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Research article

Research on safety risk control of prepared foods from the perspective of supply chain

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ABSTRACT

Prepared foods bring great convenience to people's lives, but they also entail safety risks in all aspects, from production to sales. The cooperation of the supply chain and the supervision of the government are key to promoting the safety management of prepared foods. This paper considers the government's regulation, focuses on the interaction relationship between the producer and the retailer of prepared foods, and builds an evolutionary game model to analyze the influence of collaborative decision-making between prepared food producers and retailers in preventing and controlling food safety risks under the government's regulatory strategy. The research finds that: (1) Under certain conditions, there are three stable equilibrium strategies within the prepared foods supply chain: bilateral low-safety inputs, unilateral high-safety inputs, and bilateral high-safety inputs. (2) Government regulators can influence the safety input behaviors of prepared food supply chain enterprises by adjusting investigation probabilities and punishment severity. (3) The safety input behaviors of these enterprises are influenced by various factors, including costs, revenues, brand image, reputation, and the consequences associated with contractual violations. This paper represents the first systematic analysis of prepared food safety from a supply chain perspective. It fills a gap in the existing literature in this area, offering guidance and suggestions for prepared food supply chain enterprises, as well as references and recommendations for government regulators.

1. Introduction

Food safety entails ensuring that all individuals have sufficient, safe, and nutritious food to meet their livelihood and activity needs. Food safety is closely correlated with human health, survival, and development [1,2] and constitutes a crucial aspect of the United Nations Sustainable Development Goals (SDGs) [3]. In recent years, a series of food safety incidents resulting from food contamination, foodborne pathogens, and food adulteration have inflicted significant harm upon consumers and society [1,4]. Addressing food safety issues is now a shared concern among all nations, which has led to the formulation of laws, regulations, and policy measures aimed at safeguarding food quality, preventing and controlling food risks, and enhancing the level of food regulation [5–7]. Nevertheless, in practice, various difficulties and challenges persist, including the lack of uniformity in food safety standards, an inadequate regulatory system, imperfect testing technology, low consumer awareness, and more [8,9]. These factors necessitate more extensive and in-depth

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research, as well as the optimization of regulatory policies.

With the rapid advancement of smart technology, the Internet of Things, and other related technologies [10], the pace of life in society continues to accelerate. As a response to the demand for convenience, efficiency, and specific consumer groups, the consumption of prepared foods has gained popularity and quickly developed worldwide. The pursuit of food and the diversification of food culture has always been integral to Chinese cultural traditions. In recent years, prepared foods have emerged as a new food model in China, particularly among young consumers. The outbreak of the pandemic in 2020 further accelerated the consumption of prepared foods for home consumption (Fig. 1). Prepared foods refer to dishes processed into semi-finished or finished products by professional vendors or merchants, conforming to specific processes and standards, which can be easily heated or consumed directly at home or on the go [8].

However, this emerging prepared food carries significant safety risks [7,8], and ensuring safety supervision in both the production and retail links (Table 1) is crucial. These links present numerous potential safety hazards, including the use of non-compliant raw materials, excessive additives, and poor hygiene conditions in the production phase. In the retail phase, issues such as cold chain interruptions, deterioration, and secondary pollution may arise. From the perspective of industry self-discipline, this requires the production and retail enterprises in the prepared food industry chain to have a high level of safety investment, but due to the uneven profit margin of prepared food and the high cost of safety investment, some small and medium-sized production and retail enterprises may lack sufficient motivation and ability to ensure the food safety of prepared food. At this time, government supervision is needed, but the current policies are not perfect, and the standardization, normalization, and regulation of prepared food are insufficient, resulting in inconsistent quality of such products in the market and challenges in protecting the rights and interests of consumers [8]. Consequently, effectively managing the food safety of prepared foods becomes a vital issue that requires resolution.

Numerous studies have consistently demonstrated that food safety risks predominantly occur within the food supply and processing chain [11,12]. Therefore, it is imperative to examine the issue of food safety from the perspective of the food supply chain. Previous research has focused on exploring synergistic mechanisms within the supply chain to prevent food safety risks and the influence of government regulations [12,13]. For instance, Lupo et al. [14] proposed that food supply chain risks can be mitigated through the implementation of mandatory preventive measures and the enforcement of penalties or sanctions, with joint responsibility shared among food operators and regulatory authorities. Liu and Wei [15] developed a contextual evaluation model for managing risks within the food supply chain, highlighting the significance of institutional factors in effective risk management. Wang and Chen [16] devised a food safety risk diffusion model that traced the transmission of risks from food producers to consumers in the supply chain. They employed the sampling rate of food products as an indicator to investigate the influence of changes in sampling rates on the propagation of food safety risks. However, research regarding the safety analysis specific to the supply chain of prepared foods, particularly concerning the equitable distribution of benefits, incentives, and information sharing among the involved parties, remains scarce. Those studies lack an analysis of the primary distribution of safety risks associated with prepared foods within the supply chain, key decision-making by stakeholders, and government regulatory measures. So, understanding and effectively mitigating the risks associated with prepared foods is an area worthy of research and attention.

Evolutionary game theory, rooted in biological evolution, replaces mixed strategies in traditional game theory with the proportions of individuals who choose different pure strategies within a population [13,17,18]. This framework provides an effective tool for analyzing decision-making among stakeholders. The evolutionary game theory by considering the proportions of different strategies across the entire population better simulates the decision-making behaviors of various stakeholders in the real world, especially suitable for analyzing the multiple stakeholder conflicts and collaborations within the supply chain [19]. In 2023, a significant public outcry in China regarding an incident related to prepared food safety piqued our research interest. Therefore, we conducted an

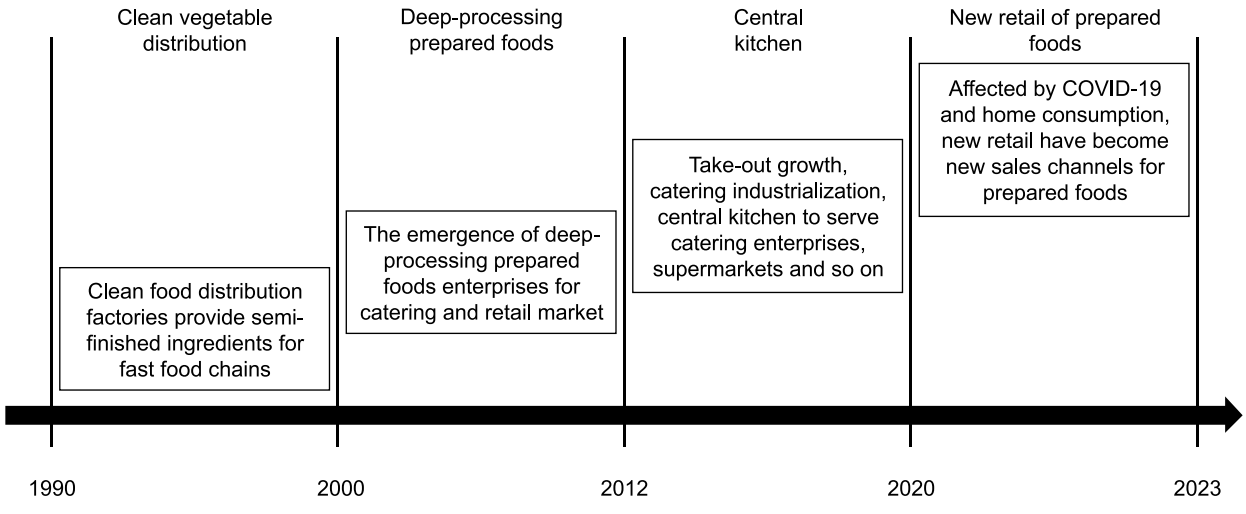

Fig. 1. Development of the prepared foods industry in China.

