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Research article

Prevention of food fraud and fraud emulation among companies in the supply chain based on a social Co-governance framework

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ABSTRACT

This study develops a three-party evolutionary game model among upstream raw material producers, midstream food producers, and downstream distributors in the food supply chain, and investigates food fraud and fraud emulation among companies in the same group based on a food safety social co-governance framework. Moreover, the equilibrium points are divided into four scenarios according to the number of groups of companies committing fraud in the supply chain and whether companies in the same group emulate each other's fraudulent behavior. The stability conditions of these scenarios are also discussed and verified by numerical simulation in MATLAB. The results show that the behavioral strategy choices of different groups of food companies in the supply chain are closely related to the level of social co-governance involving the government, market, and consumers. Government regulation, supervision between companies, and consumer reporting can all change companies' behavioral strategies. Although the level of fraud emulation among companies in the same group does not change their behavioral strategy choice, it affects the time it takes for their behavioral strategy to evolve to a stable state. Moreover, the level of social co-governance directly affects companies' behavioral strategy choices at different emulation levels.

1. Introduction

As a reflection of pursuit of market gain, it has long persisted despite market changes over thousands of years [1]. Food fraud can be traced back to ancient Rome [2]. However, food fraud is increasingly becoming a serious social problem worldwide as production specialization proceeds and markets expand [3,4]. At present, food fraud exists not only in the internal food market of a country but also widely in the global food market. Counterfeit food rejected by China Customs accounted for 30.35 % of all imported food, and counterfeit food originating from the processing stage constituted 87.7 % of all rejected imported food between 2009 and 2019 [5]. A joint operation by Europol and Interpol destroyed 19 food fraud organizations and seized counterfeit foods worth 28 million euros [6].

In essence, food fraud is a deliberate crime committed by persons pursuing economic gain [7,8], and currently ranks as the second biggest public health hazard in the world, second only to drugs [9]. Although there are many forms of food fraud, the main methods include illegally substituting or swapping ingredients, i.e., for something cheaper, adding additional ingredients, i.e., to meet testing standards for nutrients, tampering with packaging, e.g., changing dates or other information on a packet or opening it to remove some

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of the product, among others, which can serve to increase the value of the food or reducing input costs [10], but has caused numerous public health crises [11–13]. An example in 2008 is the "Sanlu milk powder" fraud incident that occurred in China in which melamine was illegally added to dairy products to increase protein content. This resulting in the poisoning of more than 2.6 million infants and the death of at least six [14].

Food fraud is closely related to various factors, such as socioeconomic development [15], food safety governance system [16,17], food technology innovation [18], characteristics of food companies [19], and corporate business ethics [20]. Moreover, most food safety problems caused by fraud occur in production and processing [21]. In the social co-governance framework, a company producing counterfeit raw materials or food are subject to not only government penalties, but also financial liability for breach of contract, as well as reputational and economic losses due to consumer reports. Therefore, the production behavior of companies depends on the balance among actors, such as the government, market, and society. Only when the interests are balanced among the actors, that is, when the social co-governance system is stable, will the companies decide on their final behavioral strategy. Wang, Xie, and Li suggested that food fraud can no longer be considered a reflection the behavior of a single company, but should be seen rather as a common speculative group behavior among companies in China and they also found fraud emulation among the companies [22,23]. Wu and Liu demonstrated that most food safety incidents in China between 2008 and 2022 were caused by numerous companies jointly committing fraud and emulating each other [24]. However, few studies, at least in the Chinese academic community, have focused on the fraudulent behavior of food companies considering emulation. The main purpose of this study is to fill this gap in literature. By focusing on the production and sales behavior of different groups of food companies in the supply chain, this study attempts to investigate whether intercompany contracts and consumer participation are effective in controlling food fraud in the context of government regulation, as well as the impact of emulation levels presented by the production safety awareness of companies on food fraud control, in order to find strategies to solve the practical dilemma of food fraud and fraud emulation among companies.

2. Literature review

Negative behaviors among companies have inherent diffusion mechanisms and can be spread by emulation [25–27]. Emulation mainly exists among companies in the same industry [28,29], geographical region [30], and social network [31], but more directly and commonly among companies in the same category or group. The underlying reasons for this phenomenon have been identified as the peer effect[1] and broken windows theory.[2] Food companies in the same group adopt the congenerous or similar technical standards, use similar production processes, face a common market environment, and form a peer group in which members interact with each other, which provides the possibility for emulation among them [32,33]. Companies in the same group tend to emulate and learn from each other's mature experiences and adopt homogeneous strategies [34].

According to the broken windows theory, the first "window" in the food market may be broken due to the huge economic benefits that companies can gain by engaging in food fraud [8]. Subsequently, if the fraud is not discovered or if there is no or insufficient punishment after discovery, there would be no deterrent effect against such fraud. This would induce emulation among companies in the same group, and extensive group fraud would become inevitable [35,36]. Steinberg P and Engert S noted that the food industry and consumers worldwide lose up to 3 billion euros a year due to food fraud [37].

Food fraud can occur anywhere along the supply chain, from raw material production [38], production and processing [39], and logistics, to distribution and retail, albeit to varying degrees [40,41]. Therefore, government regulation alone cannot effectively deal with food safety issues in complex market environments [42,43], especially when faced with extensive corporate moral hazard [44–46], and numerous studies have shown an obvious government failure in the food market [42,43]. Market failure also occurs when food safety information is not effectively transmitted in the market [47]. According to modern public governance theories, social forces have unique functions beyond the capabilities of both government and market, especially when either or both fail [48–50]. Social forces can thus be seen as a third-sector force that corrects government and market failures [51,52]. Moreover, this third-sector participation in social co-governance of food safety enhances the flexibility of governance in addressing food safety issues, increases the coverage of policy effects, and saves public finances [53,54].

In the social co-governance system, the government's most basic policy tool to curb food fraud is to implement appropriate financial and judicial penalties for found fraud while carrying out food quality sampling inspections of companies in accordance with the law with appropriate probability [55,56]. However, some studies also suggested that the fragmentation of the food safety social co-governance-related systems, e.g., the limited establishment and improvement of the food safety regulation system and the ineffective flow of government regulation information among agencies, resulted in practical defects of the food safety social co-governance system in China [57]. Zhang et al. reported that the low probability of government sampling inspections was an important reason for persistent food fraud incidents in China [58]. It has also been shown that low government penalties are unlikely to have a deterrent effect due to the high expected economic benefits companies can gain from fraud [59]. Therefore, the probability of government

[1] Peer effect is also known as imitative behavior and has later given rise to concepts, such as herd effect and spillover effect. It means that the attitude and behavior of an individual in a complex social network are affected by the group behavior of their peers. See Liu S, Wu D. Competing by conducting good deeds: The peer effect of corporate social responsibility. Finance Research Letters,2016,16:47–54.

[2] The broken windows theory asserts that negative phenomena that are allowed to persist in the environment encourage imitation or even more serious misbehavior. Disorder is a core issue in the broken windows theory. Negative phenomena occur when disorder is not restrained. The environment influences the behavior of companies operating within it, and companies copy each other's behavior to some extent. See also Kelling G L, Wilson J Q. Broken windows. Atlantic monthly,1982,249(3):29–38.

sampling inspection and the amount of financial penalties imposed are crucial to the government's management of food safety. It imperative for the government to find an appropriate inspection probability and amount of penalties in social co-governance.

Beyond direct government inspections, when downstream companies cannot effectively or accurately inspect upstream companies, the liquidated damages mechanism does not work and cannot therefore control food fraud by upstream companies [60]. Zhang et al. and Wan et al. reported that the probability of downstream companies inspecting food produced by upstream companies, the ability of downstream companies to detect fraud, and increased liquidated damages that upstream companies pay to downstream companies due to fraud directly influenced the behavior of upstream companies in China. They also suggested that market contracts between upstream and downstream companies had a positive effect in restricting corporate fraud [61,62]. It has also been demonstrated that market contracts reduce opportunistic behavior among companies, e.g., by stipulating a compensation mechanism, and promote self-discipline in the production or marketing of food [63–65].

Consumer participation in food safety social co-governance can not only significantly influence the regulatory strategy choices of government agencies [66,67], but also affect the behavioral strategy choices of food companies, increase the cost of committing fraud, and reduce their motivation for committing fraud [68]. If consumers who discover that a company is committing fraud promptly report that to government agencies, it would be difficult for companies committing fraud to hide [69]. Moreover, government penalties on companies or compensation paid by companies to consumers based on verified consumer reports, as well as the market reputation formed through information disclosure, will induce companies to reduce fraud and emulation [70–73]. The public has proven willingness to report fraudulent companies: more than 50 % of major food safety violations handled by the Chinese government between 2014 and 2018 were initially reported by consumers [74]. As an important institutional arrangement, social co-governance ensures food safety at a lower cost and with more effective resource allocation, and it has also been shown to maximize social welfare [75]. Thus, many countries have adopted it as the basic model for managing food safety risks [76].Therefore, preventing food fraud and curbing emulation among companies requires not only government regulation, but also supervision between companies based on market contracts and the introduction of social forces, including consumers [77]. In this way, governance forces are multiplied and social co-governance promoted [51].

Most previous studies focused on the behavioral strategy choices of food companies in the supply chain. However, few investigated fraud by food companies based within a social co-governance framework involving government regulation, supervision between companies based on market contracts, and consumer reporting. Also, few studies have examined fraud emulation among companies in the same group. The marginal contribution of this study is to construct a three-party game model among upstream, midstream, and downstream companies in the food supply chain and investigate the main factors that trigger fraud and fraud emulation among companies in the same group within a social co-governance framework based on the reality of China. It also examines the impact of different levels of social co-governance and the behavioral strategies of each actor in the social co-governance system on food fraud in the entire supply chain. The results of this study provide policy suggestions on how to prevent food fraud and fraud emulation among companies.

3. Analytical framework and hypotheses

For the sake of simplicity in the present analysis, companies at different stages of the food supply chain are divided into three groups: upstream raw material production companies (referred to as raw material producers, X), midstream production and processing companies (referred to as food producers, Y), and downstream distribution companies (referred to as distributors, Z). Moreover, considering the traceability of raw materials or food, this study assumes that raw material producers in the supply chain only produce one type of raw materials and sell them to food producers. The ultimate goal of the behavioral strategy choices of X, Y, and Z is profit maximization. Moreover, all three actors are boundedly rational. Therefore, their initial behaviors are not optimal in terms of producing the highest profit. It is possible that they may emulate the fraudulent behavior of other companies in the same group to maximize their profits.

According to the peer effect concept, a food company's choice to commit fraud is influenced not only by fraud among other companies in the same group,[3] but also by the behavioral strategies of companies with high economic benefits, as well as regulatory forces, such as the government, market, and society. The peer effect may induce companies to commit fraud when the cost of food fraud is low, or when the behavior of other actors in social co-governance, such as the government, market, or consumers, is alienated, especially when a company's economic returns cannot ensure its survival and development. In this case, failure to curb the fraud in time would encourage fraud emulation among companies in the same group. Fig. 1 illustrates the operating logic of food fraud and emulation among companies in a supply chain based on the broken windows theory.

Based on the broken windows theory and the literature review, Fig. 2 illustrates supervision of X, Y, and Z by the government and consumers in a social co-governance framework, along with the interaction among X, Y, and Z based on market contracts. This study

[3] The factors that influence emulation of food fraud among companies are very complex. In terms of form, companies can copy the fraudulent behavior of other actors in the same supply chain, such as tampering with the production date and shelf life, etc. They can also emulate food companies in the same group; for example, aquatic product companies abuse preservatives to prevent the spoilage of processed aquatic products. Or they can also emulate non-food companies, e.g., by replacing qualified products with substandard ones. Considering that such copying requires professional skills and special tools, emulation among companies in the same group is more common. Therefore, for the sake of simplicity, this study only investigates fraud emulation among food companies in the same group. In other words, X, Y, and Z will only copy raw material producers, food producers, and food distributors, respectively, without considering copying among X, Y, and Z.

