recall the problematic product and the loss is high, the manufacturer needs to take the initiative to share more premium income to the upstream supplier and make a safe investment in the latter according to its actual situation.

In a nutshell, $h$ is the cost coefficient for constructing the product traceability recall level in the food traceability recall supply chain, and $c$ is the loss compensation caused by the problem product in the food supply chain. The relationship between the two depends on the value in different environments, that is, the difference in economic cost in management. When the development of retrospective recall technology is relatively slow and more resources are invested, the capital burden on food companies is heavier. Therefore, compared with the risk loss caused by low-quality products, companies are more inclined to choose to give up the improvement of retrospective recall technology. Conversely, for companies with strong scientific and technological strength and markets where consumers pay more attention to food quality, how to reduce the loss of problem food by further improving the level of retrospective recall, that is, pay more attention to the risk loss caused by problem food. It is a wise decision for the food company. To sum up, the relationship between the two is the cost difference that occurs according to changes in the environment such as the market.

**Corollary 3.1:**

1. The relationship between supplier's safety effort level $e$ and loss cost per unit of unrecalled food $C$.

   If $C \in (0, \underline{C})$, $\frac{\partial e}{\partial C} > 0$, and $C \in (\underline{C}, \overline{C})$, there $\frac{\partial e}{\partial C} < 0$.

2. The relationship between manufacturers' investment in upstream safety $s$ and loss cost per unit of unrecalled food $C$.

   If $C \in (0, \underline{C})$, $\frac{\partial s}{\partial c} > 0$, and $C \in (\underline{C}, \overline{C})$, $\frac{\partial s}{\partial c} < 0$.

3. The relationship between the manufacturer's traceability recall level $t$ and loss cost per unit of unrecalled food $C$,

when $C \in (0, \overline{C})$, $\frac{\partial t}{\partial c} > 0$, and $\underline{C} = \left(k q \eta^2 - q^4 \alpha^3 (-1+\theta)^2 \theta + \sqrt{-hkq^4 \alpha^2 \eta^2 (-1+\theta)^2 + \left(kq\eta^2 - q^4 \alpha^3 (-1+\theta)^2 \theta\right)^2}\right) / \left(q^4 \alpha^2 (-1+\theta)^2\right)$;

$\overline{C} = \left(h + \sqrt{h(h + 4q\alpha\theta)}\right) / (2q)$.

Theorem 3.1 shows that when the unit loss cost caused by defective products in the food supply chain increases gradually, both the safety investment intensity of the manufacturer and the safety effort level of the supplier increase first and then decrease. The traceability level of the entire food supply chain increases with the increase in the unit loss cost of the unrecalled products. This makes us intuitively feel that when a food safety incident occurs, as the loss cost of unrecalled food increases, enterprises will further improve the traceability level of the supply chain, and at the same time, they will make more investment in safety and improve the food safety level while taking responsibility for the unrecalled products. However, companies are constrained by their inherent resources and within the range of affordability, when faced with low losses of unrecalled food per unit, producers will make safety investments to suppliers to encourage them to establish higher safety efforts to obtain more food safety premiums for consumers and higher profits for the food chain. When the loss cost of unit non-recall increases gradually, facing the dilemma of higher and higher safety investment demand and the premium benefits of safe food, manufacturers are more inclined to improve the traceability level of the food supply chain to reduce the loss of defective products and maintain their profit maximization. Suppliers are also forced to make lower level safety efforts when manufacturers reduce their safety investments. Therefore, higher unit non-recall product losses can promote the establishment of a traceability system in the food supply chain but may not be conducive to improving the safety and quality of food chain products.

**Corollary 3.2:**

1. The relationship between the profit of manufacturer $\pi_m$ and loss cost per unit of unrecalled food $C$.

   i. If $C \in \left(0, \frac{hk\eta^2}{kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta}\right)$, then $\frac{\partial \pi_m}{\partial C} < 0$, or $C \in \left(\frac{hk\eta^2}{kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta}, \frac{k\eta^2}{q^3\alpha^2(-1+\theta)^2} - \alpha\theta\right)$, $\frac{\partial \pi_m}{\partial C} > 0$.

   ii. The relationship between the profit of supplier $\pi_s$ and loss cost per unit of unrecalled food $C$.

   iii. If $C \in \left(0, \frac{kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta - \sqrt{-hkq^4\alpha^2\eta^2(-1+\theta)^2 + \left(kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta\right)^2}}{q^4\alpha^2(-1+\theta)^2}\right)$, we get $\frac{\partial \pi_s}{\partial C} > 0$, or $C \in \left(\frac{kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta - \sqrt{-hkq^4\alpha^2\eta^2(-1+\theta)^2 + \left(kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta\right)^2}}{q^4\alpha^2(-1+\theta)^2}, \frac{kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta + \sqrt{-hkq^4\alpha^2\eta^2(-1+\theta)^2 + \left(kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta\right)^2}}{q^4\alpha^2(-1+\theta)^2}\right)$, then $\frac{\partial \pi_s}{\partial C} < 0$.

With the increase in the unit loss cost of the unrecalled food safety incidents, manufacturers tend to make more safety investments in upstream suppliers to reduce compensation costs caused by food safety at the beginning. Manufacturers continue to improve the traceability level of the food chain at this time, which makes the overall profit of the manufacturer decrease as the unit loss of unrecalled products increases. On the contrary, after receiving the manufacturer's investment in safety, suppliers can implement a higher level of food safety, which will increase the supplier's revenue without increasing the unit cost of the recall. This is a counter-intuitive situation. The so-called “free rider” phenomenon occurs when the upstream supplier gains from the loss compensation of the downstream manufacturer in the face of traceability failure. Then, the increase of unit unrecalled losses reduces the enthusiasm of manufacturers to improve the safety and quality of products, reduces the safety investment of suppliers to save their costs, and instead puts resources into product retrospective recall to reduce the loss of problematic products. This encourages manufacturers to make more security investments and have higher returns than before. With the reduction of manufacturers' safety investment, suppliers' initiative in product safety efforts has also decreased, and the benefit of "free-riding" has declined, so the supplier's income has begun to decrease.

**Corollary 4:** When $k_1 = \max\left(\frac{C^2\alpha^2(1-\theta)^2+\alpha\eta(1-\theta)\left(h(\alpha\theta+C)-C^2\right)}{h\eta^2}, \frac{\alpha^2(1-\theta)^2 h(\alpha\theta+C)}{h\eta^2}\right)$ and $k_2 = \frac{C^2\alpha^3(1-\theta)^2\theta}{(C-h)\eta^2}(h<c)$, or $k_2 = \infty(h>c)$. Then,

The relationship between the cost factor of the manufacturer's safety investment k and supplier's safety effort level $e$, manufacturers' investment in upstream safety $s$, the manufacturer's traceability recall level $t$.

$$\text{If } k \in (k_1, k_2), \frac{\partial e}{\partial k} < 0, \text{ or } \frac{\partial s}{\partial k} < 0, \frac{\partial t}{\partial k} > 0.$$

The relationship between the cost factor of the manufacturer's safety investment k and the profit of manufacturer $\pi_m$, the profit of supplier $\pi_m$.

$$\text{If } k \in (k_1, k_2), \frac{\partial \pi_m}{\partial k} < 0; \frac{\partial \pi_s}{\partial k} < 0.$$

The theorem shows that the increase in the safety investment cost coefficient of the food supply chain means that suppliers need to invest more resources to obtain the same investment effect as before, which intensifies the safety investment burden of the enterprise. This reduces the initiative of suppliers to improve the safety efforts of the food chain when the safety investment is reduced. However, manufacturers will choose to focus on food traceability recall when faced with high food safety investment and low effects, in an attempt to reduce the safety loss incurred in the food safety incident.

