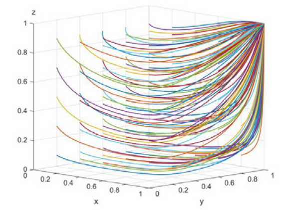
Tripartite evolutionary game of food safety regulation during storage and transportation



Juego evolutivo tripartito de la regulación de la seguridad alimentaria durante el almacenamiento y el transporte

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RESUMEN

- La inocuidad de los alimentos requiere la cooperación del gobierno, consignatarios de alimentos y transportistas de alimentos durante el almacenamiento y el transporte, lo que carece de atención en la literatura existente. Para analizar la evolución dinámica y los factores de influencia de las estrategias adoptadas por las partes interesadas en la regulación de la seguridad alimentaria, se introdujo en este estudio la teoría de juegos evolutivos. Se construyó un modelo de juego evolutivo tripartito en el que participan el gobierno, los consignadores de alimentos y los transportistas de alimentos durante el almacenamiento y el transporte, utilizando Matlab para el análisis y la verificación. Los resultados muestran que: (1) Se puede animar a los consignadores y transportistas de alimentos a introducir factores de seguridad durante el almacenamiento y el transporte y a llevar a cabo una operación conforme si el gobierno aumenta las multas a las empresas por operaciones no conformes, aumentando así la probabilidad de una regulación exitosa. (2) Los consignadores de alimentos pueden obtener ciertos beneficios y mejorar la reputación corporativa a través de la aportación de seguridad durante el almacenamiento y el transporte, lo que les animará a gestionar sus inversiones estratégicamente. Además, cuanto más graves sean los problemas relacionados con la seguridad alimentaria durante el almacenamiento y el transporte, mayor será el impacto negativo en la empresa, y esto puede llevar a los consignadores de alimentos a poner más énfasis en la seguridad alimentaria. (3) Si aumenta la probabilidad de que los consignadores de alimentos expongan a los transportistas de alimentos a operaciones no conformes, la pérdida de cuota de mercado que sufran los transportistas debido a operaciones no conformes y el impacto negativo resultante serán mayores, y los transportistas de alimentos prestarán más atención al problema de la seguridad alimentaria. Este estudio enriquece la investigación teórica sobre la regulación de la seguridad alimentaria durante el almacenamiento y el transporte y proporciona ideas orientativas para mejorar la regulación de la seguridad alimentaria.
- **Palabras clave:** Regulación de la seguridad alimentaria, Almacenamiento y transporte, Juego evolutivo tripartito.

ABSTRACT

Food safety requires the cooperation of government, food consignors and food carriers during storage and transportation, which lacks attention in the existing literature. To analyze the dynamic evolution and influence factors of strategies made by stakeholders in food safety regulation, evolutionary game theory was introduced in this study. A tripartite evolutionary game model involving government, food consignors and food carriers during storage and transportation was constructed using Matlab for analysis and verification. Results show that: (1) Food consignors and carriers can be encouraged to input safety factors during storage and transportation and carry out compliant operation if the government increases the fines on enterprises for non-compliant operation, thus elevating the probability of successful regulation. (2) Food consignors can gain certain benefits and enhance corporate reputation through safety input during storage and transportation, which will encourage them to manage their investments strategically. Moreover, the more severe the issues related to food safety during storage and transportation are, the greater the negative impact on the enterprise will be, and this can prompt food consignors to place more emphasis on food safety. (3) If the probability of food consignors exposing food carriers for non-compliant operation increases, the market share loss brought to the carriers due to non-compliant operation and the negative impact arising from this will be higher, and food carriers will pay more attention to the food safety problem. This study enriches the theoretical research on food safety regulation during storage and transportation and provides guiding insights for improving food safety regulation.

Keywords: Food safety regulation, Storage and transportation, Tripartite evolutionary game.

1. INTRODUCTION

Food safety is closely related not only to people's health and daily life but also to economic development, social stability, and the image of the country and the government [1]. Food safety problems in the production, processing, and sales trigger a series of food safety problems during storage and transportation. In recent years, food safety incidents have occurred frequently during storage and transportation, including the incident of a tanker loading edible oil directly after unloading oil from coal in China in 2024. To cut costs, some food carriers used the same tankers for transporting both edible oil and non-food substances, such as kerosene and chemical liquids, often washing tanks only at the mouth. This practice has seriously compromised food safety and raised widespread public concern. A comparable incident occurred in 2021. Chelsea Sugar in New Zealand imported sugar raw materials from Australia using cargo ships that had previously carried metal sulfides. The cleaning of these ships was not thorough, and a damaged pipeline on board made the pollution situation worse. After some of the products were produced and sold, it was found that the lead content exceeded the standard, and the company had to conduct a large-scale recall. The pursuit of profit maximization by food carriers leads to an opportunistic behavioral tendency when making transportation decisions, causing an increasing number of food safety risks. Ensuring food safety during storage and transportation is the responsibility of both food carriers and consignors and government regulatory authorities. However, the government and food consignors are more focused on food safety in the food production, processing, and sales, while neglecting food safety regulation during storage and transportation.