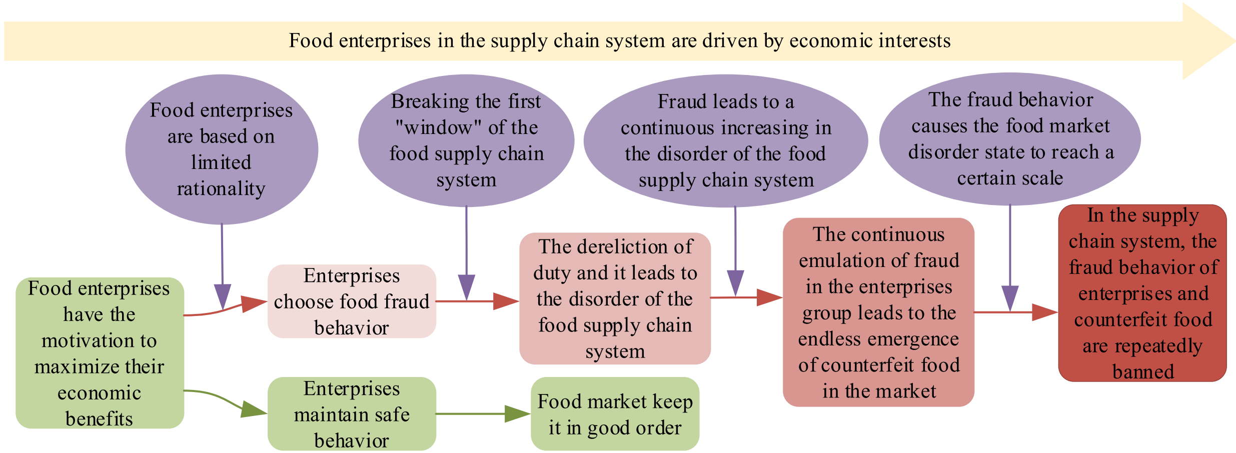

Fig. 1. Operating logic of food fraud and emulation among companies in the supply chain.

attempts to establish a social co-governance system composed of the government, companies, and consumers based on the reality of China,[4] and develops a three-party evolutionary game model among X, Y, and Z to investigate the balance and stability conditions of their behavioral strategy choices. Then, the main factors that affect the fraud and emulation among companies in the same group in the supply chain are analyzed.

Different countries have different laws and methods for regulating food companies. In China's current legal and regulatory system, the most common methods government agencies use to regulate companies are sampling inspections and financial penalties.[5] For the purpose of this study, government agencies use sampling to inspect X, Y, and Z for fraud and impose different financial penalties on companies committing fraud according to the nature of the fraud and the harm caused in accordance with the law. Assume that the probability of government agencies discovering fraud by sampling inspections of companies and the amount of financial penalties imposed are n_i and M_i ($i \in \{1,2,3\}$), respectively, where n_i and M_i reflect the level of regulation of corporate fraud by government agencies. Based on the above analysis, the following hypotheses are proposed.

Hypothesis 1. The set of behavioral strategy choices for X is {producing safe raw materials, producing counterfeit raw materials}, with probabilities of x and 1-x ($x \in [0,1]$), respectively. Assuming that X chooses safe production and the expected production cost is C_1. In this case, it inspects the quality of raw materials it produces in accordance with the law and technical standards to meet the requirements for safe food production by Y. Assume that its expected cost of self-inspection is C_2 and the expected economic return from selling safe raw materials to Y is R_1. Then, X's expected profit is $R_1 – C_1 - C_2$.

When X chooses to produce counterfeit raw materials and sells them to Y in pursuit of higher profits, it is assumed that the expected cost of producing counterfeit raw materials is C_3, where obviously, $C_3 < C_1$. In this case, X does not inspect the quality of raw materials it produces. Assume that the government inspects the quality of raw materials produced by X with probability of n_1. If fraud is discovered, X would be subject to a financial penalty of M_1 in accordance with the law. In other words, X receives a financial penalty of $n_1 M_1$ from the government.

Meanwhile, if Y chooses safe production, it would check the quality of the raw materials produced by X according to prevailing standards. Assume that the probability of such a sampling inspection is u_1. When Y discovers that X produced counterfeit raw materials, X shall pay a financial compensation of P_1 to Y according to the contract between them. In other words, the financial compensation that X needs to pay to Y is $u_1 P_1$. Therefore, when X chooses counterfeit production, the expected profits from supplying raw materials to a Y who chooses safe production or chooses counterfeit production are $R_1 – C_3 - n_1 M_1 - u_1 P_1$ and $R_3 – C_3 - n_1 M_1$, respectively.

Hypothesis 2. The set of behavioral strategy choices for Y is {producing safe food, producing counterfeit food}, with probabilities of y and 1-y ($y \in [0,1]$), respectively. When Y chooses safe production, it checks the quality of raw materials produced by X according to relevant standards. Assuming that the expected cost of safe production is C_4 and the cost of sampling inspection is C_5. When X is found to have produced counterfeit raw materials, it shall pay a financial compensation of P_1 to Y according to the contract. In other words, although Y pays an expected inspection cost of C_5, it will receive financial compensation of $u_1 P_1$ from X if fraud is discovered. At this point, Y can purchase similar raw materials that meet quality standards in the market for production.

Y also inspects the food it produces according to the standards to avoid being rejected by Z due to quality reasons. Assume that its

[4] Social forces have a complex composition and generally include non-governmental organizations, social groups, industry associations, news media, consumers, and volunteers. For the sake of simplicity, only consumers are included as a representative social force in this study.

[5] The government regulates food companies in accordance with the law in many ways, including administrative, financial, and judicial means. Only sampling inspection and financial penalties are discussed in this study.

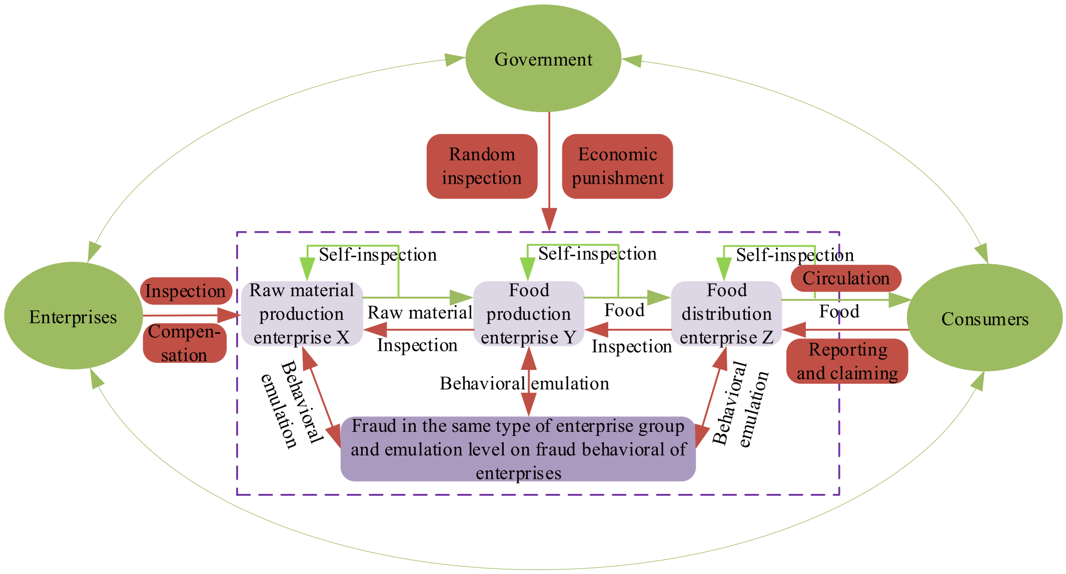

Fig. 2. Interaction among government, enterprises, and consumers in the social co-governance framework.

expected cost of self-inspection is C_6 and the expected economic return from selling food to Z is R_2. Therefore, when Y chooses safe production, its expected profit would be $R_2–C_4$-C_5-C_6 when purchasing safe raw materials from X. When it discovers the fraudulent behavior of X and purchases qualified raw materials from another producer, its expected profit would be $R_2–C_4$-$2C_5–C_6+u_1P_1$.

When Y chooses to produce counterfeit food and sells it to Z due to pursuit of higher profit, the expected production cost for Y is C_7, where obviously, $C_7<C_4$. In this case, Y does not inspect the quality of food it produces or the raw materials produced by X. Assume that the government inspects the quality of food produced by Y with probability of n_2, and imposes a financial penalty of M_2 on Y when fraud is found. In other words, Y receives a financial penalty of n_2M_2 from the government.

If Z chooses safe sales, it would check the quality of food produced by Y according to relevant standards. Assuming that the probability of sampling inspection is u_2. When Z discovers that Y produced counterfeit food, Y shall pay a financial compensation of P_2 to Z according to the contract between them. In other words, the financial compensation that Y needs to pay to Z is u_2P_2. Therefore, when Y chooses counterfeit production, the expected profits from selling food to a Z who chooses safe sales and chooses counterfeit sales are $R_2–C_7$-n_2M_2-u_2P_2 and $R_2–C_7$-n_2M_2, respectively.

Hypothesis 3. The set of behavioral strategy choices for Z is {selling safe food, selling counterfeit food}, with probabilities of z and 1-z ($z \in [0,1]$), respectively. When Z chooses safe sales, it checks the quality of food produced by Y according to relevant standards. Assume that the expected cost of safe sales is C_8 and the cost of sampling inspection is C_9. When Y is found to have produced counterfeit food, it shall pay a financial compensation of P_2 to Z according to the contract. In other words, although Z pays an expected inspection cost of C_9, it receives a financial compensation of u_2P_2 from Y. At this point, Z can purchase similar food that meet quality standards in the market for sale.

Meanwhile, Z also inspects the food it sells according to applicable standards to avoid consumer reports. Assuming that its expected cost of self-inspection is C_{10} and the expected economic return from selling food to consumers is R_3. Therefore, when Z chooses safe sales, its expected profit would be $R_3–C_8$-C_9-C_{10} when purchasing safe food from Y. When it discovers the fraudulent behavior of Y and purchases qualified food from another producer, its expected profit would be $R_3–C_8$-$2C_9–C_{10}+u_2P_2$.

When Z chooses to sell counterfeit food to consumers due to pursuit of higher profit, the expected sales cost is C_{11}, where obviously, $C_{11}<C_8$. In this case, Z does not inspect the quality of food it sells or the raw materials produced by Y. Assuming that the government inspects the quality of food sold by Z with probability of n_3, and imposes an expected financial penalty of M_3 on Z when fraud is found. In other words, Z receives a financial penalty of n_3M_3 from the government. Consumers protect their legitimate interests by reporting when they purchase counterfeit food from Z. Assuming that the probability of consumer reporting is u_3, and Z pays a financial compensation of P_3 to consumers in accordance with the law. In other words, Z pays financial compensation of u_3P_3 to consumers. Therefore, the expected profit for Z is $R_3–C_{11}$-n_3M_3-u_3P_3 when selling counterfeit food.

Hypothesis 4. Fitness ζ_j is the degree of adaptation of safe or counterfeit production and sales strategies among companies in the same group. Companies tend to choose strategies with higher fitness. Assuming that the fitness ζ_j of committing fraud among companies in the X, Y, and Z groups is positively correlated with the expected economic return E_j of committing fraud, i.e., $\forall j \in \{X,Y,Z\}$; and that the functional relationship $\zeta_j(E) = 1\text{-}w_i + w_iE_j$ ($w_i \in (0,1)$, which indicates how strongly X, Y, and Z emulate the fraudulent behavior of companies in the same group), is satisfied.

On the basis of the research hypothesis in Table 1 above and the game relationship among X,Y, and Z, the payoff matrix of the tripartite game is developed as shown in Table 2.

4. Model calculation and analysis of evolutionary routes

This section will solve the replicated dynamic equations of X, Y, and Z, respectively, based on the payoff matrix in Table 2. It will also analyze the stability strategy of each participant using the theory of differential equations.