Table 1
Risk comparison of prepared foods supply chain.

Links	Risk
Production link	Problems such as using non-compliant raw materials, excessive additives, poor hygiene conditions, etc., may lead to low quality, safety hazards, consumer complaints, and other consequences of prepared food
Retail link	Problems such as cold chain interruption, deterioration, secondary pollution, etc., may lead to loss of appearance, safety risks, consumer returns, and other consequences of prepared food

investigation into the prepared food supply chain in Zhaoqing City, Guangdong Province, China. We found that the management of prepared foods safety involves complex interactions and strategic relationships among producers, retailers, and regulators. Traditional static methods are inadequate for capturing the dynamic nature of prepared foods supply chains. In contrast, evolutionary game theory is more enlightening as it can capture the dynamic and interactive characteristics of the supply chain, providing a more comprehensive understanding of the competitive dynamics and complexities faced by the prepared foods industry.

The prepared foods industry is a rapidly growing emerging sector in China, yet it presents significant risks. However, there has been minimal research on this topic, therefore our study has great originality and significance. To address the limitations of previous research, this study aims to develop an evolutionary game model that incorporates prepared foods retailers, prepared foods producers, and government regulators as key players. The government regulators serve as coordinators among the stakeholders, while their regulatory behaviors, such as sampling, inspection, and penalties, are considered as crucial exogenous variables. The study investigates the influence of diverse government regulatory strategies on the optimal decision-making of prepared food producers and retailers concerning the prevention and control of food safety risk behaviors. Specifically, this paper seeks to answer the following key questions: What factors influence the safety investment behavior of prepared food retailers and producers? Furthermore, how do prepackaged food retailers and producers determine their food safety investment strategies under different government regulatory strategies?

This paper offers several valuable research contributions. Firstly, it systematically analyzes the issue of food safety in the context of prepared foods from a supply chain perspective, addressing an existing gap in the literature. Secondly, it employs a combination of dynamic evolutionary game analysis and case study analysis to examine the cooperative relationships and influencing factors among participants in the supply chain. For example, it investigates how retailers' safety assessment reviews of producers impact the safety input behavior of the producers. Lastly, this study enriches the methodology and content of food safety research by considering the interactions and feedback mechanisms within the supply chain. Overall, these contributions enhance our understanding of food safety and its management in the context of prepared food supply chains.

2. Literature review

This paper is closely related to food safety research from a supply chain perspective. On one hand, previous studies have focused on identifying and assessing food safety risks [20] and hazards along the supply chain [14]. For example, Lopez-Galvez et al. [12] examined potential tensions between microbiological safety and environmental sustainability in the supply chain of fresh produce, addressing issues throughout the food supply chain, from primary production to end-of-life, including handling, processing industry, retailers, and consumers. On the other hand, other studies have explored the design and implementation of food safety standards, traceability systems, and quality control mechanisms [21–23]. These studies have identified key factors and challenges impacting food safety in various supply chain contexts, such as information asymmetry [24], moral hazard [13], producer behavior [25], consumer behavior, and environmental impacts [12]. Additionally, they have highlighted the importance of traceability in addressing food safety issues [26]. Existing research has emphasized the need to optimize institutional design and stakeholder-based responses to address food safety challenges [27,28]. For instance, Gao et al. [13] have focused on stakeholder-based responses. In this paper, a three-party evolutionary game model involving raw material suppliers, producers, and sellers is established and validated through Matlab numerical simulation. The results demonstrate that when there is no risk within the food supply chain, the co-governance of the market, government, and society (consumers) is highly effective, and the risk level is solely dependent on the level of social co-governance. These studies provide a solid foundation for understanding the mechanisms influencing safety issues in the food supply chain and devising preventive and control strategies.

Food safety regulation encompasses various aspects, including monitoring, inspection, and enforcement, and involves topics such as the design and evaluation of food safety standards and policies [11,23,29]. It also analyzes the incentives and behaviors of actors within the food supply chain [13,25]. For instance, Liu et al. [30] conducted a systematic analysis of the current food regulatory system, discussing the co-regulation of food safety management in China. They argued that the current multi-agency structure of the food safety regulatory system leads to insufficient incentives for business actors due to information asymmetry, lack of regulatory resources, and consumer advocacy. Consequently, co-regulation has emerged as an important tool for food regulation and is increasingly promoted [31]. These studies highlight the need for government regulation to consider incentives, penalties, sampling measures, and the balance and coordination between food safety and other supply chain objectives [30–32]. However, there is currently a shortage of literature that examines prepared food safety regulation using an evolutionary game theory model. Further research is necessary to provide additional perspectives and methodologies for understanding the different government regulatory measures and their impact on the safety regulation of the prepared food industry. This will help in providing better insights for optimizing regulatory policies.

Overall, there is limited literature specifically addressing the safety supervision of the prepared food supply chain. There is a lack of systematic and dynamic analysis on this issue. Furthermore, these studies overlook the interactions and feedback mechanisms among supply chain participants, as well as the impact of incentives, penalties, sampling measures, and the balance and coordination between food safety and other supply chain objectives, along with the various conditions that could lead to multiple game scenarios. However, a significant body of research indicates that the supply chain plays a crucial role in food safety incidents and is a vital component in ensuring food safety. Therefore, a more diverse and comprehensive investigation into supply chain-centered food safety research is needed. This paper aims to fill this gap by constructing a game model for enterprises in the prepared food supply chain through dynamic evolutionary game analysis. It also examines the impact of government regulatory measures on enterprises' self-regulation behavior, thus providing valuable contributions to this field.

3. Model design

3.1. Description of the problem

Based on previous analyses, it has been determined that food safety risks primarily emerge within the food supply and processing chain [12]. Consequently, it is imperative to examine the safety of prepared foods from the standpoint of the food supply chain. Our research reveals that within the prepared food supply chain, higher levels of safety inputs correlate with reduced safety risks. These safety inputs encompass various measures such as procuring high-quality raw materials, enhancing hygiene standards throughout the processing equipment and environment, fortifying quality inspection and traceability mechanisms, improving cold-chain logistics and storage conditions, as well as bolstering consumer education and information disclosure. For producers operating within the prepared foods supply chain, safety inputs lead to improved product quality and reputation, increased market share and profits. However, they are also accompanied by escalated costs and risks.

On the other hand, retailers in the prepared foods supply chain benefit from safety inputs through improved customer satisfaction and loyalty, as well as reduced returns and claims. However, these inputs may also result in increased inventory and losses. The prevention and control of safety risks associated with prepared foods entail certain interest coordination and game dynamics between producers and retailers. For instance, producers might compromise safety standards to reduce costs, while retailers may extend the shelf life of products to boost sales. Therefore, effective prevention and control of safety risks related to prepared foods necessitate collaboration among prepared foods producers, retailers, and government regulation. This involves enacting relevant regulations, implementing rigorous inspections and penalties, as well as providing incentives and subsidies.