Relevant studies have been carried out on the influencing factors and regulation of food safety during storage and transportation. (1) Some scholars studied the influence of tools and technical factors during storage and transportation on food safety, focusing on improving cold chain logistics technology. Their results highlighted the need for accurately controlling temperature and humidity during storage and transportation environment and developing high-efficiency cold chain equipment with precise environmental control [2-4]. (2) Some scholars focused on food safety regulation by government departments during storage and transportation and recommended that the government build a complete regulation system, strengthen the whole-process regulation from source to consumption point, improve the efficiency and transparency of regulation, and pay special attention to food safety during logistics and distribution [5]. Based on the perspective of social co-governance, a few scholars also recommended the government to actively guide consumers and other social stakeholders to participate in food safety regulation [6,7]. (3) Some scholars explored food safety management in the entire process of production, processing, storage, transportation, and consumption from the perspective of the food supply chain [8,9]. (4) Some scholars analyzed the safety management of fresh food, cold chain products, and other special foods during storage and transportation. In particular, they investigated the dynamic life cycle assessment framework tailored for frozen food storage facilities and the tools used to reduce food safety risks in the cold chain system [10,11]. However, little attention has been paid to the behavioral decision of stakeholders during storage and transportation in existing literature, such as the good faith and standardized business behavior of carriers and the supervision behavior of consignors.

Food safety regulation during storage and transportation is a dynamic and systematic process involving many stakeholders, such as the government, shippers, carriers, consignors, and social organizations, leading to various conflicts of interest. Effective regulation can be implemented only by formulating a reasonable mechanism. The government, as a critical supervising subject, ensures that food consignors and carriers attach importance to food safety during storage and transportation by formulating and executing strict laws, regulations, and policies. Meanwhile, food consignors should guarantee food safety during storage and transportation and strengthen safety measures. Specifically, the qualifications of logistics enterprises should be examined prudently, the drivers and storage and transportation tools of carriers should be subject to inspections and process supervision, internal personnel should be designated to take care of goods in the tank, and sampling inspection should be done before delivery. As food transport enterprises, food carriers have the obligation to maintain food safety during storage and transportation and ensure safe delivery. To analyze the dynamic evolution and influence factors of strategies made by stakeholders in food safety regulation, the tripartite evolutionary game model involving government, food consignors and food carriers during storage and transportation is constructed using Matlab for analysis and verification.

The contributions of this study are as follows: (1) Based on evolutionary game theory, a tripartite evolutionary game model of government–food consignors–food carriers" is established for the first time to explore the evolutionary equilibrium stability and its influencing factors in the process of food safety regulation during storage and transportation. This study makes up for the lack of a single, static research perspective to some extent. (2) Meanwhile, food consignors and food carriers were taken as the critical stakeholders influencing food safety regulation during storage and transportation. This study further enriches the research on food safety regulation during storage and transportation and exploits a new research perspective. Additionally, this study is structured as follows in the supplementary material.

2. STATE OF THE ART

2.1. RESEARCH ON FOOD SAFETY REGULATION

Current research on food safety regulation concentrates on its systems, patterns, and laws [12-14]; effect evaluation [15-17]; and governance strategies [18]. In terms of food safety regulation, existing studies mainly focus on food safety management in the food production, processing, and sales, mostly starting from the participation of the government and third-party institutions. Shen et al. (2021) studied the influence of government regulation on the food quality decision of enterprises and provided a theoretical basis for the government to formulate food safety regulation policies from the perspective of product substitutability [19]. Several scholars have studied food safety regulation problems from the perspective of social co-governance. Based on a social co-governance framework, Wu et al. (2024) established a tripartite evolutionary game model including food suppliers, food producers, and consumers to explore the influence of the reputation mechanism and market contracts of supply chain subjects on enterprises' choice of quality investment behavioral strategies under the legal regulation of the government [6]. Gao et al. (2023) constructed a tripartite evolutionary game model including raw material suppliers, producers, and sellers. The equilibrium points were divided into four risk scenarios according to the number of risk links in the food supply chain: zero link risk, single-link risk, double-link risk, and three-link risk. Multiple regulatory forces of stakeholders such as the government, market and society are needed to prevent the risks of all links in the supply chain from appearing simultaneously [20]. Yang et al. (2024) and Chang et al. (2020) set out from the perspective of social co-governance and built an evolutionary game model of the government, food enterprises, and public participation to solve the dishonest operation of food enterprises and the market failure caused by information asymmetry. They proposed that the government should increase punishment, strengthen enterprise self-discipline, guide the public to participate in governance, and build a multi-subject coordinated social co-governance pattern [7,21].