4.1. Replicated dynamic equation of tripartite behavioral strategy selection

Assuming that E_{x1}, E_{x2}, and E_x represent the expected returns for the production of safe raw materials and counterfeit raw materials, and the average expected economic returns of X, respectively. Expressions (1) to (3) can be derived from the payment matrix in Table 2.

$$Ex1 = yz(R_1 - C1 - C2) + y(1 - z)(R1 - C1 - C2) + (1 - y)z(R1 - C1 - C2) + (1 - y)(1 - z)(R1 - C1 - C2) \quad (1)$$

$$E_{x2} = yz(R_1 - C_3 - n_1M_1 - u_1P_1) + y(1 - z)(R_1 - C_3 - n_1M_1 - u_1P_1) + (1 - y)z(R_1 - C_3 - n_1M_1) + (1 - y)(1 - z)(R_1 - C_3 - n_1M_1) \quad (2)$$

$$E_x = xE_{x1} + (1 - x)E_{x2} \quad (3)$$

Assuming that E_{y1}, E_{y2}, and E_y represent the expected returns for the production of safe food and counterfeit food, and the average expected economic returns of Y, respectively. Expressions (4) to (6) can be derived from the payment matrix in Table 2.

$$E_{y1} = xz(R_2 - C_4 - C_5 - C_6) + x(1 - z)(R_2 - C_4 - C_5 - C_6) + (1 - x)z(R_2 - C_4 - 2C_5 - C_6 + u_1P_1) + (1 - x)(1 - z)(R_2 - C_4 - 2C_5 - C_6 + u_1P_1) \quad (4)$$

$$E_{y2} = xz(R_2 - C_7 - n_2M_2 - u_2P_2) + x(1 - z)(R_2 - C_7 - n_2M_2) + (1 - x)z(R_2 - C_7 - n_2M_2 - u_2P_2) + (1 - x)(1 - z)(R_2 - C_7 - n_2M_2) \quad (5)$$

$$E_y = yE_{y1} + (1 - y)E_{y2} \quad (6)$$

Table 1
Parameters and descriptions.

Symbol of parameters	Meanings and descriptions
C_1	Expected production costs by X from production of safe raw materials
C_2	Expected costs of self-inspection by X
C_3	Expected production costs by X from production of counterfeit raw materials
C_4	Expected production costs by Y from production of safe food
C_5	Expected costs of test by Y of raw materials produced by X
C_6	Expected costs of self-inspection by Y
C_7	Expected production costs by Y from production of counterfeit food
C_8	Expected sales costs by Z from sales of safe food
C_9	Expected costs of test by Z of food produced by Y
C_{10}	Expected costs of self-inspection by Z
C_{11}	Expected sales costs by Z from sales of counterfeit food
n_1	Probability of government regulatory department's random inspection of X
n_2	Probability of government regulatory department's random inspection of Y
n_3	Probability of government regulatory department's random inspection of Z
M_1	Economic penalty imposed by government regulatory department on X
M_2	Economic penalty imposed by government regulatory department on Y
M_3	Economic penalty imposed by government regulatory department on Z
R_1	Expected economic benefits by X from production of raw materials
R_2	Expected economic benefits by X from production of food
R_3	Expected economic benefits by X from sales of food
u_1	Probability of Y inspecting X
u_2	Probability of Z inspecting Y
u_3	Probability of reporting by consumers
P_1	Economic compensation payed by X to Y for breaking a contract
P_2	Economic compensation payed by Y to Z for breaking a contract
P_3	Economic compensation payed by Z to consumers for selling counterfeit food
w_i, i∈{1,2,3}	Intensity of X,Y,and Z imitating the fraud behavior of similar enterprises
ζ_j, j∈{X,Y,Z}	Behavioral strategy fitness of X,Y,and Z
x	Probability of X producing safe raw materials
y	Probability of Y producing safe food
z	Probability of Z selling safe food

Table 2
Payoff matrix of tripartite game.

		Production enterprises	Distributing business	
			Selling safe food (z)	Selling counterfeit food (1-z)
Raw material producers	Producing safe raw materials *(x)*	Producing safe food *(y)*	$R_1–C_1-C_2$, $R_2–C_4-C_5-C_6$,$R_3–C_8-C_9-C_{10}$	$R_1–C_1-C_2$, $R_2–C_4-C_5-C_6$,$R_3–C_{11}-n_3M_3-u_3P_3$
		Producing counterfeit food (1-y)	$R_1–C_1-C_2$, $R_2–C_7-n_2M_2-u_2P_2$,$R_3–C_8-2C_9–C_{10}+u_2P_2$	$R_1–C_1-C_2$,$R_2–C_7-n_2M_2$,$R_3–C_{11}-n_3M_3-u_3P_3$
	Producing counterfeit raw materials (1-x)	Producing safe food *(y)*	$R_1–C_3-n_1M_1-u_1P_1$, $R_2–C_4-2C_5–C_6+u_1P_1$,$R_3–C_8-C_9-C_{10}$	$R_1–C_3-n_1M_1-u_1P_1$, $R_2–C_4-2C_5–C_6+u_1P_1R_3–C_{11}-n_3M_3-u_3P_3$
		Producing counterfeit food (1-y)	$R_1–C_3-n_1M_1$, $R_2–C_7-n_2M_2-u_2P_2$, $R_3–C_8-2C_9–C_{10}+u_2P_2$	$R_1–C_3-n_1M_1$,$R_2–C_7-n_2M_2$,$R_3–C_{11}-n_3M_3-u_3P_3$

Assuming that E_{z1}, E_{z2}, and E_z represent the expected returns for the sales of safe food and counterfeit food and average expected economic returns of Z, respectively. Expressions (7) to (9) can be derived from the payment matrix in Table 2.

$$E_{z1} = xy(R_3 - C_8 - C_9 - C_{10}) + x(1-y)(R_3 - C_8 - 2C_9 - C_{10} + u_2P_2) +$$
$$(1-x)y(R_3 - C_8 - C_9 - C_{10}) + (1-x)(1-y)(R_3 - C_8 - 2C_9 - C_{10} + u_2P_2) \tag{7}$$

$$E_{z2} = xy(R_3 - C_{11} - n_3M_3 - u_3P_3) + x(1-y)(R_3 - C_{11} - n_3M_3 - u_3P_3) + (1-x)y(R_3 - C_{11} - n_3M_3 - u_3P_3) + (1-x)(1-y)(R_3 - C_{11} - n_3M_3 - u_3P_3) \tag{8}$$

$$E_z = zE_{z1} + (1-z)E_{z2} \tag{9}$$

4.2. Evolutionary game model in which companies in the same group emulate each other's fraudulent behavior

Taking the X group as an example, $\zeta_x(E_{x1}) = 1\text{-}w_1+w_1E_{x1}$, $\zeta_x(E_{x2}) = 1\text{-}w_1+w_1E_{x2}$, and $\zeta_x(E_x) = 1\text{-}w_1+w_1E_x$ represent the fitness of safe and counterfeit production and the average fitness among companies in this group, respectively. The growth rate of the number of companies in the X group that choose safe production is equal to the difference between the fitness of safe production and the average fitness. When the growth rate of the number of companies choosing safe production is negative, that is, when $\zeta_x(E_{x1})\text{-}\zeta_x(E_x) < 0$, counterfeit production has a higher fitness in the X group. In other words, X who chooses counterfeit production would continue to choose to produce counterfeit raw materials, while X who chooses safe production would begin to emulate counterfeit production. According to evolutionary game theory, the replication dynamic equation shown in Equation (10) can be derived from Equations (1)–(3).

$$F(x) = dx/dt = [\zeta_x(E_{x1}) - \zeta_x(E_x)]x = w_1(E_{x1} - E_x)x$$
$$= w_1x(1-x)(E_{x1} - E_{x2}) = w_1x(1-x)(yu_1P_1 + n_1M_1 + C_3 - C_1 - C_2) \tag{10}$$

Similarly, the replication dynamic equation shown in Equation (11) can be derived from Equations (4)–(6).

$$F(y) = dy/dt = [\zeta_y(E_{y1}) - \zeta_y(E_y)]y = w_2(E_{y1} - E_y)y$$
$$= w_2y(1-y)(E_{y1} - E_{y2}) = w_2y(1-y)[(u_1P_1 - C_5)(1-x) + n_2M_2 + zu_2P_2 + C_7 - C_4 - C_5 - C_6] \tag{11}$$

In the same way, the replicon dynamic equation shown in Equation (12) can be derived from Equations (7)–(9).

$$Fz = dz/dt = [\zeta_z(E_{z1}) - \zeta_z(E_z)]z = w_3(E_{z1} - E_z)z$$
$$= w_3z(1-z)(E_{z1} - E_{z2}) = w_3z(1-z) = [(u_2P_2 - C_9)(1-y) + n_3M_3 + u_3P_3 + C_{11} - C_8 - C_9 - C_{10}] \tag{12}$$

On the basis of the above three replicated dynamic sub-equations, namely Equations (10)–(12), the tripartite replicated dynamic equation shown in Equation (13) is generated.

$$\begin{cases} F(x) = w_1x(1-x)(yu_1P_1 + n_1M_1 + C_3 - C_1 - C_2) \\ F(x) = w_2y(1-y)[(u_1P_1 - C_5)(1-x) + n_2M_2 + zu_2P_2 + C_7 - C_4 - C_5 - C_6] \\ F(z) = w_3z(1-z)[(u_2P_2 - C_9)(1-y) + n_3M_3 + u_3P_3 + C_{11} - C_8 - C_9 - C_{10}] \end{cases} \tag{13}$$

4.3. Analysis of evolutionary route

From Equation (13), the probability of X, Y, and Z choosing safe behavioral strategies is represented by x(t), y(t), and z(t) respectively, and it changes over time. Their stability strategies and equilibrium points can be analyzed using the stability theory of differential equations.

According to the stability theory of differential equations, when the following formula is established: $y = y^* = (C_1 + C_2 - C_3 - n_1M_1)/u_1P_1$, then $E_{x1} - E_{x2} = 0$. The dynamic equation will be satisfied: $F(x) = 0$ and every X is in evolutionary stability.

When E_{x1}-$E_{x2} \neq 0$, $x = 0$ and $x = 1$ can be obtained from $F(x) = 0$, which means that there may be two equilibrium points.Solving the partial derivative of the replication dynamic Equation (10), and we can obtain the following Equation (14):

$$d(F(x)) / dx = w_1(1 - 2x)(E_{x1} - E_{x2}) \tag{14}$$

Proposition 1. *According to formula (14), if E_{x1}-$E_{x2} < 0$, then $y < y^*$, and we can get further $d(F(x))/dx|_{x=0} < 0$ and $d(F(x))/dx|_{x=1} > 0$. At this time, $x = 0$ is the evolutionary stability strategy, that is, X chooses to produce counterfeit raw materials.*

Proposition 2. *Similarly, if $E_{x1} - E_{x2} > 0$, then $y > y^*$, and we can get further $d(F(x))/dx|_{x=0} > 0$ and $d(F(x))/dx|_{x=1} < 0$. In this case, $x=1$ is the evolutionary stability strategy, that is, X chooses to produce safe raw materials. The phase diagrams of the strategy evolution of X are shown in Fig. 3, where the arrow indicates the direction of evolution of X toward $x=0$ or $x=1$.*

According to the stability theory of differential equations, when the following formula is established: $z = z^* = [C_4 + C_5 + C_6 - C_7 + (x - 1)(u_1P_1 - C_5) - n_2M_2]/u_2P_2$, then $E_{y1} - E_{y2} = 0$. The dynamic equation will be satisfied: $F(y) = 0$ and every Y is in evolutionary stability.

When $E_{y1} - E_{y2} \neq 0$, $y = 0$ and $y = 1$ can be obtained from $F(y) = 0$, which means that there may be two equilibrium points. Solving the partial derivative of the replication dynamic equation (10), *and we can obtain the following* equation (15):

$$d(F(y)) / dy = w_2(1 - 2y)(E_{y1} - E_{y2}) \tag{15}$$

Proposition 3. *According to formula (15), if $E_{y1} - E_{y2} < 0$, then $z < z^*$, and we can get further $d(F(y))/dy|_{y=0} < 0$ and $d(F(y))/dy|_{y=1} > 0$. At this time, $y=0$ is the evolutionary stability strategy, that is, Y chooses to produce counterfeit food.*

Proposition 4. *In the same way, if $E_{y1} - E_{y2} > 0$, then $z > z^*$, and we can get further $d(F(y))/dy|_{y=0} > 0$ and $d(F(y))/dy|_{y=1} < 0$. In this case, $y=1$ is the evolutionary stability strategy, that is, Y chooses to produce safe food. The phase diagrams of the strategy evolution of Y are shown in Fig. 4, where the arrow indicates the direction of evolution of Y toward $y=0$ or $y=1$.*

According to the stability theory of differential equations, when the following formula is established: $y = y^* = 1 - (C_8 + C_9 + C_{10} - C_{11} - u_3P_3 - n_3M_3)/(u_2P_2 - C_9)$, then $E_{z1} - E_{z2} = 0$. The dynamic equation will be satisfied: $F(z)=0$ and every Z is in evolutionary stability.