In this paper, we concentrate on the prevention and control of safety risks by involving prepared food producers and retailers. We introduce government regulation as an exogenous variable into this framework and construct an evolutionary game model to analyze it. The two key stakeholders form a complex system of evolutionary game (Fig. 2). In this game, the government regulates the prepared foods industry. However, the intensity of governmental regulation may vary across different regions. Consequently, producers and retailers within the prepared foods supply chain in various regions weigh their costs and benefits under specific levels of regulation to decide whether to make high-safety investments. The entry of prepared food products into the market results in varying outcomes; safe products are favored, while unsafe ones are not, leading to feedback for producers and retailers, further influencing their decisions. This dynamic process forms a game where decisions evolve over time.

3.2. Model assumptions

Based on the analysis of the aforementioned issues, we have developed a decision-making framework for stakeholders engaged in safety investments within the prepackaged food supply chain. These stakeholders primarily consist of producers, retailers, and

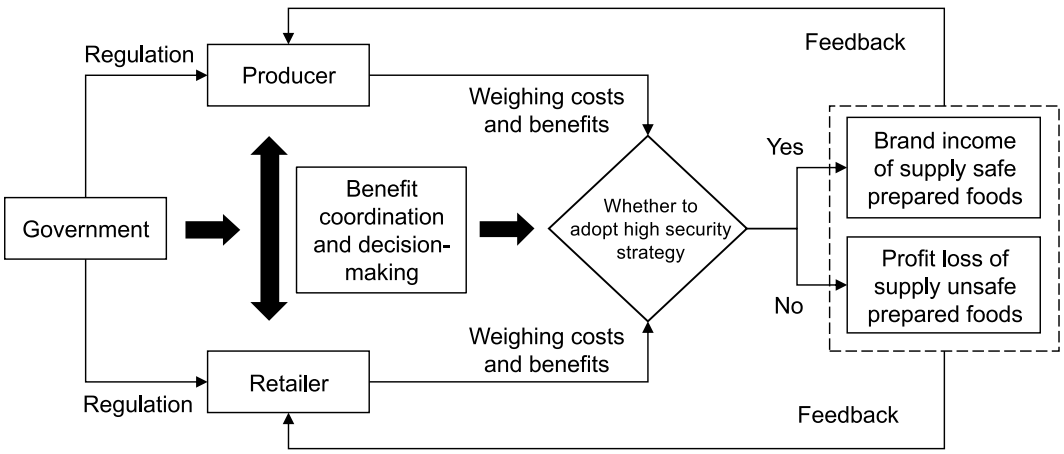

Fig. 2. Evolutionary gaming system for safety risk control of prepared foods under the supply chain perspective.

government regulators, who play a role as exogenous factors. Consequently, we have refined the behavioural parameters of game-theoretic agents and established the following assumptions (Table 2).

Assumption 1. There are two agents involved in the study, namely the producer and the retailer. The producer has the option to adopt either a high or low-safety input strategy, while the retailer can choose between a high or low-safety input strategy as well. Let x ($0 \leq x \leq 1$) represent the probability of the producer selecting high-safety inputs, and 1 - x denote the probability of the producer opting for low-safety inputs. Similarly, let y ($0 \leq y \leq 1$) signify the probability of the retailer choosing high safety inputs, and 1 - y indicate the probability of the retailer selecting low safety inputs.

Assumption 2. The government regulator is responsible for scrutinizing and sanctioning the actions of both producers and retailers. Let a ($0 \leq a \leq 1$) represent the probability of the government regulator investigating and penalizing a producer, and let b ($0 \leq b \leq 1$) denote the probability of it undertaking the same measures against a retailer. Moreover, it is assumed that when penalizing a producer, the government regulator imposes a fine of amount F_m, whereas, for retailers, the fine amount is denoted as F_r.

Assumption 3. Producers are commercial entities engaged in the processing of prepared foods. The safety inputs utilized by producers significantly influence the quality and safety of the resulting products. We assume that when opting for high-safety inputs, producers bear an additional cost denoted as C_m, while no additional cost is incurred when choosing low-safety inputs. Furthermore, we assume that there exists a probability α ($0 \leq \alpha \leq 1$) indicating the likelihood of producers producing inferior and harmful foodstuffs when high safety inputs are chosen, whereas this probability is always 1 when low safety inputs are chosen.

Assumption 4. A retailer refers to a commercial entity involved in the purchase of prepared foods from producers for subsequent sale to consumers. The retailer's income is derived from the revenue generated by the sale of prepared foods, which is then reduced by the costs of purchase, safety inputs, government penalties, and retailer default penalties. It is assumed that the price at which the retailer procures prepared foods from the producer remains unaffected by the strategies employed by both the producer and the retailer. Additionally, we assume that when opting for high-safety inputs, the producer incurs an additional cost denoted as C_r, while no additional cost is incurred when low-safety inputs are selected. Furthermore, assuming a high safety input, the retailer is presumed to conduct safety assessments and sample tests for identifying inferior and harmful prepared foods, with a probability denoted as β ($0 \leq \beta \leq 1$). Conversely, no assessments or sample tests are conducted when choosing low-safety inputs. Moreover, if the retailer's sample test reveals that the producer has supplied inferior and harmful prepared foods, a penalty denoted as P is imposed for breaching the contract.

Assumption 5. Let's assume that the long-term brand benefits brought to the supply chain when selling safe food are represented by D. The proportion of brand benefits shared by producers is denoted by γ. In the case of inferior and harmful food, the resulting loss in profits for the supply chain is denoted by S, which is distributed between the producers and retailers according to a certain ratio. We assume that the proportion of profit loss borne by the producers is represented by θ ($0 \leq \theta \leq 1$).

3.3. Payment matrix

Based on the above assumptions, the following payment matrix can be obtained (Table 3). In the prepared food supply chain safety management, under the influence of government regulation, some possible game scenarios between Producers and Retailers are: (1) low safety inputs for both producers and retailers, which may occur when the government regulation is weak or absent, and there is a lack of trust and cooperation between Producers and Retailers, and consumers have limited information and choices. (2) High safety inputs for producers and low safety inputs for retailers, which may occur when the government regulation is unbalanced or imperfect, and Producers choose high safety inputs to protect and enhance their brand value, but also bear higher costs and risks. Retailers choose low safety inputs to reduce costs and risks, and pursue short-term benefits. (3) Low safety inputs for producers and high safety inputs

Table 2
Parameters and their meanings.

Parameter	Meaning
x	Probability that a producer chooses a high-safety input
y	Probability of retailers choosing high-safety inputs
a	Probability of government regulators investigating and punishing producers
F_m	Amount of penalties imposed on producers by government regulators
b	Probability of retailers being investigated and punished by government regulators
F_r	Amount of penalties imposed on retailers by government regulators
C_m	Additional costs paid by producers when choosing high-safety inputs
C_r	Additional costs paid by retailers when they opt for high-safety inputs
α	Probability of supplying inferior and harmful food that may be produced when producers choose low-safety inputs
β	Probability that a retailer will conduct a safety assessment of prepared foods and sample poor quality and harmful prepared foods when choosing high-safety inputs
P	Penalties for non-compliance by a retailer when a sample test reveals that a producer has supplied inferior and harmful prepared foods
D	Long-term brand benefits to the supply chain when selling safe foods
γ	Producer's share of brand revenue
S	Loss of revenue to the supply chain when poor quality and harmful food products are present
θ	Producer's share of loss of earnings

Table 3
Payment matrix.