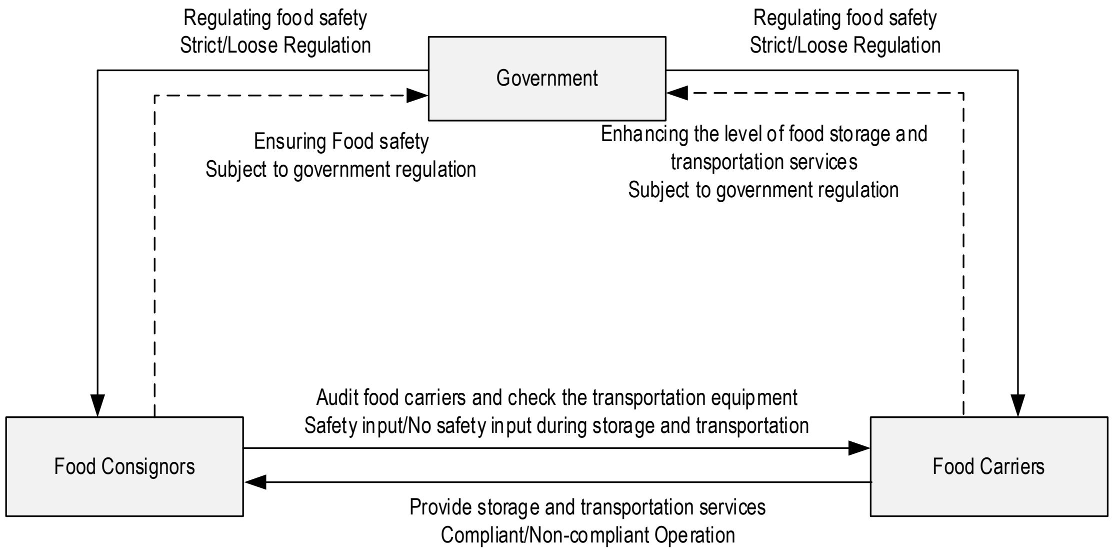

Fig. 1. Interactions Among the Government, Food Consignors, and Food Carriers.

2.2. RESEARCH ON FOOD SAFETY DURING STORAGE AND TRANSPORTATION

At present, the governments of Europe, Asia, and the United States have introduced relevant policies regarding food safety during storage and transportation, as shown in Table 1 of the supplementary material. In terms of technical factors affecting food safety during storage and transportation, existing research mainly focuses on the cold chain logistics of fresh products. When it comes to logistics facilities and services, Considering temperature fluctuations in the logistics process, Tao et al. (2024) applied passive radiation cooling technology to packaging to enhance temperature control ability in food storage and transportation [2]. Tang et al. (2024) evaluated the impact of Internet of Things (IoT) technology on cold chain logistics service quality management and e-commerce information of fresh products in Logistics 4.0. Combining 8 main characteristics and 40 dimension-related variables, the theoretical framework of IoT-based cold chain logistics service quality management was constructed through the structural equation model [22]. In optimizing the quality management process of cold chain logistics, Kummer et al. (2020) and Alangari and Khan (2021) found that block-chain technology and artificial intelligence can effectively strengthen the quality management of cold chain supply chains [23,24]. Huang et al. (2023) put forward a new method of food freshness prediction based on multi-perception technology and machine learning algorithm. They considered machine learning to be a novel method for improving food freshness and the quality management level of cold chain logistics [25]. Some scholars have conducted relevant research on cold chain logistics based on quality management tools. Shen et al. (2024) put forward a dynamic life cycle assessment framework for refrigerated food storage facilities, which can adapt to the temporal changes of operating conditions and energy use, as well as interact with real-time monitoring data and fluctuating energy rates to provide more accurate and time-sensitive environmental impact and cost assessments [10]. Wu and Hsiao (2021) effectively reduced food safety risks in the cold chain system by using the

Symbol	Meaning	Symbol	Meaning
R_1	Public credibility brought to the government by strict regulation	F_3	Fine imposed by consignors on carriers because of non-compliant operation
C_{11}	Cost of strict government regulation for food consignors	B	Additional revenue of consignors from safety input
C_{12}	Cost of strict government regulation for food carriers	L_2	Loss induced by the exposure of any product quality problem in case of no safety input by consignors
F_1	Government fine imposed on consignors because of no safety input	R_3	Revenue of carriers from non-compliant operation
F_2	Government fine imposed on carriers for non-compliant operation	C_3	Additional cost paid by carriers for compliant operation
P_1	Probability of successful government regulation	L_3	Enterprise loss due to exposure of consignors' non-compliant operation
L_1	Loss from insufficient government regulation	x	Probability of strict government regulation
R_2	Revenue of consignors from no safety input	y	Probability for consignors to conduct safety input
C_2	Cost added by safety input of consignors	z	Probability of carriers' compliant operation
P_2	Probability for consignors to find and expose the non-compliant operation of carriers	/	/