## 5 | NUMERICAL SIMULATION

In this section, to verify the validity and correctness of the proposed propositions and inferences, matlab2019 is used for numerical simulation analysis. To ensure the generality of the various values, refer to Chao et al. (2009) and Dai et al. (2020, 2021); numerical examples are used to intuitively illustrate the results of this article. The following figure focuses on the impact of different parameters on the food supply chain. Among them, the safety effort premium sharing ratio, the unit's unrecalled food loss cost, and the safety investment cost coefficient on the manufacturers, suppliers in the food supply chain, research on the impact of the best product safety efforts and product recall strategies on business decisions is discussed.

Figure 3 respectively shows the relationship between food safety investment decisions, recall level, and product safety efforts of manufacturers and suppliers under different circumstances and the proportion of food safety premium sharing. The figure on the left shows that when the unit's loss of unrecalled products is lower than the tracking recall cost coefficient of the food supply chain, the increase in the share of the safety premium has a win–win effect in the early stage. Manufacturers are more interested in investing in the food safety of upstream suppliers, who also have the motivation to improve product safety efforts. In addition, manufacturers can reduce recall costs by reducing the level of traceability in the supply chain. Once the share ratio of safety premium exceeds the threshold, it can be found from the image that even though the safety investment of producers is increasing, the enthusiasm of suppliers to improve safety efforts begins to decline, which makes the producers have to increase the traceability level to offset the negative effect of reducing safety efforts in the food supply chain. However, with the further imbalance of sharing ratio, safety efforts continue to decrease, and manufacturers' willingness to invest in safety has also begun to weaken, turning more investment resources into improving the level of food traceability. Therefore, the conclusion in the theorem is verified again. When the sharing proportion of safety premium exceeds a certain range and the difference of profit-sharing is large, both parties will be disadvantageous and become losers.

Figure 3, right, shows when the unit cost of unrecalled products is higher than the tracked cost factor. Through the intuitive discovery of the right, in order to manage the risks caused by low-quality food, the manufacturer chooses to invest in the safety of the supplier from the beginning. The initial safety investment failed to meet the needs

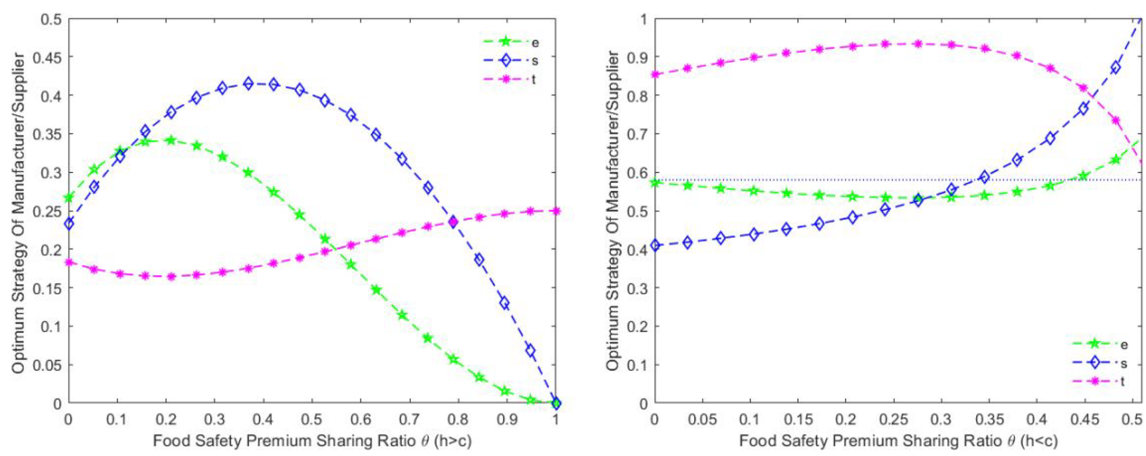


**FIGURE 3** Optimal decision under the sharing ratio of safety premium (left: higher recall coefficient; right: higher non-recall losses) [Color figure can be viewed at wileyonlinelibrary.com]

of suppliers, and the increase in the share of food safety premiums has made suppliers less motivated to improve product safety. The further increase in safety investment by manufacturers stimulates suppliers to improve their product safety efforts. The former reduces the investment in retrospective recall while improving food safety. It can be understood that members of the food chain are more inclined to devote more resources to improving food safety, rather than improving the traceability of product recalls. They realize that for the food supply chain that focuses on safety and quality, the improvement of traceability is a temporary solution but not a permanent cure. The key is to improve the safety and health of food, and they can also obtain the benefits of higher safety premiums.

Figure 4 analyzes the relationship between the income of each member in the food supply chain and the share ratio of safety premium. Through comparison, it is found that the overall trend of manufacturer's profit with the proportion of safety premium sharing has little change in the difference between the traceability cost coefficient and the loss per unit of unrecalled product. This is because the manufacturer should always maintain a balanced relationship between safety investment and traceability level while ensuring the maximization of their interests. When safety investment intensity is large, the requirements for traceability level will be reduced. Conversely, a higher level of traceability means less investment in safety. Therefore, the leading producer in the early stage can obtain a higher proportion of the profit of food safety premium. While in the later stage, their overall profit declines due to the reduced enthusiasm of suppliers to improve food safety and the high loss of unrecalled products.

However, we find that the utility function of suppliers varies under different circumstances. If the traceability cost coefficient is higher than the loss per unit of unrecalled product, the supplier's revenue will increase with the share of the safety premium, and the image will appear convex. Even though the dominant players receive more food safety premiums, the benefits of high-safety investment are more conducive to suppliers to improve food safety and increase their profits. When the benefits of safety investment fail to further motivate suppliers, the latter will be less enthusiastic about food safety efforts, resulting in a negative circular effect. The reduction in food safety efforts and the high share of safety premiums have made suppliers' revenues fall even faster. If the loss cost of unrecalled products is large, although the manufacturer always increases the upstream safety investment, the latter also continuously improves the food safety efforts. However, leaders will occupy more consumers' premiums for safe food, driving down the revenue of suppliers. Therefore, when large-scale production companies face more severe food safety incidents, their upstream suppliers are often more severely affected.

Figure 5 shows that the increase of the loss cost of unrecalled food makes the manufacturer continuously improve the traceability level of the food chain and strive to recall the food on the largest scale to reduce the loss caused by food safety incidents. Moreover, to punish food enterprises with quality problems to a certain extent has the motivation to promote the improvement of food safety. However, when the punishment is too heavy and exceeds the range that enterprises can bear, manufacturers will often neglect the improvement of