		Producers	
		High safety inputs (x)	Low safety inputs (1-x)
Retailers	High safety inputs (y)	$\gamma\ D - C_m\ (1-\gamma)\ D - C_r$	$-a\ \alpha\ F_m - \beta\ \alpha\ P - \theta\ \alpha\ S$ $-b\ \alpha\ (1-\beta)\ F_r - C_r + \beta\ \alpha\ P - (1-\theta)\ \alpha\ S$
	Low safety inputs (1-y)	$-C_m$ 0	$-a\ \alpha\ F_m - \theta\ \alpha\ S$ $-b\ \alpha\ F_r - (1-\theta)\ \alpha\ S$

for retailers, which may occur when the government regulation is unbalanced or imperfect, and Producers choose low safety inputs to pursue short-term benefits. Retailers choose high safety inputs to protect and enhance their brand value, but also bear higher costs and risks. (4) High safety inputs for both producers and retailers, which may occur when the government regulation is strong or perfect, and Producers and Retailers both choose high safety inputs to protect and enhance their brand value, increase their profits and benefits, and also meet the consumers' health and rights, and promote long-term sustainable development.

4. Model analysis

4.1. Analysis of replication dynamics

Considering a producer's selection of either a high-safety input strategy denoted as U_{11}, or a low-safety input strategy, denoted as U_{12}, and defining the average return as $\overline{U}_1$, we can derive Equation (1).

$$\begin{cases} U_{11} = -C_m(1-y) + y(-C_m + D\gamma) \\ U_{12} = y(-aF_m\alpha - P\alpha\beta - S\alpha\theta) + (1-y)(-aF_m\alpha - D\gamma - S\alpha\theta) \\ \overline{U}_1 = xU_{11} + (1-x)U_{12} \end{cases} \tag{1}$$

Based on the principles of the Malthusian dynamic equation, Equation (2) represents the replication dynamic equation for a producer who opts for a high-safety input strategy.

$$F(x) = \frac{dx}{dt} = x(U_{11} - \overline{U}_1) = (-1+x)x(C_m - aF_m\alpha - Py\alpha\beta - D\gamma - S\alpha\theta) \tag{2}$$

Considering the choices available to the retailer, whereby the expected return for selecting a high-safety input strategy is denoted as U_{21}, and the expected return for opting for a low-safety input strategy is denoted as U_{22}, we define the average return as $\overline{U}_2$. In light of this, Equation (3) can be derived.

$$\begin{cases} U_{21} = x(-2C_r + D(1-\gamma)) + (1-x)(-C_r - bF_r\alpha(1-\beta) + P\alpha\beta - S\alpha(1-\theta)) \\ U_{22} = (1-x)(-bF_r\alpha - D(1-\gamma) - S\alpha(1-\theta)) \\ \overline{U}_2 = yU_{21} + (1-y)U_{22} \end{cases} \tag{3}$$

Equally, Equation (4) represents the replication dynamics for a retailer who selects a high-safety input strategy.

$$F(y) = \frac{dy}{dt} = y(U_{21} - \overline{U}_2) = (-1+y)y(C_r(1+x) + (bF_r + P)(-1+x)\alpha\beta + D(-1+\gamma)) \tag{4}$$

4.2. Stable equilibrium analysis

By associating Equation (2) and Equation (4), we can establish a comprehensive two-dimensional dynamical system (I), which can be expressed as Equation (5).

$$\begin{cases} F(x) = (-1+x)x(C_m - aF_m\alpha - Py\alpha\beta - D\gamma - S\alpha\theta) \\ F(y) = (-1+y)y(C_r(1+x) + (bF_r + P)(-1+x)\alpha\beta + D(-1+\gamma)) \end{cases} \tag{5}$$

Table 4
Determinants and traces of evolutionary equilibrium points.

Equilibrium	detJ	trJ
(0,0)	$(-C_r + (b\ F_r + P)\ \alpha\ \beta - D\ (-1+\gamma))\ (-C_m + a\ F_m\ \alpha + D\ \gamma + S\ \alpha\ \theta)$	$-C_m - C_r + a\ F_m\ \alpha + (b\ F_r + P)\ \alpha\ \beta - D\ (-1+\gamma) + D\ \gamma + S\ \alpha\ \theta$
(0,1)	$(C_r - (b\ F_r + P)\ \alpha\ \beta + D\ (-1+\gamma))\ (-C_m + a\ F_m\ \alpha + P\ \alpha\ \beta + D\ \gamma + S\ \alpha\ \theta)$	$-C_m + C_r + a\ F_m\ \alpha + P\ \alpha\ \beta - (b\ F_r + P)\ \alpha\ \beta + D\ (-1+\gamma) + D\ \gamma + S\ \alpha\ \theta$
(1,0)	$(-2\ C_r - D\ (-1+\gamma))\ (C_m - a\ F_m\ \alpha - D\ \gamma - S\ \alpha\ \theta)$	$C_m - 2\ C_r - a\ F_m\ \alpha - D\ (-1+\gamma) - D\ \gamma - S\ \alpha\ \theta$
(1,1)	$(2\ C_r + D\ (-1+\gamma))\ (C_m - a\ F_m\ \alpha - P\ \alpha\ \beta - D\ \gamma - S\ \alpha\ \theta)$	$C_m + 2\ C_r - a\ F_m\ \alpha - P\ \alpha\ \beta + D\ (-1+\gamma) - D\ \gamma - S\ \alpha\ \theta$
(M, N)	$((2\ C_r + D\ (-1+\gamma))\ (C_r - (b\ F_r + P)\ \alpha\ \beta + D\ (-1+\gamma))\ (-C_m + a\ F_m\ \alpha + D\ \gamma + S\ \alpha\ \theta)\ (-C_m + a\ F_m\ \alpha + P\ \alpha\ \beta + D\ \gamma + S\ \alpha\ \theta))/(P\ \alpha\ \beta\ (C_r + (b\ F_r + P)\ \alpha\ \beta))$	0

Let $(F(x),F(y)) = (0,0)$, we can get E_1 (0,0), E_2 (0,1), E_3 (1,0), E_4 (1,1), E_5 $((-C_r + D + b\,F_r\,\alpha\,\beta + P\,\alpha\,\beta - D\,\gamma)/(C_r + b\,F_r\,\alpha\,\beta + P\,\alpha\,\beta)$, $(C_m - a\,F_m\,\alpha - D\,\gamma - S\,\alpha\,\theta)/(P\,\alpha\,\beta))$. The local stability of these equilibrium points can be determined through the analysis of the Jacobi matrix. An equilibrium point is considered stable when $detJ > 0$ and $trJ < 0$. Referring to previous works [33,34], the determinant and traces of the five equilibrium points are calculated (Table 4), allowing for further assessment of their asymptotic stability.

From Table 4, it can be observed that the equilibrium point (M, N), where $trJ = 0$, clearly does not meet the criteria for a stable equilibrium point. Therefore, the equilibrium point (M, N) is not further analyzed. Consequently, this study aims to meticulously analyze the conditions for the four stable equilibrium: E_1(0,0), E_2(0,1), E_3(1,0), and E_4(1,1).