Table 1. Parameters descriptions

Strategy choice of tripartite subjects		Revenue of government	Revenue of food consignors	Revenue of food carriers
Safety input (y) and compliant operation (z)	Strict regulation (x)	$R_1-C_{11}-C_{12}$	R_2-C_2+B	R_3-C_3
	Loose regulation ($1-x$)	0	R_2-C_2+B	R_3-C_3
No safety input ($1-y$) and compliant operation (z)	Strict regulation (x)	$R_1-C_{11}-C_{12}+P_1F_1$	$R_2-P_1F_1-P_1L_2$	R_3-C_3
	Loose regulation ($1-x$)	0	R_2	R_3-C_3
Safety input (y) and non-compliant operation ($1-z$)	Strict regulation (x)	$R_1-C_{11}-C_{12}+P_1F_2$	$R_2-C_2+B+P_2F_3$	$R_3-P_1F_2-P_1L_3-P_2F_3-P_2L_3$
	Loose regulation ($1-x$)	$-L_1$	$R_2-C_2+B+P_2F_3$	$R_3-P_2F_3-P_2L_3$
No safety input ($1-y$) and non-compliant operation ($1-z$)	Strict regulation (x)	$R_1-C_{11}-C_{12}+P_1F_1+P_1F_2$	$R_2-P_1F_1-P_1L_2$	$R_3-P_1F_2-P_1L_3$
	Loose regulation ($1-x$)	$-L_1$	R_2	R_3

Table 2. Pay-off matrix of the tripartite evolutionary game.

failure mode and effects analysis tool. FMEA can be used as a preventive tool to diagnose food safety risks in the food cold chain and reduce these risks through effective control strategies [11]. Wang et al. (2022) analyzed quality risk factors such as logistics distribution, loading and unloading, and sorting based on social networks and put forward relevant strategies to improve the logistics management level of fresh products [26]. For food safety regulation during storage and transportation, Trivedi et al. (2019) highlighted the need to regularly monitor and maintain food quality standards throughout the supply chain, stating that special attention should be paid to the safety of food supply chains from the logistics and distribution aspects [5].

To sum up, food safety during production, processing, and sales has been extensively investigated. However, the influence of organizational or individual management behavioral factors on food safety during storage and transportation has been scarcely explored in existing literature. Therefore, this study will focus on the influence of the decision-making behavior and collaborative effect of stakeholders on food safety regulation during storage and transportation. The results are expected to provide a theoretical basis for further exploring the food safety regulation problem during storage and transportation.

3. METHODOLOGY

3.1. PROBLEM DESCRIPTION

Food safety regulation during storage and transportation involves three major subjects: the government, food consignors, and food carriers. All three have different objectives and interests and tend to make decisions for the sake of maximizing their own benefits with bounded rationality. Food carriers provide consignors with food storage and transportation services, and to maximize their economic benefits, they may seek profits through non-compliant operation during storage and transportation, thus affecting food safety. However, food consignors should also conduct safety measures during food storage and transportation, such as qualification examinations for carriers, mandatory inspections of carriers' storage and transportation equipment, and sampling inspections before food delivery. The government should supervise food safety during storage and transportation by examining whether food consignors implement safety inputs during storage and transportation and whether food carriers implement compliant operation. The interactions are illustrated in Fig. 1.

3.2. MODEL ASSUMPTIONS

According to the tripartite game interactions, assume the three interest subjects—the government, food consignors, and food carriers—are all of bounded rationality. The parameters of the tripartite evolutionary game model are listed in Table 1. Additionally, four assumptions are elaborately described in the supplementary material.

3.3. MODEL FORMULATION

The mixed strategy game matrix of government, food consignors, and food carriers based on the above assumptions is shown in Table 2.

3.4. STABILITY ANALYSIS OF SUBJECTS

E_{11} is set as the expected revenue of the government when choosing the "strict regulation" strategy, E_{12} is set as the expected revenue of the government when choosing the "loose regulation" strategy, and E_1 is the average expected revenue.

$$\begin{aligned} E_{11} = {} & (R_1-C_{11}-C_{12})yz+(R_1-C_{11}-C_{12}+P_1F_1)(1-y)z \\ & +(R_1-C_{11}-C_{12}+P_1F_2)y(1-z)+(R_1-C_{11}-C_{12}+P_1F_1+P_1F_2)(1-y)(1-z) \end{aligned} \quad (1)$$

$$E_{12} = -L_1y(1-z)-L_1(1-y)(1-z) \quad (2)$$

$$E_1 = xE_{11}+(1-x)E_{12} \quad (3)$$

E_{21} is set as the expected revenue of food consignors when choosing the "safety input" strategy, E_{22} is set as the expected revenue of food consignors when choosing the "no safety input" strategy, and E_2 is the average expected revenue.