When $E_{z1} - E_{z2} \neq 0$, $z=0$ and $z=1$ can be obtained from $F(z)=0$, which means that there may be two equilibrium points. Solving the partial derivative of the replication dynamic equation (10), *and we can obtain the following* equation (16):

$$d(F(z)) / dz = w_3(1 - 2z)(E_{z1} - E_{z2}) \tag{16}$$

Proposition 5. *According to formula (16), if $E_{z1} - E_{z2} < 0$, then $y > y^*$, and we can get further $d(F(z))/dz|_{z=0} < 0$ and $d(F(z))/dz|_{z=1} > 0$. At this time, $z=0$ is the evolutionary stability strategy, that is, Z chooses to sell counterfeit food.*

Proposition 6. *Similarly, if $E_{z1} - E_{z2} > 0$, then $y < y^*$, and we can get further $d(F(z))/dz|_{z=0} > 0$ and $d(F(z))/dz|_{z=1} < 0$. In this case, $z=1$ is the evolutionary stability strategy, that is, Z chooses to sell safe food. The phase diagrams of the strategy evolution of Z are shown in Fig. 5, where the arrow indicates the direction of evolution of Z toward $z=0$ or $z=1$.*

4.4. Analysis of stability of evolutionary game equilibrium points

If $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$ in the replicated dynamic Equation (13), then there are eight equilibrium points in the three-

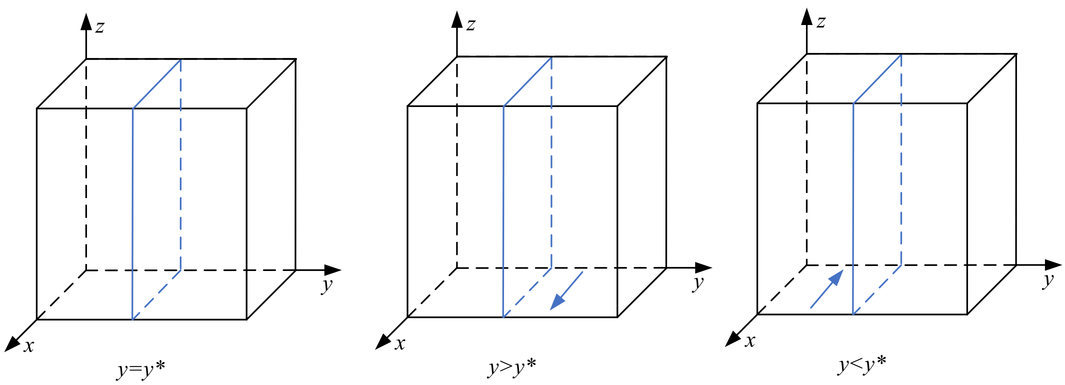

Fig. 3. *Evolutionary phase diagram of X behavioral strategies.*

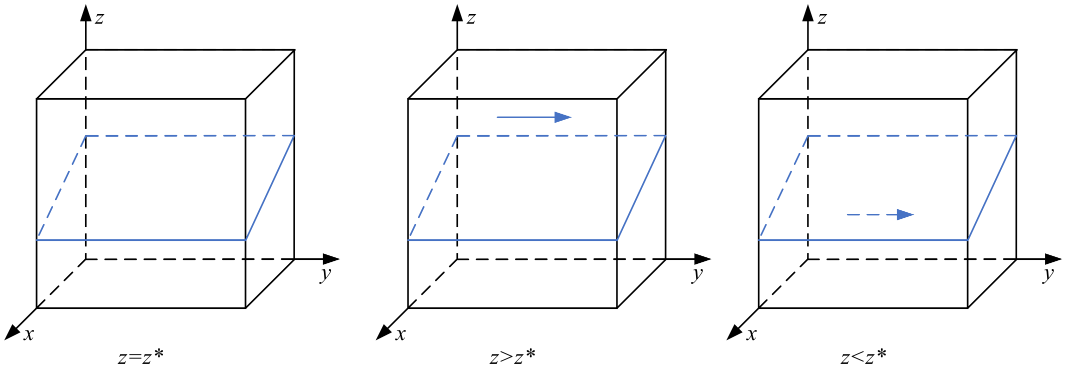

Fig. 4. *Evolutionary phase diagram of Y behavioral strategies.*

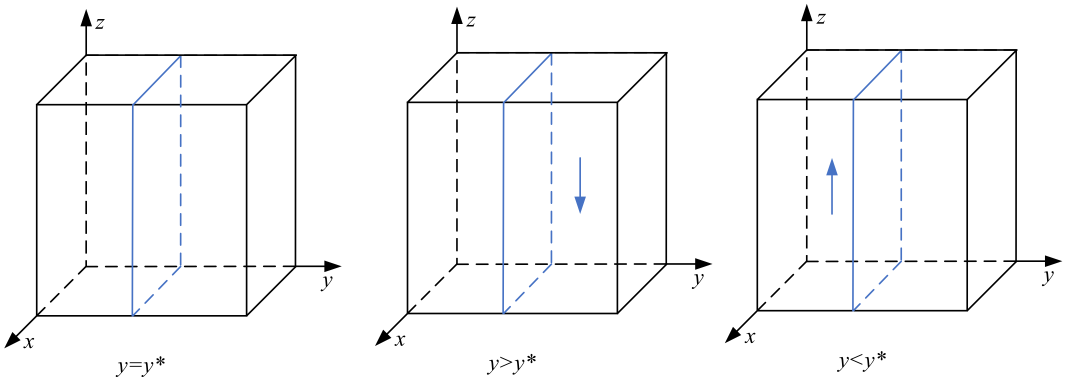

Fig. 5. *Evolutionary phase diagram of Z behavioral strategies.*

Table 3
System equilibrium point eigenvalues and progressive stability conditions.

Equilibrium points	λ			Stability conditions
	λ_{i1}	λ_{i2}	λ_{i3}	
$E_1(0,0,0)$	$w_1\begin{pmatrix} n_1M_1+C_3 \\ -C_1-C_2 \end{pmatrix}$	$w_2\begin{pmatrix} u_1P_1+n_2M_2+C_7 \\ -C_4-2C_5-C_6 \end{pmatrix}$	$w_3\begin{pmatrix} u_2P_2+n_3M_3+ \\ u_3P_3+C_{11}-C_8 \\ -2C_9-C_{10} \end{pmatrix}$	(1)
$E_2(0,0,1)$	$w_1\begin{pmatrix} n_1M_1+C_3 \\ -C_1-C_2 \end{pmatrix}$	$w_2\begin{pmatrix} u_1P_1+n_2M_2+u_2P_2 \\ +C_7-C_4-2C_5-C_6 \end{pmatrix}$	$-w_3\begin{pmatrix} u_2P_2+n_3M_3+ \\ u_3P_3+C_{11}-C_8 \\ -2C_9-C_{10} \end{pmatrix}$	(2)
$E_3(0,1,0)$	$w_1\begin{pmatrix} u_1P_1+n_1M_1 \\ +C_3-C_1-C_2 \end{pmatrix}$	$-w_2\begin{pmatrix} u_1P_1+n_2M_2+C_7 \\ -C_4-2C_5-C_6 \end{pmatrix}$	$w_3\begin{pmatrix} n_3M_3+u_3P_3 \\ +C_{11}-C_8 \\ -C_9-C_{10} \end{pmatrix}$	(3)
$E_4(1,0,0)$	$-w_1\begin{pmatrix} n_1M_1+C_3 \\ -C_1-C_2 \end{pmatrix}$	$w_2\begin{pmatrix} n_2M_2+C_7 \\ -C_4-C_5-C_6 \end{pmatrix}$	$w_3\begin{pmatrix} u_2P_2+n_3M_3+ \\ u_3P_3+C_{11}-C_8 \\ -2C_9-C_{10} \end{pmatrix}$	(4)
$E_5(1,1,0)$	$-w_1\begin{pmatrix} u_1P_1+n_1M_1 \\ +C_3-C_1-C_2 \end{pmatrix}$	$-w_2\begin{pmatrix} n_2M_2+C_7 \\ -C_4-C_5-C_6 \end{pmatrix}$	$w_3\begin{pmatrix} n_3M_3+u_3P_3 \\ +C_{11}-C_8 \\ -C_9-C_{10} \end{pmatrix}$	(5)
$E_6(1,0,1)$	$-w_1\begin{pmatrix} n_1M_1+C_3 \\ -C_1-C_2 \end{pmatrix}$	$w_2\begin{pmatrix} n_2M_2+C_7 \\ -C_4-C_5-C_6 \end{pmatrix}$	$-w_3\begin{pmatrix} u_2P_2+n_3M_3+ \\ u_3P_3+C_{11}-C_8 \\ -2C_9-C_{10} \end{pmatrix}$	(6)
$E_7(0,1,1)$	$w_1\begin{pmatrix} u_1P_1+n_1M_1 \\ +C_3-C_1-C_2 \end{pmatrix}$	$-w_2\begin{pmatrix} u_1P_1+n_2M_2+u_2P_2 \\ +C_7-C_4-2C_5-C_6 \end{pmatrix}$	$-w_3\begin{pmatrix} n_3M_3+u_3P_3 \\ +C_{11}-C_8 \\ -C_9-C_{10} \end{pmatrix}$	(7)
$E_8(1,1,1)$	$-w_1\begin{pmatrix} u_1P_1+n_1M_1 \\ +C_3-C_1-C_2 \end{pmatrix}$	$-w_2\begin{pmatrix} n_2M_2+u_2P_2+C_7 \\ -C_4-C_5-C_6 \end{pmatrix}$	$-w_3\begin{pmatrix} n_3M_3+u_3P_3 \\ +C_{11}-C_8 \\ -C_9-C_{10} \end{pmatrix}$	(8)
Condition (i): $\lambda_{i1},\lambda_{i2}\lambda_{i3}<0$				

dimensional (3D) space $K = \{(x, y, z) | 0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1\}$: E1(0,0,0), E2(0,0,1), E3(0,1,0), E4(1,0,0), E5(1,1,0), E6(1,0,1), E7(0,1,1), and E_8(1,1,1). In order to analyze the progressive stability of the equilibrium points, the Jacobi matrix and its eigenvalues can be calculated according to the following Equation (17).

$$J = \begin{bmatrix} \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z \\ \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z \\ \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

$$= \begin{bmatrix} w_1(1-2x)(yu_1P_1 + n_1M_1 + C_3 - C_1 - C_2) & w_1x(1-x)u_1P_1 & 0 \\ -w_2y(1-y)(u_1P_1 - C_5) & w_2(1-2y)\begin{bmatrix} (u_1P_1 - C_5)(1-x) + n_2M_2 \\ +zu_2P_2 + C_7 - C_4 - C_5 - 6 \end{bmatrix} & w_2y(1-y)u_2P_2 \\ 0 & -w_3z(1-z)(u_2P_2 - C_9) & w_3(1-2z)\begin{bmatrix} (u_2P_2 - C_9)(1-y) + n_3M_3 \\ +u_3P_3 + C_{11} - C_8 - C_9 - C_{10} \end{bmatrix} \end{bmatrix} \quad (17)$$

Based on the stability theory of Lyapunov [78–80], the equilibrium points are asymptotically stable when all the eigenvalues (λ) of the Jacobian matrix are less than zero, as shown in Table 3.

5. Verification analysis of the stability conditions of the system equilibrium points

According to the number of groups committing fraud in the food supply chain and whether companies in the same group emulate each other's fraudulent behavior, the eight equilibrium points are divided into four scenarios: In Scenario I, no company in the food supply chain commits fraud (and hence there is no emulation of fraud). In Scenarios II, III, and IV, one, two, or all three of the X, Y and Z groups commit fraud, respectively, and companies in the same group emulate each other's fraudulent behavior. Specifically, E_8 (1,1,1) corresponds to Scenario I; E_5 (1,1,0), E_6 (1,0,1), and E_7(0,1,1) correspond to Scenario II; E_2 (0,0,1), E_3 (0,1,0), and E_4 (1,0,0) correspond to Scenario III; E_1 (0,0,0) corresponds to Scenario IV. Based on the research hypothesis above and Table 3, we established the parameter values for each equilibrium point as shown in Table 4 and conducted a numerical simulation for each equilibrium point.