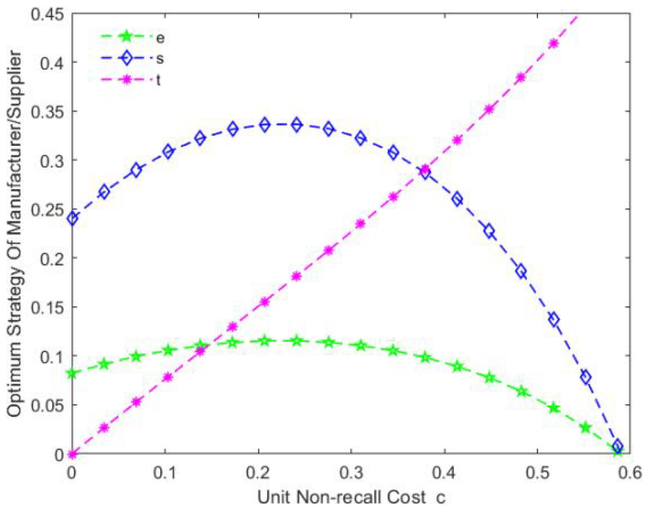


**FIGURE 5** Optimal decision of unit non-recall cost [Color figure can be viewed at wileyonlinelibrary.com]

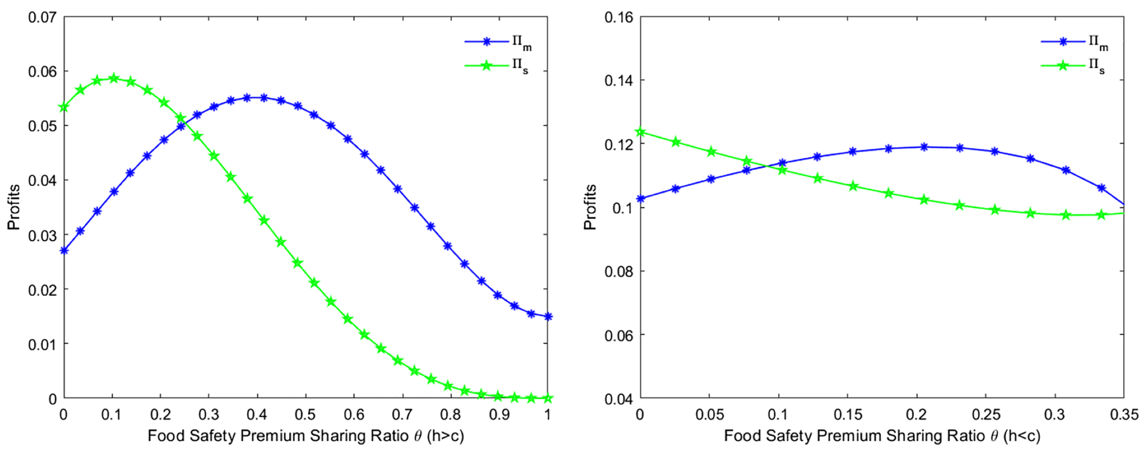


**FIGURE 4** Profit value under sharing ratio (left: higher recall coefficient; right: higher non-recall losses) [Color figure can be viewed at wileyonlinelibrary.com]

product safety due to the loss of recall. Therefore, when the unit's loss of unrecalled food gradually increases, the manufacturer will simultaneously invest in safety and improve the level of a product recall, and the overall profit will drop by a large margin. The increased punishment of the problem food and the high requirement of safety investment force manufacturers to be inclined to improve the traceability recall of the food supply chain. However, in terms of loss cost, safety investment cost, and traceability input, the overall cost decreases, so the overall profit increases.

The revenue curve of the supplier in Figure 6 shows that when the loss of the unit without recall increases, its revenue also increases. This is a "free rider" behavior. Through high-penalty food safety policies, suppliers can get more premium benefits from consumers' safety efforts under the manufacturer's high-level safety investment. When the latter chooses to reduce the safety investment and increase the recall investment to reduce the loss of the unrecalled part, the free-riding effect disappears and the supplier's income declines. Therefore, we know that food safety policy has a significant impact on the decision-making of food enterprises.

As shown in Figure 7, when the cost of safety investment increases, the producers of the food supply chain will reduce their safety investment on upstream suppliers, and the latter will also make low-level safety efforts under the condition of reduced investment support. When suppliers can obtain more safety investment from manufacturers, they can provide consumers with food with higher safety efforts. Higher quality products mean lower incidences of food safety incidents and lower traceability requirements for the overall food supply chain. Finally, the former chooses to reduce the losses caused by the problem food by investing in traceability recall of the food chain.

As shown in Figure 8, the increase of food safety investment cost makes the food enterprises in the food supply chain tend to focus on product recall, but give up the improvement of food safety, and the income of each member also decreases. For the overall optimization of the food chain, how to reduce the cost of food safety investment and technical problems has become an urgent target for the government and food enterprises.

## 6 | EXTENSION

With the development of the social economy, agriculture is gradually transforming to digitalization, trying to optimize the industrial structure by taking digital technologies such as the Internet of Things, big data, and blockchain as the core. As a digital layer, blockchain has the characteristics of data tamper-proof, traceability, and enhancing peer trust among nodes (Wang et al., 2021), which can provide consumers and other members of the supply chain with reliable and trustworthy products' source and product information (Kamble et al., 2020). Besides, it can effectively improve consumers' trust in product quality and expand market demand. Meanwhile, the decentralized database

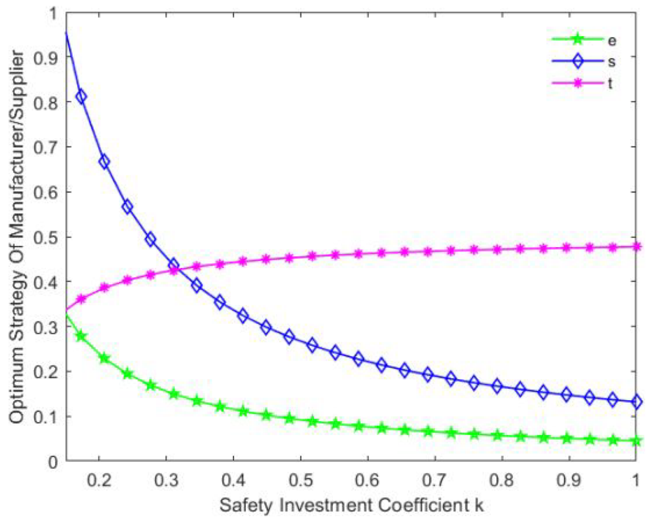


FIGURE 7 Optimal decision under safe investment coefficient [Color figure can be viewed at wileyonlinelibrary.com]

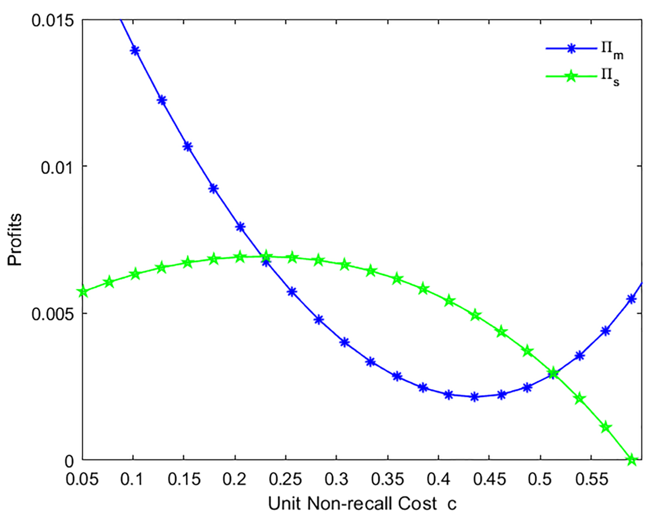


FIGURE 6 Optimal benefit of unit non-recall cost [Color figure can be viewed at wileyonlinelibrary.com]

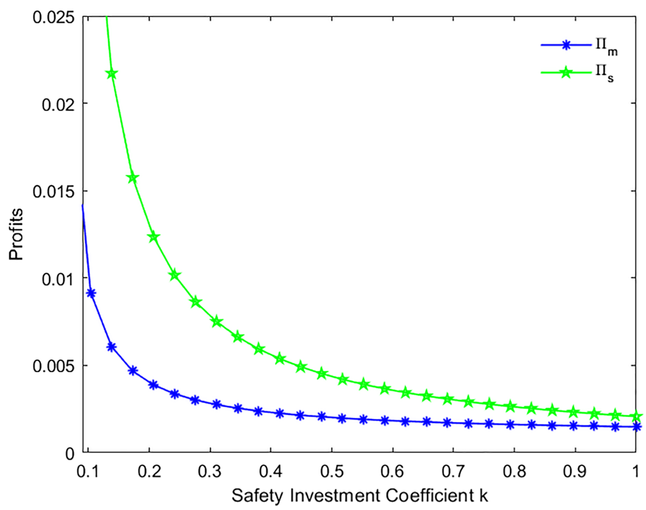


FIGURE 8 Optimal benefit under safe investment coefficient [Color figure can be viewed at wileyonlinelibrary.com]

technology can prevent information from being tampered with and the data information is authentic and reliable. The traceability function of data information of each node can help solve the mistrust among manufacturers in each link of the supply chain (Salah et al., 2019), shirk each other's responsibility, and achieve a fair and clear distribution of responsibility (Hastig & Sodhi, 2020) to optimize the supply chain, downstream manufacturers introduced blockchain traceability for product recalls. The information sharing on the chain can identify the source of the problem food, and the upstream supplier needs to bear the responsibility for the loss of the problem food. Combining the above model assumptions, we analyze the optimal strategy of each member of the food chain under the condition that the supplier and the manufacturer share the loss cost of the unrecalled products.