$$E_{21} = (R_2-C_2+B)xz+(R_2-C_2+B)(1-x)z+(R_2-C_2+B+P_2F_3)x(1-z)+(R_2-C_2+B+P_2F_3)(1-x)(1-z) \quad (4)$$

$$E_{22} = (R_2-P_1F_1-P_1L_2)xz+R_2(1-x)z+(R_2-P_1F_1-P_1L_2)x(1-z)+R_2(1-x)(1-z) \quad (5)$$

$$E_2 = yE_{21}+(1-y)E_{22} \quad (6)$$

E_{31} is set as the expected revenue of food carriers when choosing the "compliant operation" strategy, E_{32} is set as the expected revenue of food carriers when choosing the "non-compliant operation" strategy, and E_3 is the average expected revenue.

$$E_{31} = (R_3 - C_3)xy + (R_3 - C_3)(1-x)y + (R_3 - C_3)x(1-y) + (R_3 - C_3)(1-x)(1-y) \quad (7)$$

$$E_{32} = (R_3 - P_1F_2 - P_1L_3 - P_2F_3 - P_2L_3)xy + (R_3 - P_2F_3 - P_2L_3)(1-x)y + (R_3 - P_1F_2 - P_1L_3)x(1-y) + R_3(1-x)(1-y) \quad (8)$$

$$E_3 = zE_{31} + (1-z)E_{32} \quad (9)$$

The replicator dynamics equation of the government is

$$F(x) = dx/dt = (E_{11} - E_1)x = x(1-x)(-C_{11} - C_{12} + L_1 + R_1 + P_1F_1 + P_1F_2 - P_1F_1y - P_1F_2z - L_1z) \quad (10)$$

The replicator dynamics equation of food consignors is

$$F(y) = dy/dt = (E_{21} - E_2)y = y(1-y)(B - C_2 + P_2F_3 + P_1F_1x + P_1L_2x - P_2F_3z) \quad (11)$$

The replicator dynamics equation of food carriers is

$$F(z) = dz/dt = (E_{31} - E_3)z = z(1-z)(-C_3 + P_1F_2x + P_2F_3y + P_1L_3x + P_2L_3y) \quad (12)$$

All subjects do not know whether their own strategies are the optimal due to the information asymmetry among the three game parties. Thus, they have to adjust their strategies continuously by observing those of the counterparties, finally reaching an equilibrium state. According to the theory of evolutionary game, the stability analysis of subjects are implemented in the supplementary material.

3.5. EQUILIBRIUM POINT STABILITY ANALYSIS

Following the method proposed by Friedman (1991), the Jacobi matrix can be obtained by taking the derivative of the replicated dynamical system equation, and the corresponding asymptotic stability analysis results can be obtained by inputting eight equilibrium points into the matrix.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \quad (13)$$

where:

$$\frac{\partial F(x)}{\partial x} = (1-2x)(-C_{11} - C_{12} + L_1 + R_1 + P_1F_1 + P_1F_2 - P_1F_1y - P_1F_2z - L_1z)$$

$$\frac{\partial F(x)}{\partial y} = x(1-x)P_1F_1$$

$$\frac{\partial F(x)}{\partial z} = x(x-1)(P_1F_2 + L_1)$$

$$\frac{\partial F(y)}{\partial x} = y(1-y)(P_1F_1 + P_1L_2)$$

$$\frac{\partial F(y)}{\partial y} = (1-2y)(B - C_2 + P_2F_3 + P_1F_1x - P_2F_3z + P_1L_2x)$$

$$\frac{\partial F(y)}{\partial z} = y(y-1)P_2F_3$$

$$\frac{\partial F(z)}{\partial x} = z(1-z)(P_1F_2 + P_1L_3)$$

$$\frac{\partial F(z)}{\partial y} = z(1-z)(P_2F_3 + P_2L_3)$$

$$\frac{\partial F(z)}{\partial z} = (1-2z)(-C_3 + P_1F_2x + P_2F_3y + P_1L_3x + P_2L_3y)$$