The evolution paths of the three-party game among X, Y, and Z were numerically simulated using MATLAB to analyze the impact of relevant parameters on the evolution paths. The minimum discrete time interval for calculating the values for each variable for every iteration during the simulation, that is, the time step, affects the simulation accuracy and calculation efficiency, and ultimately the evolution path of the asymptotic stability strategy. Therefore, according to the replicator dynamic Equation (13), the time step is

Table 4
Equilibrium points and assignment for every parameter.

Parameters	Equilibrium points							
	E_1(0,0,0)	E_2(0,0,1)	E_3(0,1,0)	E_4(1,0,0)	E_5(1,1,0)	E_6(1,0,1)	E_7(0,1,1)	E_8(1,1,1)
Scenarios	IV	III	III	III	II	II	II	I
w_1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
w_2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
w_3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
u_1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
u_2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
u_3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
n_1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
n_2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
n_3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
C_1	4	4	5	3	5	4	4	6
C_2	2	2	2	2	2	2	2	2
C_3	1	1	1	1	1	1	1	1
C_4	2	3	1	3	1	3	3	5
C_5	2	2	2	2	2	2	2	2
C_6	2	2	2	2	2	2	2	2
C_7	1	1	1	1	1	1	1	1
C_8	6	4	6	6	7	4	4	7
C_9	2	2	2	2	2	2	2	2
C_{10}	1	1	1	1	1	1	1	1
C_{11}	1	1	1	1	1	1	1	1
P_1	5	4	4	3	3	3	3	8
P_2	4	4	5	5	6	4	7	8
P_3	5	10	6	6	7	8	8	10
M_1	6	6	4	12	12	12	5	10
M_2	6	5	10	5	12	6	10	10
M_3	5	8	7	6	7	10	12	12

expressed as Δt, and the three-party dynamic game evolution system is expressed as follows

$$\begin{cases} \dfrac{dx(t)}{dt} \approx \dfrac{x(t+\Delta t)-x(t)}{\Delta t} = w_1 x(1-x)(yu_1P_1 + n_1M_1 + C_3 - C_1 - C_2) \\ \dfrac{dy(t)}{dt} \approx \dfrac{y(t+\Delta t)-y(t)}{\Delta t} = w_2 y(1-y)[(u_1P_1 - C_5)(1-x) + n_2M_2 + zu_2P_2 + C_7 - C_4 - C_5 - C_6] \\ \dfrac{dz(t)}{dt} \approx \dfrac{z(t+\Delta t)-z(t)}{\Delta t} = w_3 z(1-z)[(u_2P_2 - C_9)(1-y) + n_3M_3 + u_3P_3 + C_{11} - C_8 - C_9 - C_{10}] \end{cases} \tag{18}$$

Furthermore, letting the time step in Equation (18) to be $\Delta t = 1$, the following findings shown in Equation (19) can be derived from the three-party system expression:

$$\begin{cases} x(t+1) = x(t)(2-x(t))w_1(y(t)u_1P_1 + n_1M_1 + C_3 - C_1 - C_2) \\ y(t+1) = y(t)(2-y(t))w_2\left[(u_1P_1 - C_5)(1-x(t)) + n_2M_2 + z(t)u_2P_2 + C_7 - C_4 - C_5 - C_6\right] \\ z(t+1) = z(t)(2-z(t))w_3[(u_2P_2 - C_9)(1-y(t)) + n_3M_3 + u_3P_3 + C_{11} - C_8 - C_9 - C_{10}] \end{cases} \tag{19}$$

Scenario I: Here, no group of companies commits fraud, and no emulation of fraud among companies in the same group. Because all the parameters set in Table 4 satisfy condition (8) in Table 3, the initial intentions of X, Y, and Z may be set at (0.4,0.5,0.6), (0.5,0.7,0.8), and (0.7,0.8,0.9), respectively, which indicates the selection of a behavioral strategy by X, Y, and Z under different initial intentions. The results of the simulation shown in Fig. 6(a)–6(d) indicate that under the three initial intentions, the strategies of X, Y, and Z all evolve into E_8 (1,1,1), which means {producing safe raw materials, producing safe food, selling safe food}. This suggests that

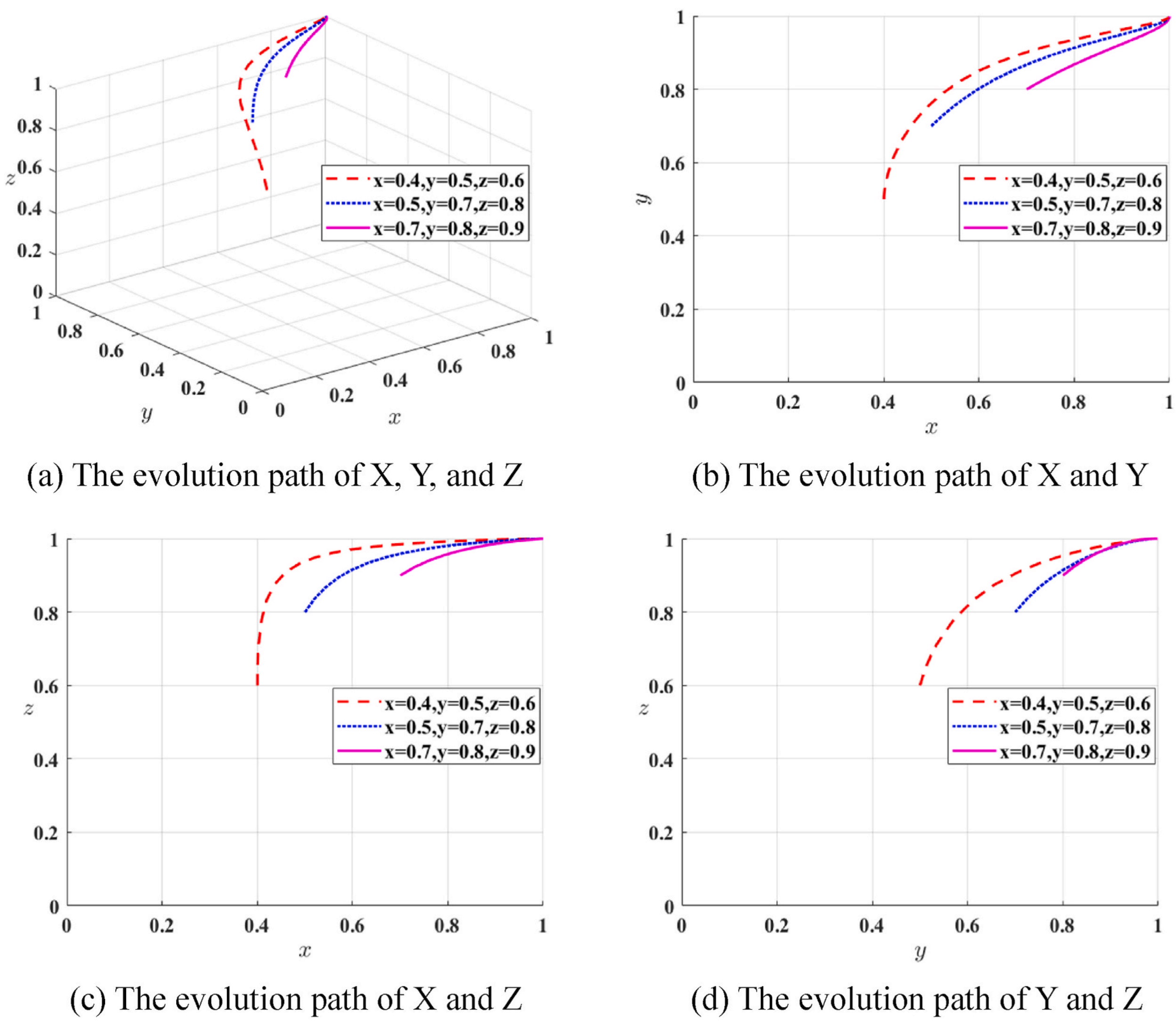

Fig. 6. Equilibrium point E_8 (1,1,1) stability test and evolution path of each participant.

the system's evolution to a stable state where no group of companies commit fraud and no emulation of fraud emerges among companies in the same group is not related to the initial willingness of each individual actor to choose a safe strategy and not commit food fraud. Rather, initial willingness only affects the time when the system reaches the equilibrium point. In other words, the higher the initial willingness, the shorter the time for the system to evolve to a stable state. According to the hypotheses, when X, Y, and Z expect higher returns from choosing to commit fraud than that from choosing a safe strategy, they would have the initial motivation to commit fraud. According to condition (8), $u_1P_1 + n_1M_1 > C_1 + C_2 - C_3$, $n_2M_2 + u_2P_2 > C_4+C_5 + C_6 - C_7$, and $n_3M_3 + u_3P_3 > C_8+C_9 + C_{10} - C_{11}$. This indicates that when financial penalties imposed by the government on X, Y, and Z, financial compensation paid by companies for breach of contract, and compensation paid by Z to consumers are large, actors that choose a fraudulent strategy will face economic losses far exceeding the economic costs, which are reduced by this strategy. In this case, companies will choose a safe strategy. In this scenario, the overall safety of the food supply chain and the social co-governance level both reach their highest levels.

Scenario II: One group of companies commits fraud, followed by emulation of fraud among companies in the same group. Because all the parameters set in Table 4 satisfy conditions (5)–(7) in Table 3, the initial intentions of X, Y, and Z may be set at (0.4,0.5,0.6), (0.5,0.7,0.8), and (0.7,0.8,0.9), respectively, which indicates the selections of behavioral strategy by X, Y, and Z under different initial intentions. The results of the simulation shown in Figs. 7–9 indicate that under the different initial intentions, the strategies of X, Y, and Z severally evolve into {producing safe raw materials, producing safe food, selling counterfeit food}, {producing safe raw materials, producing counterfeit food, selling safe food}, {producing counterfeit raw materials, producing safe food, selling safe food}. This scenario suggests that the evolution of the system to a stable state where one group of companies commits fraud with emulation of fraud among companies in the same group is only related to its stability conditions, but not to each actor's initial willingness. However, the higher the initial willingness of a group of companies to choose a safe strategy, the less time it takes to evolve to a stable state of implementing a safe strategy, and the longer it takes to evolve to a stable state of implementing a fraudulent strategy. Using E_5 as an example, condition (5) indicates that when $n_3M_3 + u_3P_3 < C_8+C_9 + C_{10} - C_{11}$, i.e., when government regulation and consumer supervision are insufficient to have a deterrent effect on the sale of counterfeit food by Z, Z reduces costs by selling counterfeit food and obtains higher expected profits, which in turn induces companies in the Z group emulate this fraudulent behavior. Subsequently, although Z relaxes its supervision of Y, increased financial penalties imposed by the government on Y, i.e., $n_2M_2 > C_4+C_5 + C_6 - C_7$, can curb Y's motivation to produce counterfeit food. In this case, the food supply chain system eventually evolves to a state where only the Z group commits fraud, with emulation of fraud among companies in this group. The overall risk of the supply chain and the social co-governance are both at a medium level.

Scenario III: Two groups of companies commit fraud, with emulation of fraud occurring among companies in the same group. Because all the parameters set in Table 4 satisfy conditions (2)–(4) in Table 3, the initial intentions of X, Y, and Z may be set at (0.4,0.5,0.6), (0.5,0.7,0.8), and (0.7,0.8,0.9), respectively, which indicates the selections of behavioral strategy by X, Y, and Z under different initial intentions. The results of the simulation shown in Figs. 10–12 indicate that under the different initial intentions, the strategies of X, Y, and Z severally evolve into {producing counterfeit raw materials, producing counterfeit food, selling safe food}, {producing counterfeit raw materials, producing safe food, selling counterfeit food}, {producing safe raw materials, producing counterfeit food, selling counterfeit food}. This suggests that the evolution of the system to a stable state where two groups of companies commit fraud with emulation of fraud among companies in the same group is not related to the initial willingness of X, Y, or Z. However, the higher the initial willingness of companies to choose a safe strategy, the less time it takes to evolve to a stable state of implementing a safe strategy, and the longer it takes to evolve to a stable state of implementing a fraudulent strategy. Using E_4 as an example, condition (4) indicates that when Z sells counterfeit food and relaxes supervision of Y, if the government does not increase the financial penalties on Y in a timely manner, i.e., $n_2M_2 < C_4+C_5 + C_6 - C_7$, government regulation alone will not have a deterrent effect on counterfeit food production by Y. In this case, both the Y and Z groups choose to commit fraud, with emulation of fraud among companies in the same group. At this point, the overall risk of the food supply chain remains at a high level, and social co-governance is at a low level.