$$\underset{s,t}{\mathrm{Max}}\ \pi_m = (p-w)q-(1-r)(1-e)q(1-t)C-\frac{1}{2}ks^2-\frac{1}{2}ht^2\#, \tag{12}$$

$$\underset{e}{\mathrm{Max}}\ \pi_s = (w-u)q-\frac{1}{2}\varphi Z(s)e^2-r(1-e)q(1-t)C\#, \tag{13}$$

where $r$ is the part of the upstream supplier that bears the loss of non-recall. To solve this problem, the backward induction method is used to solve the optimal safety effort decision of food suppliers:

$$e^{**} = \frac{s(r(1-t)C+\alpha(1-\theta))}{\eta}\#. \tag{14}$$

Obtain the response function of the supplier to the manufacturer's investment.

Then, the manufacturer makes a decision based on the supplier's response function and decides its optimal investment level $s$ and optimal traceability level $t$, to maximize its income, where we get the Hessian matrix of the profit of the food manufacturer under the food traceability level $t$ and the investment in the supplier $s$. According to the previous calculation results, $|\mathrm{H}| = \sqrt{kh}-\alpha(1-\theta)(1-r)\mathrm{C}/\eta > 0$; see Appendix A for the specific form of H, indicating that the manufacturer has an optimal decision-making solution for retrospective recall and safety investment in the food supply chain, $s^*$ and $t^*$. Then, the supplier's optimal decision is obtained by substituting the manufacturer's optimal decision into the supplier's response function. As the result of the solution is too complicated, we use numerical examples to display the results numerically.

Figure 9 shows safety investment and traceability recall under cost-sharing. After the introduction of blockchain technology in the agricultural product supply chain, due to information sharing, suppliers need to bear a portion of the loss of unrecalled products in food safety incidents. It can be found that suppliers in the food chain are more motivated to increase product safety efforts with clearer responsibility for food safety issues, indicating that information sharing is conducive to promoting food safety and quality. When the manufacturer shares the loss of unrecalled products with the upstream, it will increase the safety investment of suppliers to help them better improve the safety and quality of products. Besides, considering that the upstream will work hard to improve products when faced with food safety penalties, manufacturers will reduce their investment in food retrospective recalls. With the increase in the share of the proportion, after the safety investment reaches the upper limit of the threshold, the manufacturer chooses to reduce the safety investment. Because it has higher requirements on the supplier to bear more losses of food safety events, the manufacturer can take a "free ride" from the supplier at this time.

Figure 10 shows the safety decision of investment and effort under the cost-sharing ratio. We considered the situation where the two companies share the problematic food loss when the manufacturer does not implement a retrospective recall strategy (the dotted line in Figure 10 is $t=0$; that is, the system has no traceable recall). It can be understood as a benefit-sharing and cost-sharing model in which the upstream and downstream of the food supply chain jointly face the food safety incident. Manufacturers' investment in downstream food safety gradually decreases with the increase of the proportion of sharing. The increase in the loss of unrecalled food prompts suppliers to improve food safety to reduce the punishment. When the

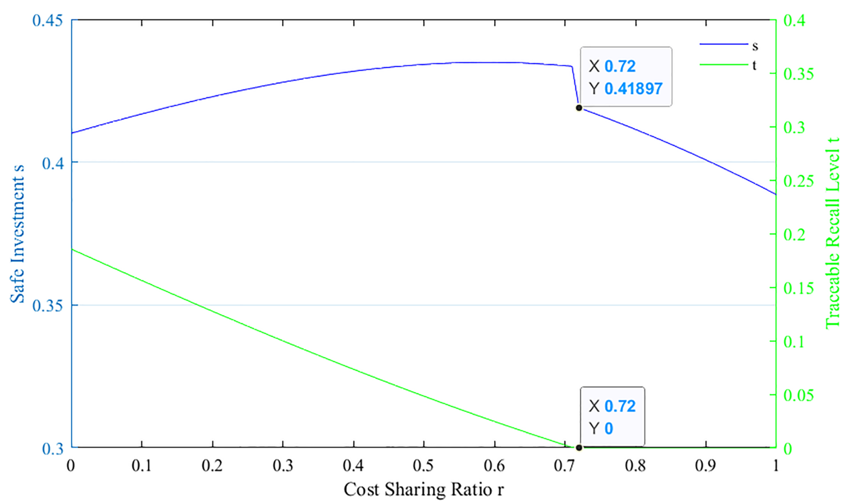


**FIGURE 9** Safety investment and traceability recall under cost-sharing [Color figure can be viewed at wileyonlinelibrary.com]

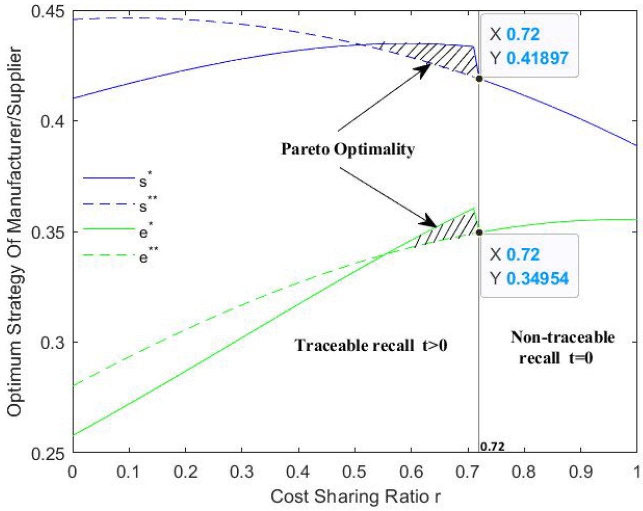


**FIGURE 10** Safety decision of investment and effort under the cost-sharing ratio [Color figure can be viewed at wileyonlinelibrary.com]

share ratio continues to increase, the marginal benefit brought by food safety improvement decreases, and the motivation of suppliers to improve safety also decreases. Therefore, suppliers' safety efforts show a trend of first increasing and then decreasing. Therefore, formulating an effective food safety sharing mechanism is conducive to further improving food safety quality and optimizing the overall benefits of the food supply chain.

## 7 | CONCLUSIONS

### 7.1 | Conclusions and management suggestion

With strict food monitoring and consumers' emphasis on safety and health, product safety and quality have gradually become a problem to be solved in the food supply chain. In addition, advances in technology, such as blockchain and RFID technology, have made the traceability system an important function of the supply chain, aiming to solve the problem of product recalls. Different from traditional quality improvement measures, such as improving the food's safety, which helps reduce the probability of food product recalls. Supply chain traceability helps reduce product recalls that cannot be determined to be safe due to the proportion of products recalled. Besides, in practice, the investment cost of a traceability system can be the variable cost of equipping each product with equipment or information records, while the safety investment cost of food products is usually a large company's weaker upstream or downstream cooperation, which includes the fixed equipment cost or technology cost raised by the supplier. Therefore, the efficiency of managing recalls in the supply chain is determined by the interaction of traceability, the safety investment of partners, and the optimization of product safety efforts. This article uses a game theory model to capture the total interaction between a single manufacturer and the supply chain and consumers and considers the relationship between the traceability investment of large downstream companies and the upstream safety efforts regarding the sharing of food safety premiums. The interaction between product safety efforts and the optimization of retrospective recall capabilities in the food supply chain is studied. Through the analysis of the safety premium sharing ratio, the loss cost of unrecalled products per unit, and the investment cost coefficient, the best product safety efforts and traceability capabilities in the food supply chain are found. Finally, we find that there is Pareto optimal condition in food chain retrospective recall strategy compared with no recall strategy. Retrospective recall of defective products is beneficial to improve the optimal strategies of the food supply chain and improve the overall welfare. At the end of the paper, the management suggestions and strategies suitable for food enterprises are given.