Equilibrium point	Eigenvalue	Eigenvalue symbol	Stable conditions	Stability
$E_1(0,0,0)$	$\lambda_1 = -C_{11} - C_{12} + L_1 + R_1 + P_1F_1 + P_1F_2$, $\lambda_2 = B - C_2 + P_2F_3$, $\lambda_3 = -C_3$	×, ×, -	$\lambda_1 < 0$, $\lambda_2 < 0$	ESS
$E_2(0,1,0)$	$\lambda_1 = -C_{11} - C_{12} + L_1 + R_1 + P_1F_2$, $\lambda_2 = -B + C_2 - P_2F_3$, $\lambda_3 = -C_3 + P_2F_3 + P_2L_3$	×, ×, ×	$\lambda_1 < 0$, $\lambda_2 < 0$, $\lambda_3 < 0$	ESS
$E_3(0,0,1)$	$\lambda_1 = -C_{11} - C_{12} + R_1 + P_1F_1$, $\lambda_2 = B - C_2$, $\lambda_3 = C_3$	×, ×, +	/	Unstable Point
$E_4(0,1,1)$	$\lambda_1 = -C_{11} - C_{12} + R_1$, $\lambda_2 = -B + C_2$, $\lambda_3 = C_3 - P_2F_3 - P_2L_3$	×, ×, ×	$\lambda_1 < 0$, $\lambda_2 < 0$, $\lambda_3 < 0$	ESS
$E_5(1,0,0)$	$\lambda_1 = C_{11} + C_{12} - L_1 - R_1 - P_1F_1 - P_1F_2$, $\lambda_2 = B - C_2 + P_1F_1 + P_2F_3 + P_1L_2$, $\lambda_3 = -C_3 + P_1F_2 + P_1L_3$	×, ×, ×	$\lambda_1 < 0$, $\lambda_2 < 0$, $\lambda_3 < 0$	ESS
$E_6(1,1,0)$	$\lambda_1 = C_{11} + C_{12} - L_1 - R_1 - P_1F_2$, $\lambda_2 = -B + C_2 - P_1F_1 - P_2F_3 - P_1L_2$, $\lambda_3 = -C_3 + P_1F_2 + P_1L_3 + P_2F_3 + P_2L_3$	×, ×, ×	$\lambda_1 < 0$, $\lambda_2 < 0$, $\lambda_3 < 0$	ESS
$E_7(1,0,1)$	$\lambda_1 = C_{11} + C_{12} - R_1 - P_1F_1$, $\lambda_2 = B - C_2 + P_1F_1 + P_1L_2$, $\lambda_3 = C_3 - P_1F_2 - P_1L_3$	×, ×, ×	$\lambda_1 < 0$, $\lambda_2 < 0$, $\lambda_3 < 0$	ESS
$E_8(1,1,1)$	$\lambda_1 = C_{11} + C_{12} - R_1$, $\lambda_2 = -B + C_2 - P_1F_1 - P_1L_2$, $\lambda_3 = C_3 - P_1F_2 - P_1L_3 - P_2F_3 - P_2L_3$	×, ×, ×	$\lambda_1 < 0$, $\lambda_2 < 0$, $\lambda_3 < 0$	ESS

Note: + is a positive value, - is a negative value, × cannot be determined as positive or negative.
Table 3. Stability analysis of equilibrium points.

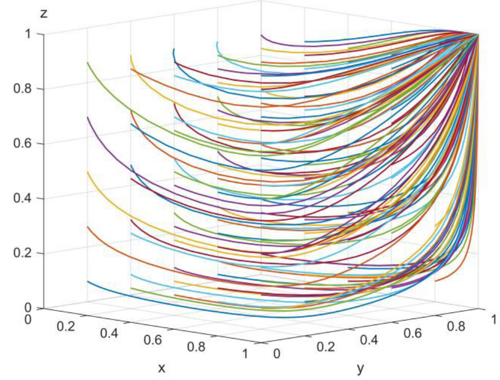

Fig. 2. Results after array evolution 50 times.

The three eigenvalues corresponding to each equilibrium point can be obtained by substituting the equilibrium points into the Jacobian matrix. According to the Lyapunov indirect method, if all eigenvalues of the equilibrium point are negative real numbers, then the equilibrium point is stable (i.e., an ESS). Table 3 shows the stability judgment results of the equilibrium point.

The table 3 reveals that the eigenvalue of E_3 has positive values and is thus an unstable point. E_1, E_2, E_4, E_5, E_6, E_7, and E_8 can be ESS stable points only if all their eigenvalues are smaller than 0. Among them, $E_8(1,1,1)$ is a relatively ideal state, needing to meet the conditions of $C_{11}+C_{12}-R_1<0$, $-B+C_2-P_1F_1-P_1L_2<0$ and $C_3-P_1F_2-P_1L_3-P_2F_3-P_2L_3<0$. In particular, the government will select strict regulation when the public credibility brought by this strategy is greater than the cost of strict regulation for food consignors and carriers. Food consignors will choose safety input if the cost paid for it is smaller than the sum of the additional revenue that can be acquired, the improvement of enterprise reputation, the fine imposed after being investigated by the government, and the negative impact on the enterprise. Food carriers will be inclined toward compliant operation if the cost paid for such operation is smaller than the fine paid after being investigated by the government, the compensation for product losses after non-compliant operation is found and exposed by food consignors, and the negative impact on the enterprise. In this case, the evolutionary strategy is "strict regulation–safety input–compliant operation".