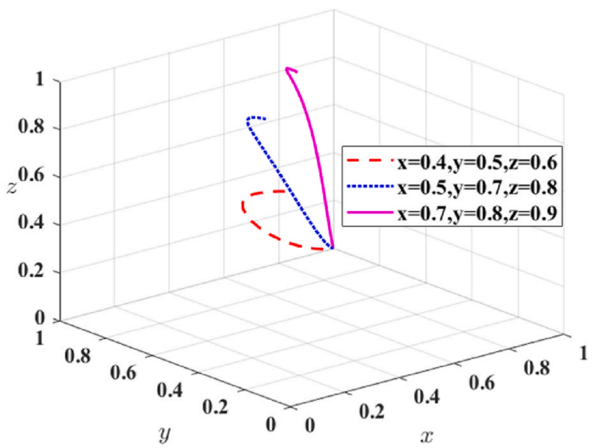

Fig. 7. Equilibrium point E_5 (1,1,0) stability test.

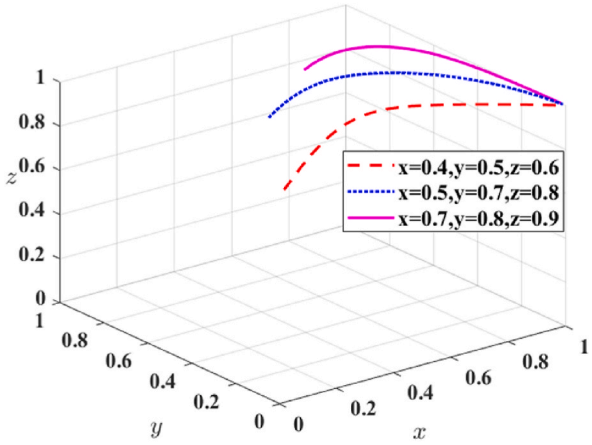

Fig. 8. Equilibrium point E_6 (1,0,1) stability test. (Left).

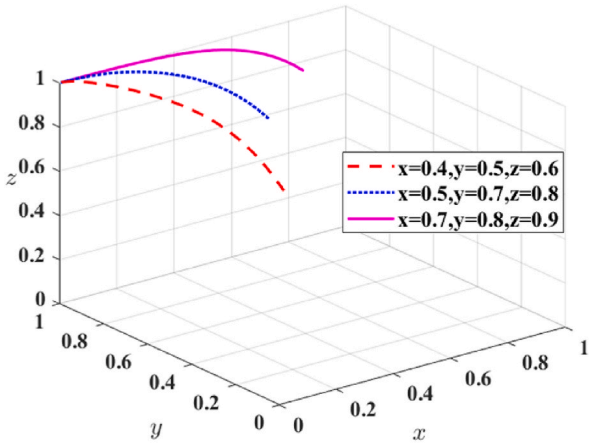

Fig. 9. Equilibrium point E_7 (0,1,1) stability test. (Right).

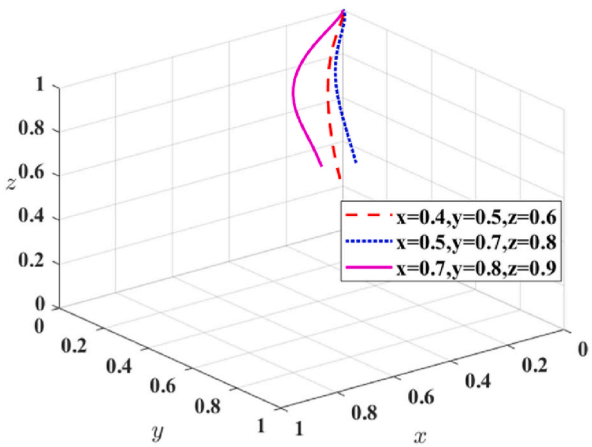

Fig. 10. Equilibrium point E_2 (0,0,1) stability test.

Scenario IV: All three groups of companies commit fraud, with emulation of fraud occurring among companies in the same group, Because all the parameters set in Table 4 satisfy condition (1) in Table 3, the initial intentions of X, Y, and Z may be set at (0.4,0.5,0.6), (0.5,0.7,0.8), and (0.7,0.8,0.9), respectively, which indicates the selections of behavioral strategy by X, Y, and Z under different initial intentions. The results of the simulation shown in Fig. 13(a)–13(d) indicate that under the different initial intentions, the strategies of

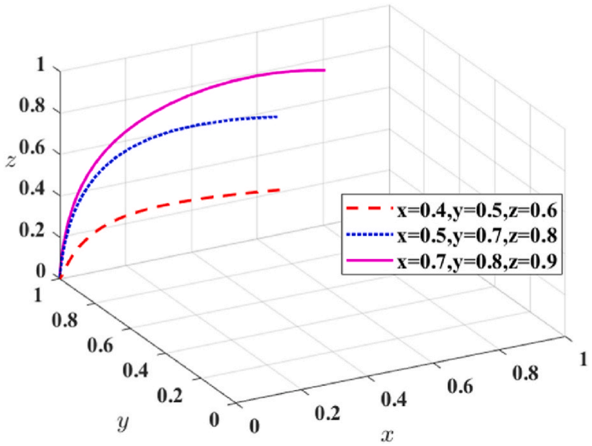

Fig. 11. Equilibrium point E_3 (0,1,0) stability test. (Left).

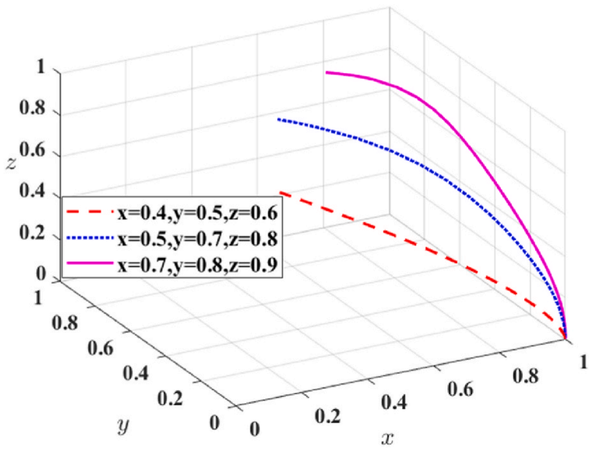

Fig. 12. Equilibrium point E_4 (1,0,0) stability test. (Right).

X, Y, and Z all evolve into {producing counterfeit raw materials, producing counterfeit food, selling counterfeit food}. This suggests that the evolution of the system to a stable state where all three groups of companies commit fraud with emulation of fraud among companies in the same group is again not related to the actors' initial willingness status. A higher initial willingness is associated with a longer time to evolve to a stable state than a lower initial willingness. According to condition (1), $n_1M_1 < C_1+C_2 - C_3$, $n_2M_2 + u_1P_1 < C_4+2C_5 + C_6 - C_7$, and $n_3M_3 + u_3P_3 + u_2P_2 < C_8+2C_9 + C_{10} - C_{11}$. This indicates that when the financial penalties imposed by the government on X, Y, and Z, the financial compensation paid by companies for breach of contract, and the compensation paid by Z to consumers are small, actors that choose a fraudulent strategy will only face small economic losses, which are far lower than reductions in economic costs attained by this strategy. In this case, companies choose a fraudulent strategy with emulation of fraud occurring among companies in the same group. In this scenario, the overall risk of the food supply chain is high, and the social co-governance level is low.

Social co-governance of food safety risk is rich in connotation and has various forms. This study designs a social co-governance system composed of the government, X, Y, Z, and consumers, which perform their respective responsibilities to jointly prevent food fraud based on the common values of ensuring food safety. Thus, E_1(0,0,0), E_2(0,0,1), E_3(0,1,0), E_4(1,0,0), E_5(1,1,0), E_6(1,0,1), E_7(0,1,1), and E_8(1,1,1) are the eight equilibrium points of this social co-governance system composed of the government, X, Y, Z, and consumers. They are the result of the evolution of the actors' behavioral strategies to achieve relative balance. Thus, they represent the system's level of social co-governance in different scenarios. Accordingly, the relation between the system's equilibrium points and the social co-governance level is summarized in Fig. 14. It can be seen that the gradual transition from E_1(0,0,0) to E_8(1,1,1) is in fact an evolutionary process in which X, Y, and Z continue to adjust their behavioral strategies, and the government, companies, and consumers jointly participate in social co-governance to achieve a shift from low to high social co-governance.

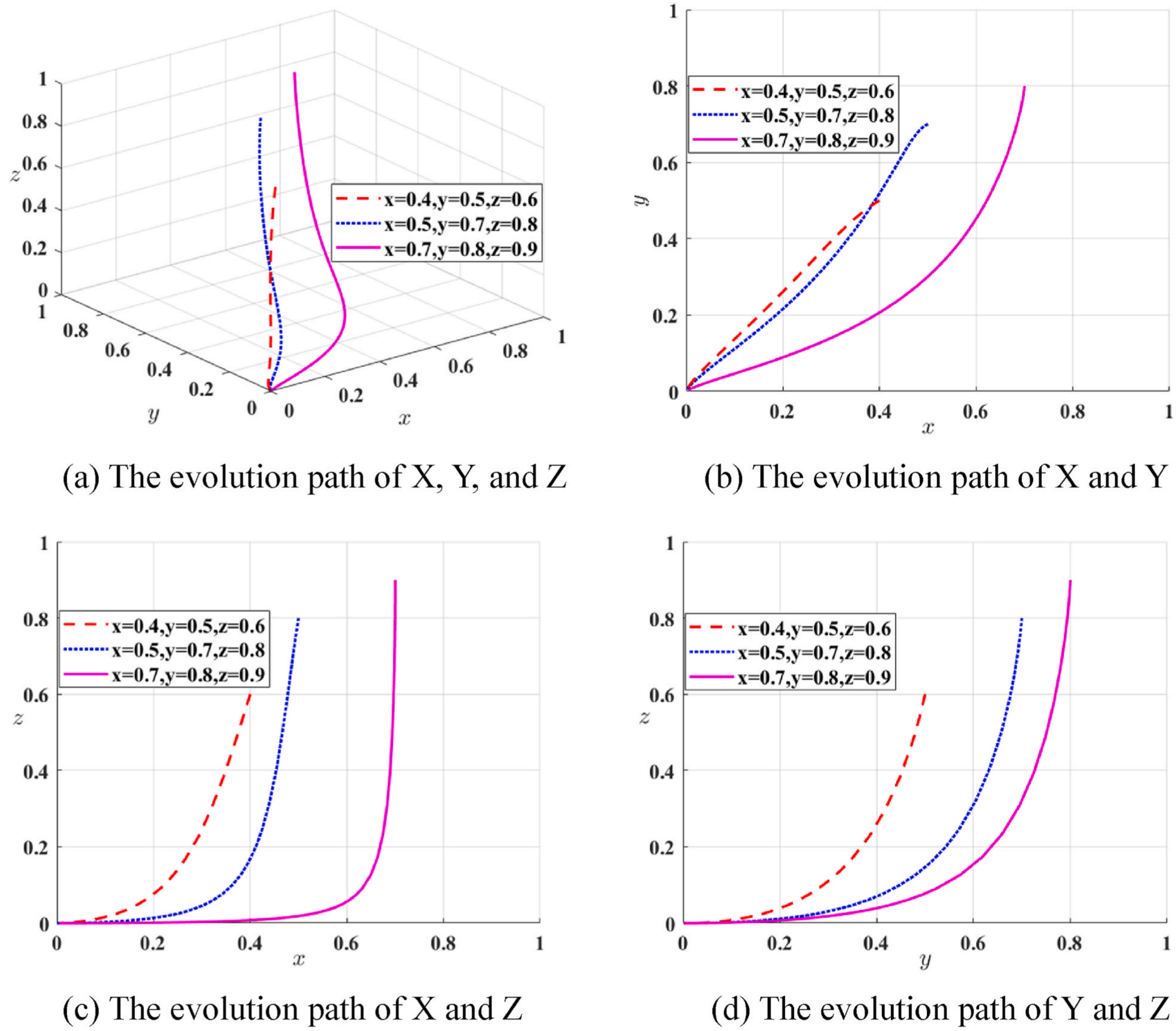

Fig. 13. Equilibrium point E_1 (0,0,0) stability test and evolution path of each participant.