This article summarizes the main findings and enlightenments from different aspects. First, for each member of the food supply chain, there is the only optimal food safety effort, following ability, and safety investment in a closed expression. The share of the consumer premium brought by product safety improvement among members of the food chain affects the optimal decision of both parties is found. When the loss cost of a unit's unrecalled products is lower than the traceable cost coefficient, the manufacturer has more product safety premiums that are conducive to the optimization of the entire food supply chain. However, when the share ratio of the safety premium is too large, the supplier's enthusiasm will be reduced. The safety and quality of food chain products are negative, and more resources are invested in the recall system for problematic products. On the other hand, when the cost coefficient of retrospective recall is low, manufacturers will choose higher retrospective capabilities, and suppliers face a higher share of the security premium, and only when the downstream investment exceeds a certain threshold, will they have the motivation to increase product safety and quality. In addition, the high cost of loss of unrecalled products has prompted the food supply chain to abandon the improvement of food safety and choose to invest in the retrospective recall function. Besides, when the cost of the unit's failure to recall the product is low, the supplier can use the supervision and punishment of the manufacturer to obtain a higher level of investment in safety, resulting in a "free rider" phenomenon. Finally, the increase in the food safety investment cost coefficient has increased the burden on the overall food supply chain, which is not conducive to the improvement of the safety of food products, and the income of various food companies has also declined.

### 7.2 | Contribution and management suggestions

On the one hand, the food industry's policies and regulations on food safety and quality need to be formulated according to the company's affordability. When the product safety and quality requirements of food companies are too high and the punishment is too heavy, it will often have counterproductive effects. Companies in the food chain are more inclined to solve problem products by building a traceable recall system, rather than choosing to improve the safety and quality of their products. On the other hand, manufacturers need to share as much food safety premium revenue as possible with upstream suppliers to incentivize them to improve product safety. Otherwise, manufacturers need to make more safety investments to help their suppliers maintain the motivation to improve product quality. In addition, suppliers can also cooperate with manufacturers to cope with the increase in safety investment costs and unrecallable food losses, to obtain the optimal strategy and maximum benefits for higher social benefits.

### 7.3 | Future research directions

This article is the first attempt to analyze the interaction between traceability, food safety, and investment optimization under the coordination of upstream and downstream. In this article, the impact of food safety efforts on consumer utility is only considered. In addition, in real life, there are a large number of consumers concerned about whether there is traceability in the food supply chain. Therefore, future research will further divide the consumer groups in terms of traceability and explore the equilibrium relationship between them. In addition, there is no specific analysis and discussion on the part of the cost that can be recalled. The following will conduct research on the high recall cost and the high penalty cost of non-recall loss. Moreover, because of the current development of traceability technology, its tracking ability can accurately locate the source of the product's problem and determine the specific responsible party. Therefore, the cost-sharing of the recall strategy caused by different reasons is the next issue that I want to study. Finally, extending this interaction between traceability and security investment to a multi-channel supply chain and exploring the differences in the results are of very practical interest and research significance.

## DATA AVAILABILITY STATEMENT

n/a

## ORCID

*Junhai Ma* https://orcid.org/0000-0002-0827-5143

## ENDNOTE

[1] Please refer to the appendix for specific formulas of $\theta_s^h$ and $\theta_m^h$.

## REFERENCES

Aiello, G., Enea, M., & Muriana, C. (2015). The expected value of the traceability information. *European Journal of Operational Research*, *244*(1), 176–186. https://doi.org/10.1016/j.ejor.2015.01.028

Asioli, D., Boecker, A., & Canavari, M. (2014). On the linkages between traceability levels and expected and actual traceability costs and benefits in the Italian fishery supply chain. *Food Control*, *46*, 10–17. https://doi.org/10.1016/j.foodcont.2014.04.048

Bao, B. S., Ma, J. H., & Goh, M. (2020). Short- and long-term repeated game behaviours of two parallel supply chains based on government subsidy in the vehicle market. *International Journal of Production Research*, *58*(24), 1–24. https://doi.org/10.1080/00207543.2020.1711988

Bellemare, M. F. (2012). As you sow, so shall you reap: The welfare impacts of contract farming. *World Development*, *40*(7), 1418–1434. https://doi.org/10.1016/j.worlddev.2011.12.008

Bhaskaran, S. R., & Krishnan, V. (2009). Effort, revenue, and cost-sharing mechanisms for collaborative new product development. *Management Science*, *55*(7), 1152–1169. https://doi.org/10.1287/mnsc.1090.1010

Bondareva, M., & Pinker, E. (2019). Dynamic relational contracts for quality enforcement in supply chains. *Management Science*, *65*(3), 1305–1321.

Cao, Y., Tao, L., Wu, K., & Wan, G. (2020). Coordinating joint greening efforts in an agri-food supply chain with environmentally sensitive demand. *Journal of Cleaner Production*, *277*, 123883. https://doi.org/10.1016/j.jclepro.2020.123883

Casino, F., Kanakaris, V., Dasaklis, T. K., Moschuris, S., Stachtiaris, S., Pagoni, M., & Rachaniotis, N. P. (2020). Blockchain-based food supply chain traceability: a case study in the dairy sector. *International Journal of Production Research*, *59*(19), 5758–5770. https://doi.org/10.1080/00207543.2020.1789238

Chao, G. H., Iravani, S. M. R., & Savaskan, R. C. (2009). Quality improvement incentives and product recall cost sharing contracts. *Management Science*, *55*(7), 1122–1138. https://doi.org/10.1287/mnsc.1090.1008

Chen, C., Zhang, J., & Delaurentis, T. (2014). Quality control in food supply chain management: An analytical model and case study of the adulterated milk incident in China. *International Journal of Production Economics*, *152*, 188–199. https://doi.org/10.1016/j.ijpe.2013.12.016

Dai, B., Chen, S., & Li, J. (2020). Supply chain recall efforts strategies: Manufacture's promotion vs supplier's production efforts. *Operations Research and Management Science*, *29*(6), 19–32.