4. RESULT ANALYSIS

4.1. INITIAL EVOLUTION PATH

To analyze the system evolution process more intuitively and the impact of different parameter fluctuations on the stability strategy of tripartite evolution, the dependency and restrictive relationship between parameters, as well as the defined assumptions, were considered to assign parameter values to the model. This study aimed to identify a state in which the government implements strict regulation, food consignors conduct safety input, and food carriers perform compliant operation and seek a game strategy approaching the evolutionarily stable strategy point (1, 1, 1). Assuming $R_1=35$, $C_{11}=10$, $C_{12}=20$, $C_2=30$, $C_3=30$, $F_1=15$, $F_2=15$, $F_3=10$, $P_1=0.6$, $P_2=0.6$, $L_1=30$, $L_2=30$, $L_3=20$, and $B=10$. The values were subjected to time-dependent evolution 50 times, and the results are shown in Fig. 2.

4.2. PARAMETER SENSITIVITY ANALYSIS

The stability analysis results reveal that the evolution result was greatly influenced by some parameters. Hence, some important parameters were subjected to sensitivity analysis to observe the influence of parameter changes on the strategy of the three subjects. To verify the effectiveness of the evolutionary stability analysis, the stability condition of equilibrium point (1, 1, 1) was considered and a numerical simulation was performed via MATLAB. The initial value of the three parties was taken as 0.2, the initial time was set to 0, and the evolution ending time was set to 50.

(1) Impact of government fines F_1 and F_2 on the system. With other parameters unchanged, the evolution path was simulated when F_1 and F_2 were taken as 5, 10, and 15 (Fig. 3(a)). As the government fines increased, the three game parties finally converged to 1, and the convergence rate was accelerated. The simulation results show that if the government increases the fines on enterprises, the possibility for food consignors to conduct safety input and food carriers to perform compliant operation can increase.

(2) Impact of probability of successful government regulation P_1 on the system. With other parameters unchanged, the evolution path was simulated when P_1 was taken as 0.3, 0.6, and 0.9 (Fig. 3(b)). With the increase in the probability of successful government regulation, the government and food consignors converge to 1 more rapidly. The simulation results reveal that the increasing probability of successful government regulation for food consignors can effectively constrain food consignors to select safety input and drive food carriers to choose compliant operation.

(3) Impact of the probability for food consignors to find and expose non-compliant operation of food carriers P_2 on the system. With other parameters unchanged, the evolution path was simulated when P_2 was taken as 0.3, 0.6, and 0.9 (Fig. 3(c)). As the probability for food consignors to find and expose non-compliant operation of carriers increased, food carriers converged to 1 faster. The simulation results indicate that food carriers can be more effectively constrained to select compliant operation with the increase in the probability for food consignors to find and expose the non-compliant operation of food carriers.

(4) Impact of loss to society and the government reputation from loose regulation L_1 on the system. With other parameters unchanged, the evolution path was simulated when L_1 was taken as 10, 30 and 50 (Fig. 3(d)). As the social loss and government reputation loss increased, the government strategy finally converged to 1, and the convergence rate accelerated with the growth of L_1. The simulation results show that the greater the social loss and government reputation loss triggered by loose government regulation, the more the government tends to select strict regulation.

(5) Impact of the increase and enhancement of corporate reputation of food consignors from safety input B and the market share loss in case any product quality problem is exposed by food consignors L_2 on the system. With other parameters unchanged, the evolution path was simulated when B was respectively taken as 5, 10, and 15 (Fig. 3(e)). The evolution path when L_2 was taken as 10, 30, and 50 (Fig. 3(f)). Specifically, the strategy of consignors finally converged to 1, and the convergence rate accelerated with the growth of B and L_2. The simulation results manifest that the higher the increase in additional revenue and enterprise reputation of consignors, the higher the market share loss and negative impact brought by the exposure of product quality problems in case of no safety input, and the more the consignors tend to select safety input.