Scenario 1: When $-C_m + a\,F_m\,\alpha + D\,\gamma + S\,\alpha\,\theta < 0$ and $-C_r + (b\,F_r + P)\,\alpha\,\beta - D\,(-1 + \gamma) < 0$, E_1 (0,0) represents a stable equilibrium strategy. This equilibrium strategy entails both producers and retailers adopting low levels of safety inputs. In this scenario, the costs associated with safety inputs for both producers and retailers outweigh their respective benefits. Additionally, the government's probability of investigation and penalties fails to effectively constrain the firms within the prepared foods supply chain. Consequently, neither party has any incentive to increase their level of safety input. This scenario pertains to the initial stage of safety prevention and control in the prepared foods supply chain. It is characterized by an immature market for prepared foods, a lack of safety awareness and a sense of responsibility among supply chain participants, and insufficient government supervision.

Scenario 2: When $-C_m + a\,F_m\,\alpha + P\,\alpha\,\beta + D\,\gamma + S\,\alpha\,\theta < 0$ and $C_r - (b\,F_r + P)\,\alpha\,\beta + D\,(-1 + \gamma) < 0$, E_2 (0,1) represents a stabilizing equilibrium strategy. This strategy is characterized by the producer adopting low levels of safety inputs while the retailer adopts high levels of safety inputs. Within this scenario, the cost of safety inputs for the producer outweighs the associated benefits. Furthermore, the government's probability of investigation and punishment fails to effectively constrain the producer, thereby reducing any incentive to increase their safety input level. Conversely, retailers are motivated to enhance their safety inputs given that their costs are lower than their revenues. Additionally, the government's probability of detection and imposition of penalties serves as a more effective constraint on producers.

Scenario 3: When $C_m - a\,F_m\,\alpha - D\,\gamma - S\,\alpha\,\theta < 0$ and $-2\,C_r - D\,(-1 + \gamma) < 0$, E_3 (1,0) represents a stable equilibrium strategy. The producers demonstrate a higher inclination towards implementing safety inputs, while the retailers exhibit a preference for lower safety inputs. This scenario arises due to the producer's safety input cost being outweighed by its corresponding benefits. Moreover, the government's probability of investigation and subsequent punishment effectively constraints the activities of firms in the prepared food supply chain, thereby motivating producers to enhance their safety measures. Conversely, retailers lack the incentive to increase their safety inputs as the associated costs surpass their revenues. Furthermore, the probability of government investigation and penalties fails to impose an adequate constraint on firms operating within the prepared foods supply chain.

Scenario 4: When $C_m - a\,F_m\,\alpha - P\,\alpha\,\beta - D\,\gamma - S\,\alpha\,\theta < 0$ and $2\,C_r + D\,(-1 + \gamma) < 0$, E_4 (1,1) represents a stable equilibrium strategy, characterized by both producers and retailers adopting high safety inputs. This scenario signifies an optimal state within the prepared foods supply chain, where the costs of safety inputs for producers and retailers are outweighed by the associated benefits. Furthermore, the government's probability of investigation and penalties effectively constraints firms operating within the supply chain, thereby incentivizing both parties to enhance their safety measures. This ideal scenario reflects a mature and standardized market for prepared foods, with supply chain participants demonstrating a strong sense of safety awareness and responsibility. It also highlights the effectiveness of government regulations in ensuring safety prevention and control within the supply chain.

5. Cases and simulations

5.1. Overview of cases

To ensure the model aligns closely with real-world dynamics and provides valuable insights for practical applications, we selected the prepared foods industry in Zhaoqing City, Guangdong Province, China as our illustrative example. This particular industry encompasses various stages ranging from raw material procurement to processing, production, distribution, and sales, offering a well-rounded representation. By focusing on this context, we can gain a better understanding of the synergistic relationships among stakeholders within the prepared foods industry's development.

To comprehensively assess the safety of prepared foods in Zhaoqing City, Guangdong Province, China, spanning from production to distribution, we adopted a two-fold research approach. Firstly, we collected an extensive array of secondary data, including market reports, news articles, and government policy documents. These sources allowed us to trace the historical trajectory of China's prepared foods industry. Additionally, we analyzed major stakeholder relationships embedded within this industry. Secondly, we conducted in-depth interviews with representatives from various companies and government departments. Through these interactions, we sought to gather opinions, feedback, and insights from prepared food producers, supply chain operators, and consumers. Such inquiries provided valuable information regarding their roles, motivations, and behaviors within the prepared foods industry. By synthesizing these diverse case studies, we obtained a comprehensive and systematic overview of the historical development of the prepared foods industry. Moreover, we were able to identify the driving forces behind stakeholders' behavior and the intricate interdependencies among them.

The Zhaoqing Gaoyao Prepared Foods Industrial Park holds the distinction of being China's first park dedicated to the prepared food industry and represents Guangdong Province's inaugural provincial-level modern agricultural industrial park. Focused on Cantonese cuisine, the park specializes in a diverse range of produce, including aquatic products, livestock, poultry, and vegetables. It integrates various stages of the production process, such as cultivation, processing, storage, logistics, and sales, thus establishing a comprehensive and interconnected prepared food industry chain. Recognizing the paramount importance of safety supervision within the prepared foods industry, the Zhaoqing government has implemented a series of policies and measures aimed at bolstering quality

control and risk prevention across the entire supply chain—from sourcing to distribution and consumption.

At the supply chain level, Zhaoqing is home to several prominent producers of prepared foods. These enterprises operate by national and local standards and norms, implementing rigorous quality testing procedures at every stage of production to ensure compliance and meet consumer demands. Zhaoqing's prepared foods primarily make their way to large and medium-sized supermarkets, convenience stores, catering establishments, and other end-point channels within the Pearl River Delta region and beyond. Retailers must adhere to relevant laws and regulations throughout the sales process, including proper storage and display of prepared foods, maintaining product freshness and flavor, and providing accurate product information and usage instructions to consumers. Due to the significant market risks associated with selling unsafe prepared foods, retailers are highly cautious in selecting producers to collaborate with, conducting product inspections, and establishing long-term partnerships that guarantee the safety of prepared foods.

However, some safety issues have been discovered. For example, the Market Supervision and Administration Bureau conducted random inspections on food products in the production, circulation, and catering sectors, and found some non-compliant situations. They revealed some problems of unsafe ready-to-eat dishes, such as the level of *E. coli* in frozen food products that did not meet the requirements of the "Frozen Fruit and Vegetable Products" standard. Therefore, the company faced penalties such as sealing, confiscation, and fines according to the law. Similarly, some companies also produced durian cakes that did not meet the national food safety standards for total bacterial count and acid value (calculated by fat). The government also ordered the companies to rectify and imposed penalties according to the law.

Government regulations have played a vital role in effectively penalizing unsafe practices within the prepared food supply chain. Our interviews with producers and retailers have revealed their recognition of the significance of government inspections and subsequent penalties. Consequently, they have increased their focus on safety measures to prevent any potential safety issues. These stakeholders emphasize the importance of collaborative efforts among supply chain firms in promoting food safety. Retailers' consideration of the qualifications and reputation of producers significantly influences producers' decisions regarding safety. Simultaneously, the long-standing reputation of their products serves as a motivation for producers to embrace safe production practices.