Dai, B., Nu, Y., Xie, X., & Li, J. (2021). Interactions of traceability and reliability optimization in a competitive supply chain with product recall. *European Journal of Operational Research*, *290*(1), 116–131. https://doi.org/10.1016/j.ejor.2020.08.003

Dai, J. B., Fan, L., Lee, N. K. S., & Li, J. (2017). Joint optimisation of tracking capability and price in a supply chain with endogenous pricing. *International Journal of Production Research*, *55*(18), 5465–5484. https://doi.org/10.1080/00207543.2017.1321800

Fan, J., Ni, D., & Fang, X. (2020). Liability cost sharing, product quality choice, and coordination in two-echelon supply chains. *European Journal of Operational Research*, *284*(2), 514–537. https://doi.org/10.1016/j.ejor.2020.01.003

Fan, Z.-P., Wu, X. Y., & Cao, B. B. (2020). Considering the traceability awareness of consumers: Should the supply chain adopt the blockchain technology? *Annals of Operations Research*, *37*, 837–860. https://doi.org/10.1007/s10479-020-03729-y

Hastig, G. M., & Sodhi, M. S. (2020). Blockchain for supply chain traceability: business requirements and critical success factors. *Production and Operations Management*, *29*(4), 935–954. https://doi.org/10.1111/poms.13147

Iida, T. (2012). Coordination of cooperative cost-reduction efforts in a supply chain partnership. *European Journal of Operational Research*, *222*(2), 180–190. https://doi.org/10.1016/j.ejor.2012.03.029

Jin, C., Levi, R., Liang, Q., Renegar, N., Springs, S., Zhou, J., & Zhou, W. (2021). Testing at the source: Analytics-enabled risk-based sampling of food supply chains in China. *Management Science*, *67*(5), 2985–2996. https://doi.org/10.1287/mnsc.2020.3839

Kamble, S. S., Gunasekaran, A., & Sharma, R. (2020). Modeling the blockchain enabled traceability in agriculture supply chain. *International Journal of Information Management*, *52*, 101967. https://doi.org/10.1016/j.ijinfomgt.2019.05.023

Krishnan, R., Yen, P., Agarwal, R., Arshinder, K., & Bajada, C. (2021). Collaborative innovation and sustainability in the food supply chain-evidence from farmer producer organisations. *Resources Conservation and Recycling*, *168*, 105253. https://doi.org/10.1016/j.resconrec.2020.105253

Lee, C. H., Rhee, B. D., & Cheng, T. C. E. (2013). Quality uncertainty and quality-compensation contract for supply chain coordination. *European Journal of Operational Research*, *228*(3), 582–591. https://doi.org/10.1016/j.ejor.2013.02.027

Levi, R., Singhvi, S., & Zheng, Y. (2020). Economically motivated adulteration in farming supply chains. *Management Science*, *66*(1), 209–226. https://doi.org/10.1287/mnsc.2018.3215

Liu, W., Yan, X., Wei, W., Xie, D., & Wang, D. (2018). Altruistic preference for investment decisions in the logistics service supply chain. *European Journal of Industrial Engineering*, *12*(4), 598–635. https://doi.org/10.1504/EJIE.2018.093647

Liu, X. Y., Xiong, Z. K., & Xiong, Y. (2012). Cost sharing and quality improvement incentives in the products recall considering the linear demand. *Systems Engineering-Theory & Practice*, *32*(7), 1400–1407.

Ma, J., Hou, Y. M., Wang, Z. X., & Yang, W. H. (2021). Pricing strategy and coordination of automobile manufacturers based on government intervention and carbon emission reduction. *Energy Policy*, *148*(1), 111919. https://doi.org/10.1016/j.enpol.2020.111919

Ma, J., Hou, Y. M., Yang, W. H., & Tian, Y. (2020). A time-based pricing game in a competitive vehicle market regarding the intervention of carbon emission reduction. *Energy Policy*, *142*(6), 111440. https://doi.org/10.1016/j.enpol.2020.111440

Ma, J., & Sun, L. (2018). Complexity analysis about nonlinear mixed oligopolies game based on production cooperation. *IEEE Transactions on Control Systems Technology*, *26*(4), 1532–1539. https://doi.org/10.1109/TCST.2017.2702120

Ma, J., & Xu, T. (2022). Optimal strategy of investing in solar energy for meeting the renewable portfolio standard requirement in America. *Journal of the Operational Research Society*, 1–14. https://doi.org/10.1080/01605682.2022.2032427

Matzembacher, D. E., Carmo Stangherlin, I., Slongo, L. A., & Cataldi, R. (2018). An integration of traceability elements and their impact in consumer's trust. *Food Control*, *92*, 420–429. https://doi.org/10.1016/j.foodcont.2018.05.014

Mu, L., Dawande, M., Geng, X., & Mookerjee, V. (2016). Milking the quality test: Improving the milk supply chain under competing collection intermediaries. *Management Science*, *62*(5), 1259–1277. https://doi.org/10.1287/mnsc.2015.2171

Niu, B., Jin, D., & Pu, X. (2016). Coordination of channel members' efforts and utilities in contract farming operations. *European Journal of Operational Research*, *255*(3), 869–883. https://doi.org/10.1016/j.ejor.2016.05.064

Piramuthu, S., Farahani, P., & Grunow, M. (2013). RFID-generated traceability for contaminated product recall in perishable food supply networks. *European Journal of Operational Research*, *225*(2), 253–262. https://doi.org/10.1016/j.ejor.2012.09.024

Salah, K., Nizamuddin, N., Jayaraman, R., & Omar, M. (2019). Blockchain-based soybean traceability in agricultural supply chain. *IEEE Access*, *7*, 73295–73305. https://doi.org/10.1109/ACCESS.2019.2918000

Sun, S., & Wang, X. (2019). Promoting traceability for food supply chain with certification. *Journal of Cleaner Production*, *217*, 658–665. https://doi.org/10.1016/j.jclepro.2019.01.296

Tang, S. Y., Gurnani, H., & Gupta, D. (2014). Managing disruptions in decentralized supply chains with endogenous supply process reliability. *Production and Operations Management*, *23*(7), 1198–1211. https://doi.org/10.1111/poms.12160

Thirumalai, S., & Sinha, K. K. (2011). Product recalls in the medical device industry: An empirical exploration of the sources and financial consequences. *Management Science*, *57*(2), 376–392. https://doi.org/10.1287/mnsc.1100.1267

Wang, H. H., Wang, Y., & Delgado, M. S. (2014). The transition to modern agriculture: Contract farming in developing economies. *American Journal of Agricultural Economics*, *96*(5), 1257–1271. https://doi.org/10.1093/ajae/aau036

Wang, Z., Zheng, Z. E., Jiang, W., & Tang, S. (2021). Blockchain-enabled data sharing in supply chains: Model, operationalization, and tutorial. *Production and Operations Management*, *30*(7), 1965–1985. https://doi.org/10.1111/poms.13356

Xie, L., Ma, J., & Goh, M. (2020). Supply chain coordination in the presence of uncertain yield and demand. *International Journal of Production Research*, *20*, 1–17.

Xie, Y., Tai, A. H., Ching, W. K., & Siu, T. K. (2016). Pricing strategy for a two-echelon supply chain with optimized return effort level. *International Journal of Production Economics*, *182*, 185–195. https://doi.org/10.1016/j.ijpe.2016.08.026

Xu, Y., Li, X., Zeng, X., Cao, J., & Jiang, W. (2022). Application of blockchain technology in food safety control：Current trends and future prospects. *Critical Reviews in Food Science and Nutrition*, *62*(10), 2800–2819. https://doi.org/10.1080/10408398.2020.1858752

Yao, S., & Zhu, K. (2020). Combating Product Label Misconduct: The Role of Traceability and Market Inspection. *European Journal of Operational Research*, *282*(2), 559–568.