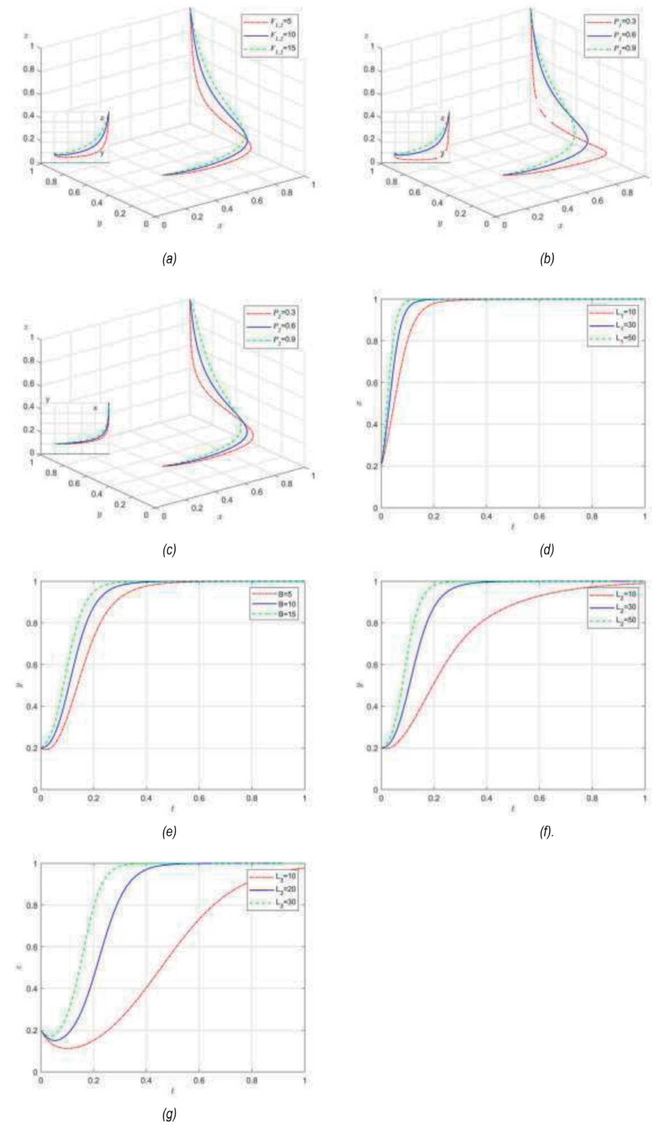

Fig. 3. Parameter sensitivity analysis.

(6) Impact of market share loss induced to food carriers due to non-compliant operation L_3 on the system. With other parameters unchanged, the evolution path was simulated when L_3 was taken as 10, 20, and 30 (Fig. 3(g)). The strategy of the food carriers finally converged to 1, and the convergence rate accelerated with the growth of L_3. The simulation results reveal that the greater the market share loss and negative impact brought to food carriers due to the exposure of non-compliant operation, the more the enterprises tend to select compliant operation.

5. DISCUSSION

Based on the above evolutionary game analysis and simulation analysis, the discussion of this study is as follows:.

(1) The evolutionary game analysis shows the new perspective proposed in this study, the government, food consignors, and food carriers are considered to supervise food safety during storage and transportation, which makes up for the lack of existing literature, and also provides a new research perspective for similar market regulation issues. The results show that, when the credibility brought by strict supervision is greater than the cost of supervision, the government will choose strict supervision; When the cost of quality and safety investment is less than the sum of income, reputation improvement and violation punishment, food consignors will choose to invest in quality and safety; When the cost of compliant operation of food carriers is less than the penalty, compensation and negative impact of violations, they will choose compliant operation.

(2) The simulation analysis shows that the regulatory effectiveness of food storage and transportation is affected by multiple factors. Even though existing literature has shown that the government, food production enterprises, third-party testing institutions, and the public play an important binding role in food safety supervision [6,7,20], this study focuses on the safety supervision of food during storage and transportation, and the research results are more systematic and comprehensive, which have not been studied or found in the existing literature.

(3) At present, for the relevant research on food safety during storage and transportation, the existing literature mainly focuses on empirical analysis, performance evaluation research, and research at the specific technical level and so on [5,22,26]. The evolutionary game theory and dynamic evolutionary process analysis method in this study are significantly different from the existing literature. It can not only more systematically and dynamically present the interaction among the strategy selection of stakeholders in the storage and transportation of food safety issues, as well as the system evolution process and its influencing factors, but also provide a powerful theoretical and analytical tool for research on regulation.

6. CONCLUSIONS

The findings show that: (1) Elevating government fines on the non-compliant operation of enterprises will drive food consignors and carriers to finally select safety input and compliant operation during storage and transportation. (2) Enterprises will be positively driven to attach importance to food safety problems in case of the increase in the probability of successful government regulation for food consignors, the probability for food consignors to find and expose the non-compliant operation of carriers, and the additional revenue and enterprise reputation acquired through safety input of food consignors. (3) Three parties will attach greater importance to food safety problems in case of increased social loss and government reputation loss triggered by inefficient government regulation, the market share loss and negative impact brought to food consignors due to product quality problems, and those brought to food carriers due to the exposure of their non-compliant operation.

The following management implications are obtained from the above conclusions: The government should review and enhance the food safety regulatory system, set clear transport standards, toughen penalties, boost enterprise self-discipline and industry norms, strengthen regulation and team building, establish an early warning and emergency mechanism, and conduct audits. Food consignors should heighten safety measures in storage and transport, allocate resources to vet carriers' qualifications and check equipment and operation, and ensure safety in production and during transit. Food carriers should cut costs via compliant operation like optimizing management and transportation, rather than compromising food safety for higher profits.

Restricted by research conditions, however, the numerical simulation of some parameters lacks actual data support, so the theoretical model remains to be further empirically analyzed based on actual data. In this study, only the influence of the government, food consignors and food carriers on the food quality and safety supervision decision was analyzed. In fact, other subjects and factors may also exert certain effects. In the follow-up study, the research on the strategy selection of more subjects will be further extended to enrich the scenarios of evolutionary game.

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