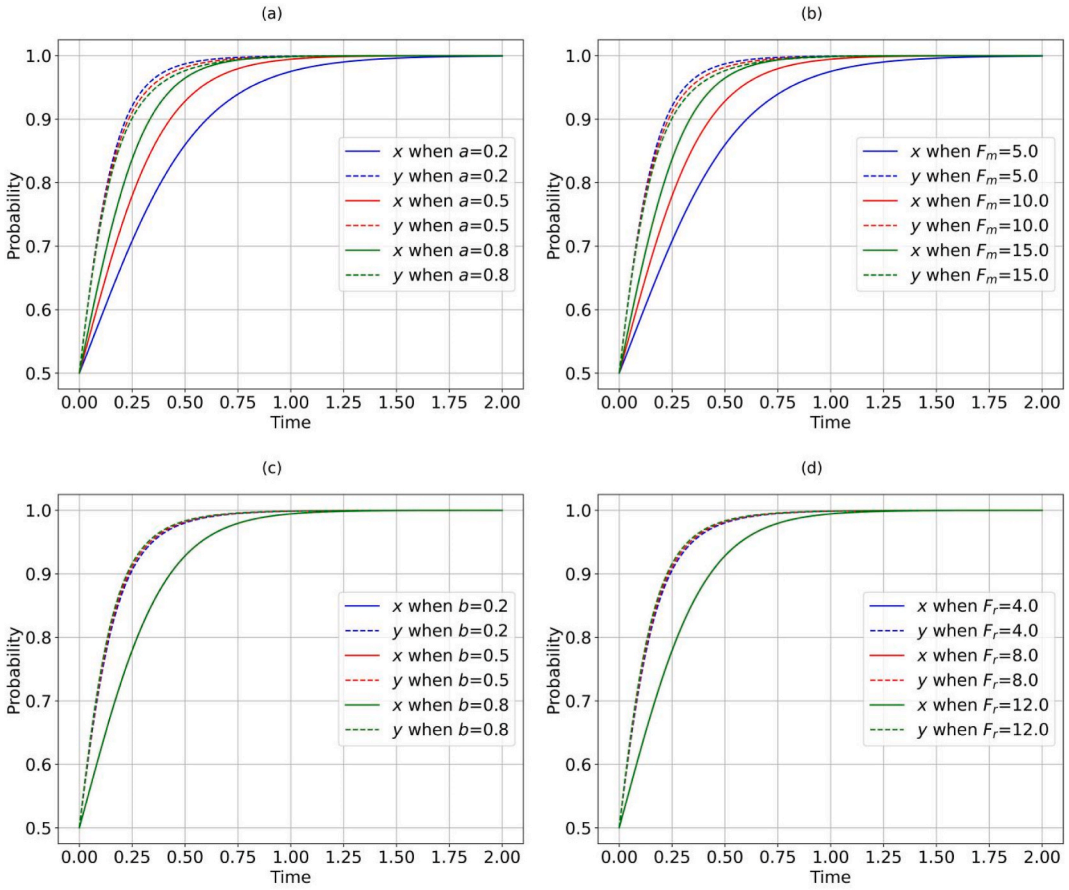

Fig. 3. Impact of government regulation.

5.2. Simulation analysis

To further evaluate the effectiveness of evolutionary game analysis and gain valuable management insights, this study employs Python 3.8 for simulation purposes. The simulation primarily focuses on analyzing comprehensive management indicators. The design of simulation parameters relies on survey data. Numerical parameters are assigned values based on real-world situations, while qualitative parameters are determined through in-depth interviews, policy documents, and other qualitative data sources. Consequently, the following initial parameters were obtained: $a = 0.5$, $F_m = 10$, $b = 0.5$, $F_r = 8$, $C_m = 25$, $C_r = 10$, $\alpha = 0.6$, $\beta = 0.6$, $P = 2$, $D = 50$, $\gamma = 0.5$, $S = 5$, $\theta = 0.5$. Additionally, given that most enterprises in the prepared foods supply chain exhibit a willingness to invest in safety measures to ensure food safety, we assume a high level of safety among producers. Thus, we posit that the proportion of high safety inputs (x) for producers is 0.5, and the proportion of high safety inputs (y) for retailers is also 0.5.

5.2.1. Impact of government regulation

The probability of investigation and the amount of penalties imposed by government regulators on producers and retailers in the prepared foods supply chain have a significant impact on the incentives for their safety inputs, and there are different mechanisms and effects of the impact. As shown in Fig. 3a and b, the equilibrium probability of high safety inputs of both producers and retailers increases when the probability of investigation and the amount of penalty imposed on producers by the government increases, and the sensitivity of high safety inputs of producers is greater, suggesting that the government's regulation can effectively inhibit the safety violations of all parties in the supply chain of prepared foods, especially those of producers. As shown in Fig. 3c and d, when the probability of investigation and the amount of punishment by the government on retailers increase, the equilibrium probability of high safety inputs by retailers increases significantly, but there is no significant effect on the equilibrium probability of high safety inputs by producers, reflecting that the government's regulation of retailers can effectively promote retailers to improve their safety level, but there is no significant transmission effect on the safety level of producers.

According to research on industrial policies [35], during the early stages of industrial development, relevant laws and regulations are often not yet comprehensive, and industry self-regulation tends to be insufficient, leading to various challenges in industry development. The prepared foods industry in China is a case in point, as safety issues in the industry are generally prone to emerge. Government intervention to provide public goods and institutional foundations for industrial development is crucial. Therefore, implementing reasonable regulatory measures is essential for the government to ensure the safe development of the prepared foods industry. Our survey on the current prepared foods industry in China highlights the lack of government regulation as a factor contributing to market disorder, resulting in problems such as the absence of standards and insufficient industry self-discipline. Previous studies have also demonstrated that legal and regulatory factors play a significant role in driving food safety within sustainable food supply chain management [36]. Hence, government regulators should develop tailored and dynamic regulatory strategies based on the safety characteristics and behavioral motivations of all parties in the prepared foods supply chain to achieve optimal safety outcomes.

5.2.2. Impact of retailer safety concern

Retailers' safety concern, including safety assessment and sampling of prepared foods, as well as penalties for producers' non-compliance, have a substantial impact on the incentives for both producers and retailers to prioritize safety within the prepared foods supply chain. These factors give rise to various influence mechanisms and effects. As shown in Fig. 4a, when the probability of safety assessment and sampling of inferior and harmful prepared foods increases when retailers choose high-safety inputs, the equilibrium probability of high safety inputs for both producers and retailers increases, and the sensitivity of high safety inputs for producers is greater, suggesting that safety assessment and sampling by retailers can effectively monitor the safety behaviours of all parties in the prepared foods supply chain, especially the producers' safety behaviour. Similarly, as shown in Fig. 4b, when the penalty for