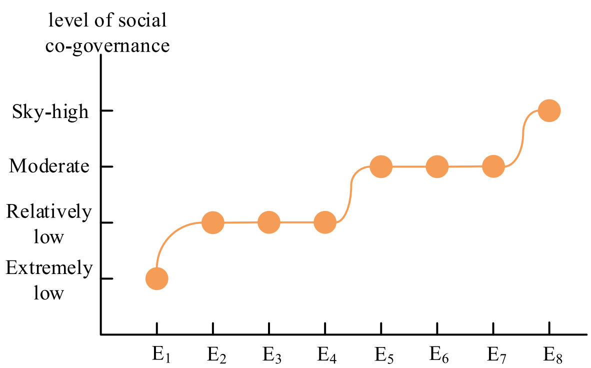

Fig. 14. Schematic diagram of the different equilibrium points and the corresponding social co-governance levels.

6. Effects of government regulation, supervision between companies, and consumer reporting on actors' behavioral strategies

The stability conditions of the equilibrium points in Scenarios I, II, III, and IV were discussed and verified above. The results show that the system's evolution to a stable state does not depend on any actor's initial willingness, but rather is only related to the level of food safety social co-governance involving the government, companies, and consumers. The section proceeds to analyzes how government regulation, supervision between companies, and consumer reporting affect the stability of equilibrium point E_8 and the behavioral strategy choices of each actor. Then, it is discussed how the system can regain the conditions of E_8, and the evolution paths of behavioral strategy choices of X, Y, and Z are revealed, together with shifts between safe or fraudulent strategies and emulation among them.

6.1. Effect of government economic punishment on the choice of subject behavioral strategy

While other parameters remaining unchanged, it is assumed that the economic penalties of government $M_1 = 2,5,8,11$, $M_2 = 1,3,9,12$, $M_3 = 1,3,10,13$. The corresponding evolutionary routes for the strategy selection of every subject are shown in Figs. 15–17. The results reveal that when $M_1 = 2$, $M_2 = 1$, and $M_3 = 1$, X, Y, and Z all choose a fraudulent strategy. As M_i increases, that is, when $M_1 = 5$, $M_2 = 3$, and $M_3 = 3$, X, Y, and Z continue to choose a fraudulent strategy, but it takes them a longer time to do so, i.e., a significantly decreased evolution speed. When M_i further increases to $M_1 = 8$, $M_2 = 9$, and $M_3 = 10$, all the three actors shift their strategy from a fraudulent one to a safe one. When M_i increases to $M_1 = 11$, $M_2 = 12$, and $M_3 = 13$, X, Y, and Z now choose a safe strategy at a significantly increased speed. Thus, it can be seen that a low M_i increases the fitness of the fraudulent strategy among companies in the X, Y, and Z groups, leading them to choose and emulate fraudulent behavior. Increased financial penalties imposed by the government on X, Y, and Z will increase the cost of choosing a fraudulent strategy, and the income of fraud will be reduced accordingly and far less than the safety production and sales behavior, thus curbing their willingness to engage in fraud to gain excess profits.

6.2. Effect of government sampling probability on the choice of subject behavioral strategy

While other parameters remaining unchanged, it is assumed that the sampling probability of government $n_1 = 0.15,0.25,0.45,0.75$, $n_2 = 0.05,0.15,0.55,0.85$, $n_3 = 0.05,0.15,0.45,0.65$. The corresponding evolutionary routes for the strategy selection of every subject are shown in Figs. 18–20.

When $n_1 = 0.15$, $n_2 = 0.05$, and $n_3 = 0.05$, X, Y, and Z all choose a fraudulent strategy. In other words, when n_i is low, they all choose opportunistic behavior to attain higher economic benefits. As n_i increases, that is, when $n_1 = 0.25$, $n_2 = 0.15$, and $n_3 = 0.15$, X, Y, and Z still choose a fraudulent strategy, but at a significantly slower evolution speed. When n_i further increases, that is, when $n_1 = 0.45$, $n_2 = 0.55$, and $n_3 = 0.45$, the equilibrium point evolves from E_1 to E_8. This suggests that an increase of n_i significantly changes the behavioral strategy choices of X, Y, and Z compelling them to abandon the speculative fraudulent strategy and gradually shift to a safe strategy. When n_i increases to $n_1 = 0.75$, $n_2 = 0.85$, and $n_3 = 0.65$, they choose a safe strategy at a significantly increased speed and the interests of the various subjects are balanced.

Further analysis of Figs. 15–20 reveals that the amount of financial penalties and the probability of sampling inspections by the government jointly influence the behavioral strategy choices of X, Y, and Z. In both cases, the government supervision is in the form of inefficient and ineffective supervision. Specifically, a high probability of government sampling inspections cannot replace low penalties. In this case, the higher economic returns X, Y, and Z can earn from choosing a fraudulent strategy are greater than the production or sales costs and economic losses. Therefore, they would continue to choose a fraudulent strategy for higher economic returns. Meanwhile, these higher returns earned through fraud and the apparent ability to not face negative consequences increases the perceived fitness of the fraudulent strategy among companies in the same group which in turn leads to emulation of fraud. Similarly, a low probability of government sampling inspections combined with high penalties will lead companies to continue to choose opportunistic fraudulent behavior due to pursuit of interests and trust in luck.

6.3. Effect of mutual supervision between enterprises on the choice of subject behavioral strategy

While the other parameters are constant, the sampling probability of Y versus X and Z versus Y is set to be $u_1 = 0.1,0.2,0.4,0.7$, $u_2 = 0.2,0.3,0.6,0.8$, respectively. The corresponding evolutionary routes for the strategy selection of every subject are shown in Figs. 21–22. Similarly, on the basis of unchanged other parameters, the economic compensation paid by X default to Y and Y default to Z is further set as $P_1 = 1,3,6,11$, $P_2 = 3,5,9,12$, and the evolution path diagram as shown in Figs. 23 and 24.As can be seen from Figs. 21 and 23, when $u_1 = 0.1$ or $P_1 = 1$, that is, when the probability of sampling inspections by Y on X or the financial compensation paid to Y by X for breach of contract is low, Y does not effectively supervise X, and X chooses to produce counterfeit raw materials. When the probability of sampling inspections by Y on X or the compensation paid to Y by X increases, that is, when $u_1 = 0.2$ or $P_1 = 3$, X will still choose to produce counterfeit raw materials, albeit at a significantly decreased evolution speed. When $u_1 = 0.4$ or $P_1 = 6$, and when $u_1 = 0.7$ or $P_1 = 11$, X shifts from producing counterfeit raw materials to producing safe ones. Moreover, higher probability of sampling inspections by Y on X or greater compensation paid to X by Y leads to X needing less time to evolve to choosing a safe strategy.

At the same time, as found in analyzing Figs. 22 and 24, when the probability of sampling inspections by Z on Y or the compensation paid to Y by Z is low, i.e., when $u_2 = 0.2$ or $P_2 = 3$, Y's behavioral strategy choices show cyclical fluctuations. Moreover, when the

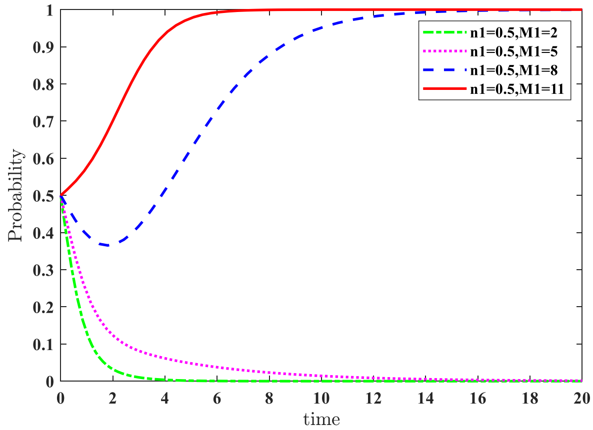

Fig. 15. Influence of M_1 on behavioral strategy of X. (Left).

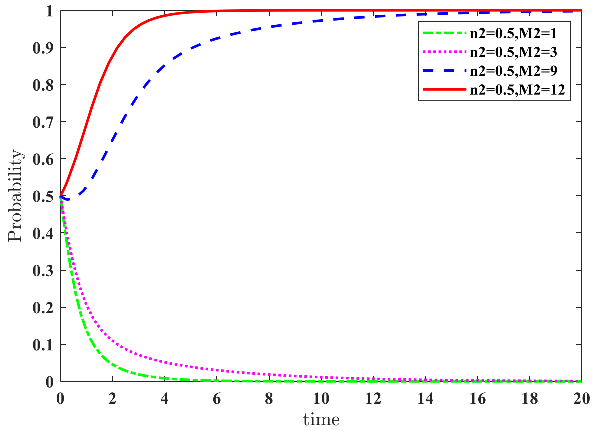

Fig. 16. Influence of M_2 on behavioral strategy of Y. (Right).

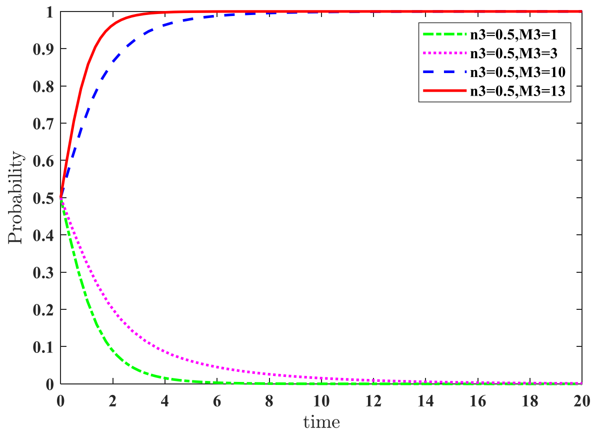

Fig. 17. Influence of M_3 on behavioral strategy of Z.

probability of sampling inspections by Z on Y or the compensation paid to Y by Z increases, i.e., when $u_2 = 0.3$ or $P_2 = 5$, Y's behavioral strategy choices show cyclical fluctuations with a shorter cycle and lower wave height. This suggests that when Y chooses a safe strategy, Y's ability to receive financial compensation from X depends directly on whether X chooses to commit fraud. When Y chooses to commit fraud, although the production costs are reduced, it needs to pay compensation to Z for breach of contract. Therefore, Y constantly adjusts its behavioral strategy choices based on economic benefits, thus causing volatility of strategy choices. When the

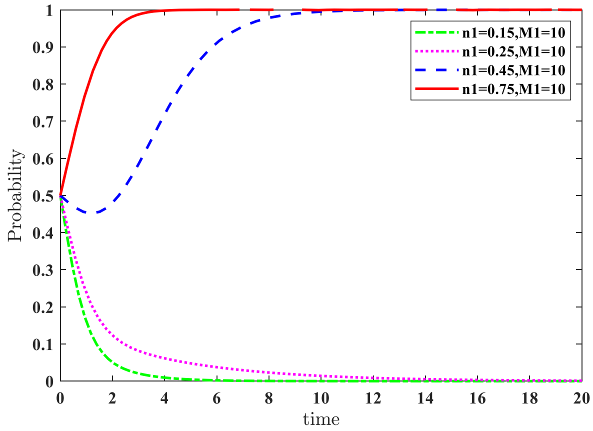

Fig. 18. Influence of n_1 on behavioral strategy of X. (Left).

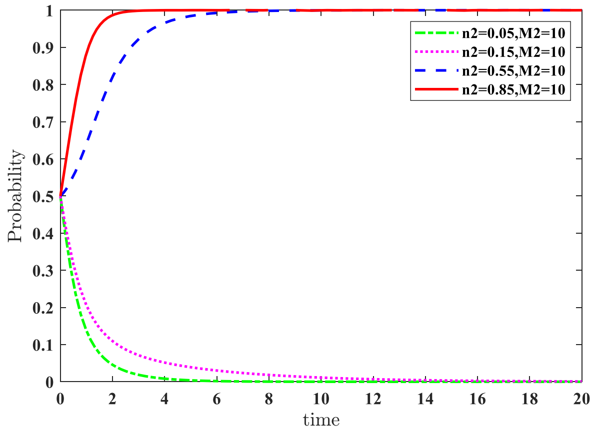

Fig. 19. Influence of n_2 on behavioral strategy of Y. (Right).