Zhang, M., Hu, H., & Zhao, X. (2020). Developing product recall capability through supply chain quality management. *International Journal of Production Economics*, *229*, 107795. https://doi.org/10.1016/j.ijpe.2020.107795

Zhao, X., Wang, P., & Pal, R. (2021). The effects of agro-food supply chain integration on product quality and financial performance: Evidence from Chinese agro-food processing business. *International Journal of Production Economics*, *231*, 107832. https://doi.org/10.1016/j.ijpe.2020.107832

Zhu, K., Zhang, R. Q., & Tsung, F. (2007). Pushing quality improvement along supply chains. *Management Science*, *53*(3), 421–436. https://doi.org/10.1287/mnsc.1060.0634

Ziggers, G. W., & Trienekens, J. (1999). Quality assurance in food and agribusiness supply chains: Developing successful partnerships. *International Journal of Production Economics*, *60-61*, 271–279. https://doi.org/10.1016/S0925-5273(98)00138-8

**How to cite this article:** Ma, J., Chen, J., & Liu, Y. (2022). Research on optimization of food supply chain considering product traceability recall and safety investment. *Managerial and Decision Economics*, *43*(8), 3953–3972. https://doi.org/10.1002/mde.3639

## APPENDIX A

**Corollary 1.1:**

I. $\frac{\partial e^*}{\partial\theta}=\frac{hq^3\alpha^2(1-\theta)\left(2kqC^2\eta^2-q^4C^2\alpha^3(1-\theta)^3+kh\eta^2(\alpha-2C-3\alpha\theta)\right)}{\left(kh\eta^2-q^4C^2\alpha^2(1-\theta)^2\right)^2}$,

$$\frac{\partial^2 e^*}{\partial\theta^2}=3q^4C^2\alpha^3(1-\theta)^2-3kh\eta^2\alpha<0.$$

So there is an optimal solution to $e^*$. Letting $2kqC^2\eta^2-q^4C^2\alpha^3(1-\theta)^3+kh\eta^2(\alpha-2C-3\alpha\theta)=0$, it obtained $\theta^A=1-\frac{\eta\sqrt{kh}}{q^2C\alpha}$.

Next, we use the same method to solve $s^*$ and $t^*$.

II. $\frac{\partial s^*}{\partial\theta}=\frac{q^2\alpha^2\eta\left(hqC^2\left(h\eta^2-q^3\alpha^2(C+\alpha)(1-\theta)^2\right)+q^5C^4\alpha^2(1-\theta)^2+kh^2\eta^2(\alpha-C-2\alpha\theta)\right)}{\left(kh\eta^2-q^4C^2\alpha^2(1-\theta)^2\right)^2}$,

$$\frac{\partial^2 s^*}{\partial\theta^2}=2\alpha\left(hq^4C^2\alpha(C+\alpha)(1-\theta)-kh^2\eta^2-q^5C^4\alpha(1-\theta)\right)<0.$$

So there is an optimal solution to $s^*$.

Letting $\frac{\partial s^*}{\partial\theta}=0$, there is $\theta^B=1+\frac{kh^2\eta^2}{q^4C^2\alpha\left(qC^2-h(C+\alpha)\right)}$.

III. $\frac{\partial t^*}{\partial\theta}=\frac{q^4\alpha^2C(1-\theta)\left(q^4C^2\alpha^3(1-\theta)^3-2kqC^2\eta^2-kh\eta^2(\alpha-2C-3\alpha\theta)\right)}{\left(kh\eta^2-q^4C^2\alpha^2(1-\theta)^2\right)^2}$,

$$\frac{\partial^2 t^*}{\partial\theta^2}=3hk\alpha\eta^2-3q^4wC^2\alpha^3(-1+\theta)^2<0.$$

Letting $\frac{\partial t^*}{\partial\theta}=0$, there $\theta^C=1-\frac{\sqrt{h}\sqrt{k\eta}}{q^2C\alpha}$ ($\theta=1+\frac{\sqrt{h}\sqrt{k\eta}}{q^2C\alpha}$ does not meet the conditions, discard).

**Corollary 2.1:**

$$\frac{\partial\pi_m}{\partial\theta}=\frac{q^4\alpha^2(-1+\theta)\left(kqw^2\eta^2+q^4w^2\alpha^3(-1+\theta)^3+hk\eta^2(-w+\alpha-2\alpha\theta)\right)(qw^2-h(w+\alpha\theta))}{\left(kh\eta^2-q^4C^2\alpha^2(1-\theta)^2\right)^2}.$$

It follows from the preceding inference that $\frac{\partial^2\pi_m}{\partial\theta^2}<0$. Let

$$(-1+\theta)\left(kqw^2\eta^2+q^4w^2\alpha^3(-1+\theta)^3+hk\eta^2(-w+\alpha-2\alpha\theta)\right)(qw^2-h(w+\alpha\theta))=0.$$

We get $\theta_m^h=1-\left(i\left(-i+\sqrt{3}\right)\left(9kq^8w^4\alpha^6\left(-qw^2+h(w+\alpha)\right)\eta^2+\sqrt{3}\sqrt{k^2q^{12}w^6\alpha^{12}\eta^4\left(27q^4\left(qw^3-hw(w+\alpha)\right)^2-32h^3k\eta^2\right)}\right)^{1/3}\right)/\left(22^{1/3}3^{2/3}q^4w^2\alpha^3\right)+(hk\alpha)/\left(9kq^8w^4\alpha^6\left(-qw^2+h(w+\alpha)\right)\eta^2+\sqrt{3}\sqrt{k^2q^{12}w^6\alpha^{12}\eta^4\left(27q^4\left(qw^3-hw(w+\alpha)\right)^2-32h^3k\eta^2\right)}\right)^{1/3}$. And we also get $\frac{\partial^2\pi_{ms}}{\partial\theta^2}<0$. Let $\frac{\partial\pi_s}{\partial\theta}=0$. So $\theta_s^h=1-\frac{\left(i\left(-i+\sqrt{2}\right)\left(3kq^8C^4\alpha^6\left(-qw^2+h(C+\alpha)\right)\eta^2+\sqrt{3}\sqrt{k^2q^{12}C^6\alpha^{12}\eta^4\left(9q^4\left(qC^3-hC(C+\alpha)\right)^2-32h^3k\eta^2\right)}\right)^{1/3}\right)}{22^{1/3}3^{2/3}q^4C^2\alpha^3}+\frac{hk\alpha\eta^2}{\left(9kq^8w^4\alpha^6\left(-qC^2+h(C+\alpha)\right)\eta^2+\sqrt{3}\sqrt{k^2q^{12}C^6\alpha^{12}\eta^4\left(27q^4\left(qC^3-hC(C+\alpha)\right)^2-32h^3k\eta^2\right)}\right)^{1/3}}$.

**Corollary 3.1:**

$$\frac{\partial e}{\partial C}=\frac{hq^3\alpha^2(-1+\theta)^2\left(hk\eta^2-2kqC\eta^2+q^4C\alpha^2(-1+\theta)^2(C+2\alpha\theta)\right)}{\left(hk\eta^2-q^4C^2\alpha^2(-1+\theta)^2\right)^2},\ \frac{\partial^2 e}{\partial C^2}<0.$$

So there is an optimal solution. Let

$$hq^3\alpha^2(-1+\theta)^2\left(hk\eta^2-2kqC\eta^2+q^4w\alpha^2(-1+\theta)^2(C+2\alpha\theta)\right)=0,$$

$$\underline{C}_e=\frac{1}{q^4\alpha^2(-1+\theta)^2}\left(kq\eta^2-q^4\alpha^3(-1+\theta)^2\theta+\sqrt{-hkq^4\alpha^2\eta^2(-1+\theta)^2+\left(kq\eta^2-q^4\alpha^3(-1+\theta)^2\theta\right)^2}\right),$$

$\overline{C}_e=\frac{h+\sqrt{h}\sqrt{h+4q\alpha\theta}}{2q}$ ($e=0$ at this very moment).

So $C\in(0,\underline{C}_e)$, there $\frac{\partial e}{\partial C}>0$. And $C\in(\underline{C}_e,\overline{C}_e)$, $\frac{\partial e}{\partial C}<0$.

$$\frac{\partial s}{\partial C}=\frac{hq^2\alpha\eta(1-\theta)\left(hk\eta^2-2kqw\eta^2+q^4w\alpha^2(-1+\theta)^2(w+2\alpha\theta)\right)}{\left(hk\eta^2-q^4w^2\alpha^2(-1+\theta)^2\right)^2},\ \frac{\partial^2 s}{\partial C^2}<0.$$

So there is an optimal solution. Let

$$hq^2\alpha\eta(1-\theta)\left(hk\eta^2-2kqC\eta^2+q^4C\alpha^2(-1+\theta)^2(C+2\alpha\theta)\right)=0,$$

$$\underline{C}_s=\underline{C}_e=\frac{1}{q^4\alpha^2(-1+\theta)^2}\left(kq\eta^2-q^4\alpha^3(-1+\theta)^2\theta+\sqrt{-hkq^4\alpha^2\eta^2(-1+\theta)^2+\left(kq\eta^2-q^4\alpha^3(-1+\theta)^2\theta\right)^2}\right).$$

So $C\in(0,\underline{C}_s)$, and $\frac{\partial s}{\partial C}>0$. Or $C\in(\underline{C}_s,1)$, we get $\frac{\partial s}{\partial C}<0$.