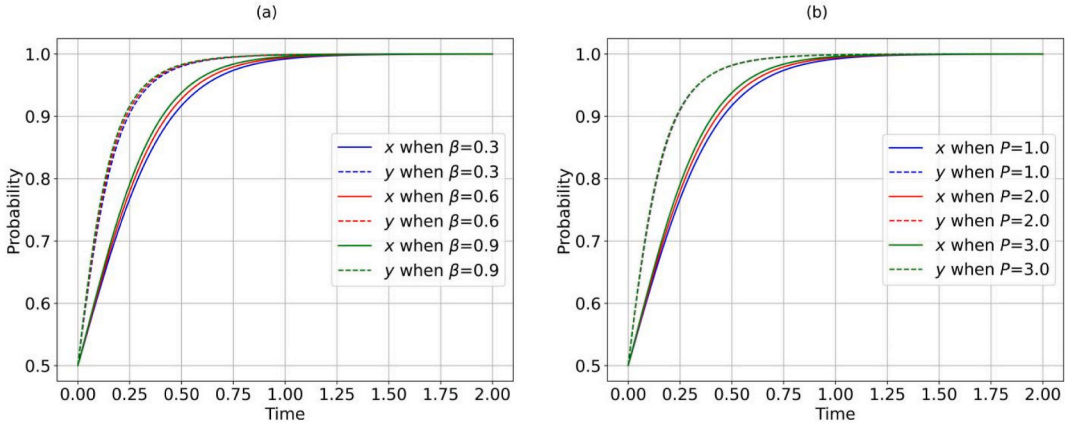

Fig. 4. Impact of retailer safety concern.

breach of contract is increased when the retailer's sampling inspection reveals that the producer provides inferior and harmful prepared foods, the equilibrium probability of the producer's high safety input increases significantly, but it does not have a significant effect on the equilibrium probability of the retailer's high safety input.

Comparatively, the safety assessment and sampling by retailers can be seen as a signaling mechanism that conveys information about the quality and safety of prepared foods to both producers and consumers. When retailers opt for high safety inputs, it indicates their elevated requirements and confidence in the quality and safety of prepared foods, thereby prompting producers to enhance their safety inputs to meet the retailer's demands and standards, while also increasing consumer trust and willingness to purchase. Therefore, the safety assessment and sampling by retailers can effectively influence the safety behavior of various parties in the prepared foods supply chain, particularly that of producers. The penalty for producer default can be viewed as an incentive mechanism that affects a producer's cost-benefit analysis and risk preference. When retailer sampling reveals that the prepared foods provided by a producer are of poor quality or harmful, the producer faces default penalties, leading to increased costs and risks, subsequently reducing the producer's profits and benefits. Consequently, the producer is motivated to enhance their safety inputs to avoid default penalties, or at least minimize the likelihood and severity of default. The safety assessment by retailers and penalties for producer default can effectively influence the safety behavior of producers. However, their impact on the safety behavior of retailers is relatively minor, as the safety inputs by retailers mainly depend on market demand and competitive pressure [37], aligning with the findings of the simulation analysis.

5.2.3. *Impact of coordination of supply chain interests*

As shown in Fig. 5a, the equilibrium probability of high safety inputs for producers significantly increases but the equilibrium probability of high safety inputs for retailers significantly decreases when the proportion of brand gains shared by producers increases, indicating that brand gains shared by producers can effectively incentivize producers to improve their safety levels, but at the same time, it can also reduce the incentives for retailers to improve their safety levels. Similarly, as shown in Fig. 5b, the equilibrium probability of high safety inputs for both producers and retailers increases when the long-term brand gains to the supply chain from selling safe food increase, suggesting that long-term brand gains to the supply chain are effective in motivating all parties in the prepared food supply chain to improve safety. As shown in Fig. 5c and d, the equilibrium probability of high safety inputs for producers increases significantly when the producer's loss of earnings and its share of losses increase, but the equilibrium probability of high

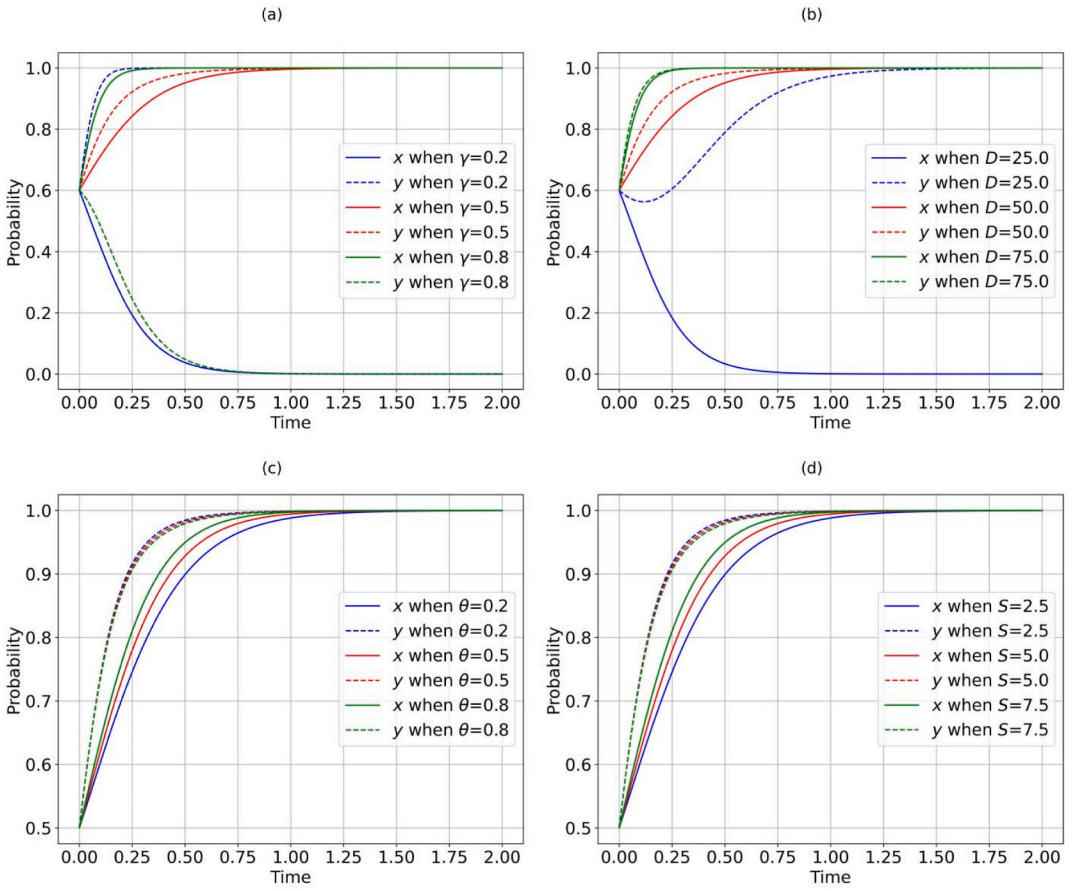

Fig. 5. Impact of coordination of supply chain interests.

safety inputs for retailers decreases significantly, reflecting that the producer's loss of earnings can effectively constrain the producer to reduce the level of safety, but at the same time it will also make the retailer rely on the producer to provide safer prepared foods and unnecessarily high safety inputs, thus reducing costs.

Many studies have focused on the effects of cost allocation and benefit-sharing mechanisms in promoting supply chain collaboration [38,39]. Similarly, for the safety of the prepared foods industry, this may also be crucial. Our research precisely demonstrates this point. It is evident that the producer's brand gain-sharing ratio and loss-sharing ratio, as well as the long-term brand gains and losses from the supply chain, significantly influence the incentivization of safety inputs for producers and retailers in the prepared foods supply chain, each operating through different influence mechanisms and effects. Certainly, our collected data also indicates that the impact of brand gains and losses in the prepared foods supply chain depends not only on their allocation proportions and long-term effects but also on their observability and measurability. If all parties in the supply chain can observe and measure the quality and safety of prepared foods, as well as the resulting brand gains and losses, then the incentivizing effect of brand gains and losses will be stronger; conversely, it will be weaker. Therefore, the prepared foods supply chain should strengthen monitoring and evaluation of quality and safety, establish mechanisms for the allocation and compensation of brand gains and losses, and enhance the observability and measurability of brand gains and losses to bolster their incentivizing effect.

6. Discussion

As the social division of labor advances, an increasing number of young individuals prioritize specializing in their respective fields rather than spending extensive time on food preparation. The convenience of prepared foods has proved to be highly beneficial for these busy individuals. However, it is undeniable that prepared foods carry greater safety risks compared to fresh vegetables, necessitating broader attention and system optimization. Drawing upon insightful literature [8,12,40], this study innovatively examines the safety risk control issues of prepared foods from a supply chain perspective. It constructs a game model in which prepared food suppliers and producers are the main entities, and government regulators act as coordinators among the stakeholders. Additionally, it explores the impacts of different regulatory strategies employed by the government on the optimal decision-making of prepared foods producers and suppliers, aiming to prevent and control risky behaviors related to food safety. Using this analytical framework, we analyze the current issues and synergistic mechanisms of safety risk prevention and control in the prepared foods industry under government supervision, focusing on the case of the prepared foods industrial park in Gaoyao District, Zhaoqing City, Guangdong Province, China. The results derived from the case analysis align with the findings of the model, validating its relevance to reality and offering valuable managerial insights.

The results of this study are in line with certain aspects of existing research. For example, government regulations can improve food safety by establishing accountability, using rewards and penalties, and promoting cooperation among supply chain participants [36, 41,42]. Additionally, achieving social co-regulation is found to be more beneficial for food safety regulation [13,30,30]. However, this study differs from previous research in several ways. Earlier studies overlooked the systematic and dynamic nature of the prepared foods supply chain, as well as the interaction and feedback mechanisms among participants within the supply chain. Furthermore, they neglected to consider the influence of changes in government regulations on the food safety behaviors of supply chain firms. In an innovative approach, this paper combines dynamic evolutionary game analysis with case study analysis to explore cooperative relationships and influential factors among supply chain participants. One such factor is the impact of safety assessment reviews conducted by retailers on the safety measures implemented by producers, an area that has received limited attention in prior studies. The findings not only support the hypotheses and research questions but also offer potential explanations. For instance, when government regulators increase the likelihood of investigations and penalties, they create incentives for prepared food supply chain firms to enhance their safety measures, thereby reducing food safety risks. Similarly, when these firms increase their safety inputs, product quality and reputation improve, leading to increased market share, profits, and overall social welfare.

The findings of this study offer valuable insights and implications for theory, practice, and policy in relevant fields. Theoretically, this paper introduces a novel analytical framework that contributes to the examination of food safety issues from a supply chain perspective, thereby enhancing the methodology and breadth of food safety research. From a practical standpoint, this paper offers guidance and recommendations to prepared food supply chain enterprises, enabling them to enhance their safety measures and bolster their competitiveness and social responsibility. From a policy perspective, this paper provides references and suggestions for government regulators, facilitating the development of more effective regulatory strategies aimed at maximizing social welfare.

Based on a comprehensive analysis of our research case and model, several management insights can be derived. Firstly, prepared food supply chain enterprises should proactively enhance their safety measures. This proactive approach not only helps mitigate food safety risks but also enhances product quality, reputation, and long-term branding advantages. Secondly, fostering cooperative relationships among supply chain participants and establishing effective mechanisms for revenue sharing and trust are essential for these enterprises. Close communication and coordination with raw material suppliers, logistics service providers, and consumers are crucial in jointly ensuring food safety. Furthermore, government regulators should strengthen their supervision of the prepared food supply chain while formulating reasonable regulatory strategies that maximize social welfare. Additionally, regulators should incentivize prepared food supply chain enterprises to enhance their safety measures by adjusting the probability of investigation and punishment. Nonetheless, it is important to strike a balance and avoid both excessive regulation and laissez-faire approaches. Moreover, regulators should enhance regulatory transparency and accountability to build public confidence in food safety. Certainly, as our analysis suggests, the observability and measurability of food safety risks are crucial. In the future, there will be a need to consider leveraging digital technologies to optimize regulations, such as using IoT, machine learning, and visualization techniques [43,44] to expedite the research and resolution of food safety decisions.

7. Conclusion

The objective of this study is to analyze the management of safety risks associated with prepared foods from a supply chain perspective. Specifically, we aim to construct an evolutionary game model involving prepared foods producers and retailers as key players, while also considering the role of government regulators as external interveners. The study investigates the influence of various regulatory strategies employed by the government on the decision-making processes of these producers and retailers in their efforts to prevent and control food safety risks. The primary findings of this study can be summarized as follows:

Firstly, the prepared foods supply chain exhibits four stable equilibrium strategies, namely: (1) low safety inputs for both producers and retailers; (2) high safety inputs for producers and low safety inputs for retailers; (3) low safety inputs for producers and high safety inputs for retailers; and (4) high safety inputs for both producers and retailers. Secondly, government regulators possess the ability to influence the safety input behavior of prepared foods supply chain enterprises by adjusting the likelihood of investigation and the severity of penalties. Thirdly, the safety input behaviors of these enterprises are influenced by various factors, including costs, revenues, brand image, reputation, and the consequences associated with contractual violations. Lastly, managerial insights and policy recommendations are proposed in this paper, emphasizing the importance of enhancing cooperation and information sharing among supply chain participants, as well as strengthening governmental regulatory accountability.

This paper also has certain limitations that may affect the generalizability and practical application of the findings. Firstly, the study assumes a two-participant model in the prepared foods supply chain, whereas, in reality, there are often multiple participants involved. Secondly, this study, being primarily qualitative in nature, may not provide precise numerical results for varying parameters. Thirdly, the paper assumes a single market environment, neglecting the possibility of multiple market environments. While these assumptions and simplifications were made to facilitate model construction and analysis, they may overlook important factors and effects. Therefore, it is recommended that future research addresses these limitations by relaxing or modifying these assumptions and simplifications to enhance the complexity and realism of the model.

To enhance our comprehension of this field, future research should consider the following aspects: Firstly, conducting thorough exploration by involving other participants in the supply chain, such as raw material suppliers, logistics service providers, and consumers. It is essential to analyze their influence on controlling safety risks associated with processed foods. Secondly, future studies should expand the use of questionnaire surveys to provide more precise numerical results for parameter sensitivity analysis, enriching the managerial implications of the research. Thirdly, achieving a more comprehensive analysis by introducing different market environments, including varying levels of competition, demand fluctuations, and technological innovations. Evaluating their impact on controlling safety risks related to processed foods is crucial. Lastly, gaining valuable insights into safety risk control related to processed foods by integrating nonlinear effects and random disturbances, such as network externalities, behavioral preferences, and uncertainty.

Data availability statement

All data in this article are included in the paper.

CRediT authorship contribution statement

Jing Gong: Writing – original draft, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Yong Sun:** Writing – original draft, Visualization, Software, Methodology, Investigation. **Hongyan Du:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition. **Xingling Jiang:** Visualization, Validation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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