$\frac{\partial t}{\partial C}=\frac{q^5w^2\alpha^2(-1+\theta)^2\left(k\eta^2-q^3\alpha^3(-1+\theta)^2\theta\right)+hkq\eta^2\left(k\eta^2-q^3\alpha^2(-1+\theta)^2(2w+\alpha\theta)\right)}{\left(hk\eta^2-q^4w^2\alpha^2(-1+\theta)^2\right)^2}$, $\frac{\partial^2 t}{\partial C^2}<0$. Let

$$\begin{aligned}&q^5C^2\alpha^2(-1+\theta)^2\left(k\eta^2-q^3\alpha^3(-1+\theta)^2\theta\right)\\&+hkq\eta^2\left(k\eta^2-q^3\alpha^2(-1+\theta)^2(2C+\alpha\theta)\right)\\&=0.\end{aligned}$$

We get

$$\underline{C}_t = \frac{\sqrt{hkq^4\alpha^2\eta^2(-1+\theta)^2\left(hkq^2\alpha^2\eta^2(-1+\theta)^2 - \left(k\eta^2 - q^3\alpha^3(-1+\theta)^2\theta\right)^2\right)} - -hkq^3\alpha^2\eta^2(-1+\theta)^2}{q^4\alpha^2(-1+\theta)^2\left(-k\eta^2 + q^3\alpha^3(-1+\theta)^2\theta\right)}.$$

$\overline{C}_t$ does not meet the conditions, discard.

Then, $C \in (0, \underline{C}_t)$, there $\frac{\partial t}{\partial C} > 0$, and $C \in (\underline{C}_t, 1)$, $\frac{\partial t}{\partial C} < 0$.

**Corollary 3.2:**

I. $\frac{\partial \pi_m}{\partial C} = \frac{hq\left(-k\eta^2 + q^3\alpha^2(-1+\theta)^2(C+\alpha\theta)\right)\left(hk\eta^2 + qC\left(-k\eta^2 + q^3\alpha^3(-1+\theta)^2\theta\right)\right)}{\left(hk\eta^2 - q^4C^2\alpha^2(-1+\theta)^2\right)^2}$, $\frac{\partial^2 \pi_m}{\partial C^2} < 0$.

Let

$$hq\left(-k\eta^2 + q^3\alpha^2(-1+\theta)^2(C+\alpha\theta)\right)\left(hk\eta^2 + qC\left(-k\eta^2 + q^3\alpha^3(-1+\theta)^2\theta\right)\right) = 0.$$

Obtained $\underline{C}_m = \frac{hk\eta^2}{kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta}$, $\overline{C}_m = \frac{k\eta^2}{q^3\alpha^2(-1+\theta)^2} - \alpha\theta$.

So $C \in (0, \underline{C}_m)$, there $\frac{\partial \pi_m}{\partial C} < 0$. And $C \in \left(\underline{C}_m, \overline{C}_m\right)$, then $\frac{\partial \pi_m}{\partial C} > 0$.

II. $\frac{\partial \pi_s}{\partial C} = -\frac{hq^4\alpha^3(-1+\theta)^3\left(hk\eta^2 - 2kqC\eta^2 + q^4C\alpha^2(-1+\theta)^2(C+2\alpha\theta)\right)}{2\left(hk\eta^2 - q^4C^2\alpha^2(-1+\theta)^2\right)^2}$, $\frac{\partial^2 \pi_s}{\partial C^2} < 0$.

Let

$hq^4\alpha^3(-1+\theta)^3\left(hk\eta^2 - 2kqC\eta^2 + q^4C\alpha^2(-1+\theta)^2(C+2\alpha\theta)\right) = 0$. There

$$\underline{C}_s = \frac{kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta - \sqrt{-hkq^4\alpha^2\eta^2(-1+\theta)^2 + \left(kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta\right)^2}}{q^4\alpha^2(-1+\theta)^2},$$

$$\overline{C}_s = \frac{kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta + \sqrt{-hkq^4\alpha^2\eta^2(-1+\theta)^2 + \left(kq\eta^2 - q^4\alpha^3(-1+\theta)^2\theta\right)^2}}{q^4\alpha^2(-1+\theta)^2}.$$

So $C \in (0, \underline{C}_s)$, there $\frac{\partial \pi_m}{\partial C} < 0$. And $C \in \left(\underline{C}_s, \overline{C}_s\right)$, there $\frac{\partial \pi_m}{\partial C} > 0$.

**Corollary 4:**

$$\frac{\partial e}{\partial k} = -\frac{hq^3\alpha^2\eta^2(-1+\theta)^2(w(h-qw)+h\alpha\theta)}{\left(hk\eta^2 - q^4w^2\alpha^2(-1+\theta)^2\right)^2} = -\frac{hq^3\alpha^2\eta^2(-1+\theta)^2\left(h(w+\alpha\theta)-qw^2\right)}{\left(hk\eta^2 - q^4w^2\alpha^2(-1+\theta)^2\right)^2} < 0.$$

According to the results of the previous calculation, $\frac{\partial e}{\partial k} < 0$. That is, as $k$ increases, $e$ is always decreasing, and

$$\frac{\partial s}{\partial k} = \frac{hq^2\alpha\eta^3(-1+\theta)(w(h-qw)+h\alpha\theta)}{\left(hk\eta^2 - q^4w^2\alpha^2(-1+\theta)^2\right)^2} < 0.$$

$$\frac{\partial t}{\partial k} = \frac{q^4w\alpha^2\eta^2(-1+\theta)^2(w(h-qw)+h\alpha\theta)}{\left(hk\eta^2 - q^4w^2\alpha^2(-1+\theta)^2\right)^2} > 0.$$

$$\frac{\partial \pi_m}{\partial k} = -\frac{2q^4\alpha^2\eta^2(-1+\theta)^2\left(qw^2 - h(w+\alpha\theta)\right)^2}{\left(2hk\eta^2 - 2q^4w^2\alpha^2(-1+\theta)^2\right)^2} < 0.$$

$$\frac{\partial \pi_s}{\partial k} = \frac{hq^4\alpha^3\eta^2(-1+\theta)^3(w(h-qw)+h\alpha\theta)}{2\left(hk\eta^2 - q^4w^2\alpha^2(-1+\theta)^2\right)^2} = \frac{hq^4\alpha^3\eta^2(-1+\theta)^3\left(h(w+\alpha\theta)-qw^2\right)}{2\left(hk\eta^2 - q^4w^2\alpha^2(-1+\theta)^2\right)^2} < 0.$$

Hessian matrix in Section 6

$$H = \begin{pmatrix} \frac{\partial^2 \pi_m}{\partial s^2} & \frac{\partial^2 \pi_m}{\partial s \partial t} \\ \frac{\partial^2 \pi_m}{\partial t \partial s} & \frac{\partial^2 \pi_m}{\partial t^2} \end{pmatrix} = \begin{pmatrix} -k & \frac{\alpha(1-\theta)(1-r)C}{\eta} \\ \frac{\alpha(1-\theta)(1-r)C}{\eta} & -h \end{pmatrix} \#$$