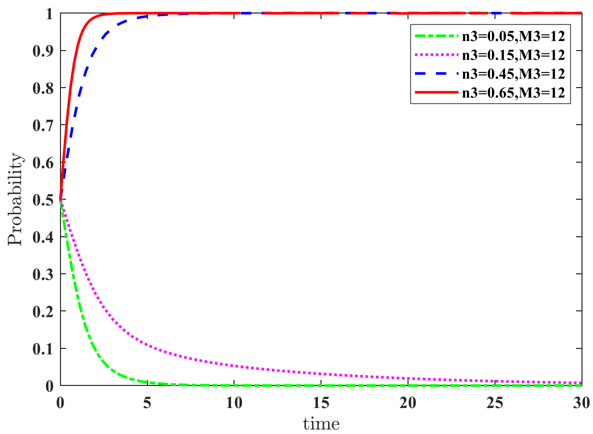

Fig. 20. Influence of n_3 on behavioral strategy of Z.

probability of sampling inspections by Z on Y or the compensation paid to Y by Z further increases, i.e., when $u_2 = 0.8$ or $P_2 = 12$, Y chooses a safe strategy at a significantly faster evolution speed than when $u_2 = 0.6$ or $P_2 = 9$.

Therefore, further combined with Figs. 21–24 we can find that supervision of X by Y and supervision of Y by Z should reach a certain level. Otherwise, X and Y would evolve into choosing a fraudulent strategy with emulation of fraud among companies in the same group. Likewise, Y's behavioral strategy choices would show cyclical changes, and downstream companies would lack the ability to

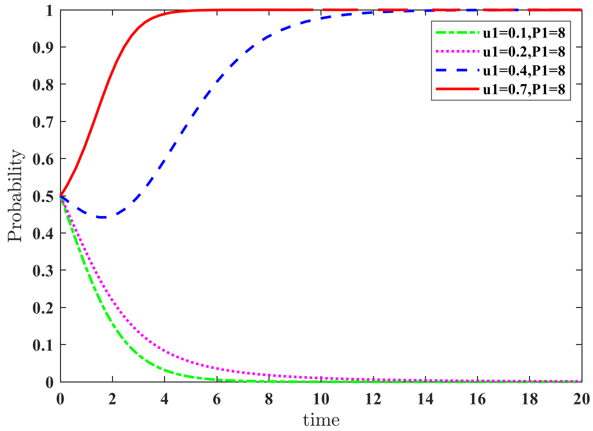

Fig. 21. Influence of u_1 on behavioral strategy of X. (Left).

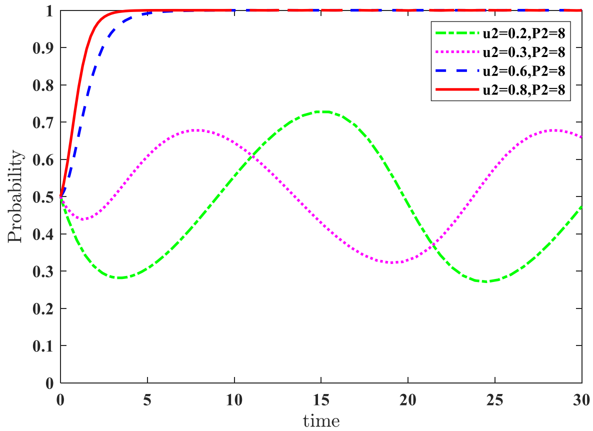

Fig. 22. Influence of u_2 on behavioral strategy of Y. (Right).

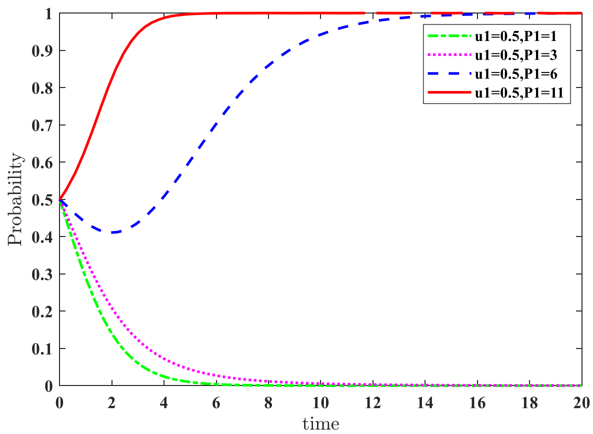

Fig. 23. Influence of P_1 on behavioral strategy of X. (Left).

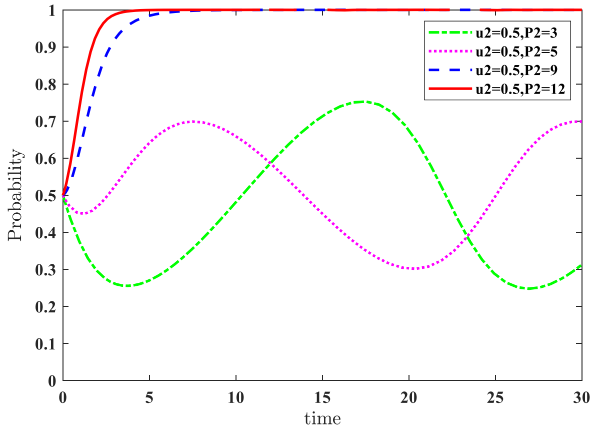

Fig. 24. Influence of P_2 on behavioral strategy of Y. (Right).

effectively supervise upstream ones. At this point, the contract signed between enterprises can not play its role effectively, and the enterprises will choose and imitate the fraud behavior to obtain higher profits.

6.4. *Effect of consumer reports on the behavioral strategy choice of distribution enterprises*

In the case that other parameters remain unchanged, the consumer report probability is set respectively $u_3 = 0.05,0.25,0.55,0.85$. The corresponding evolutionary routes for the strategy selection of every subject are shown in Fig. 25. With other parameters unchanged, further setting the economic compensation paid by Z to be $P_3 = 0.05,0.25,0.55,0.85$, respectively, which leads to the evolution path diagram of the behavioral strategy selection as shown in Fig. 26.

As shown in the analysis of Figs. 25 and 26, when the probability of consumers reporting Z or the financial compensation paid by Z to consumers is low, i.e., when $u_3 = 0.05$ or $P_3 = 1$, Z chooses to sell counterfeit food. As the probability of consumers reporting Z or the financial compensation paid by Z to consumers increases, Z's behavioral strategy choices show cyclical fluctuations with a long cycle and low wave height. Although Z has a high overall willingness to choose to sell safe food, its behavioral strategy choices fluctuate between selling safe food and counterfeit food. When the probability of consumers reporting Z or the compensation paid by Z to consumers increases, Z chooses to sell safe food at an increasing evolution speed. The results show that an increased probability of consumers reporting and higher compensation paid by Z to consumers increases the risk cost to Z from selling counterfeit food, and also reduces the fitness of the fraudulent strategy among companies in the Z group, thereby reducing their motivation to choose or emulate the sale of counterfeit food.

6.5. *Effect of emulation level on behavioral strategy choices of actors*

Under the case of constant other parameters, setting up the emulation level of X, Y and Z enterprises in their respective similar groups as $w_1 = 0.2,0.3,0.6,0.8$, $w_2 = 0.2,0.4,0.6,0.9$, $w_3 = 0.1,0.2,0.4,0.7$ simultaneously in Scenarios I and IV gives the evolution path map of behavioral strategy selection as shown in Figs. 27–29 and Figs. 30–32.

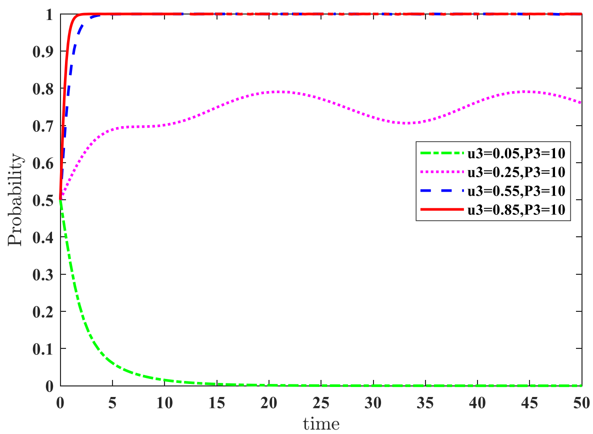

Fig. 25. Influence of u_3 on behavioral strategy of Z. (Left).

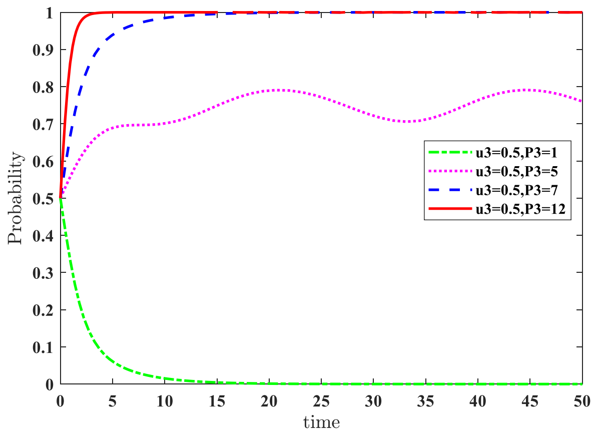

Fig. 26. Influence of P_3 on behavioral strategy of Z. (Right).

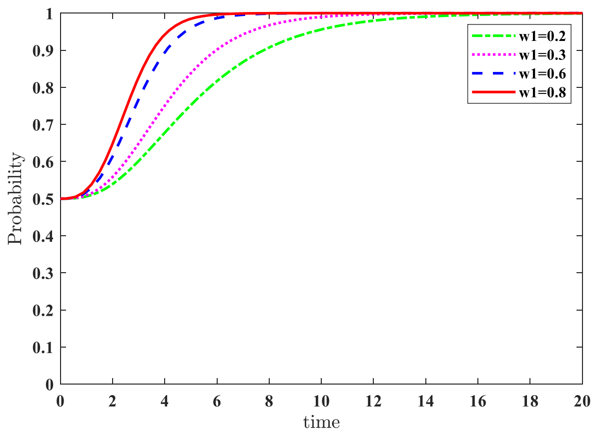

Fig. 27. Influence of w_1 on behavioral strategy of X. (Left).

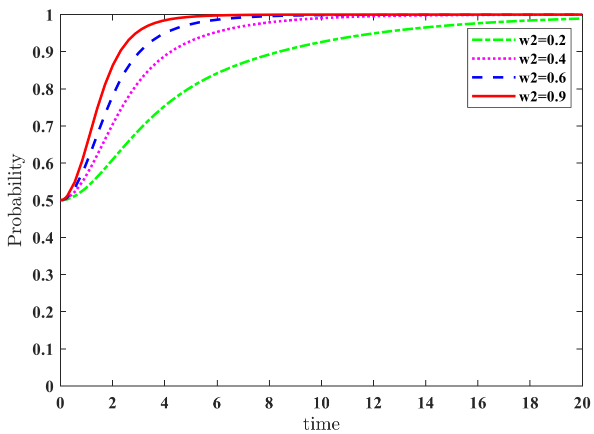

Fig. 28. Influence of w_2 on behavioral strategy of Y. (Right).

In this case, the highest social co-governance is established, and a higher emulation level results the system needing less time to reach E_8, that is, the selections of behavioral strategy finally evolved into {producing safe raw materials, producing safe food, selling safe food}. This indicates that the level of emulation among companies in the same group does not affect the actors' evolution paths or the system's final stable state. Rather, it affects the time needed for the system to evolve to the equilibrium point. Upstream, midstream, and downstream companies always choose a safe strategy.

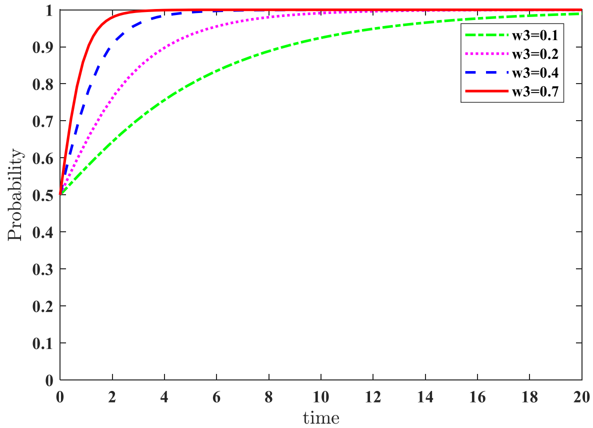

Fig. 29. Influence of w_3 on behavioral strategy of Z.

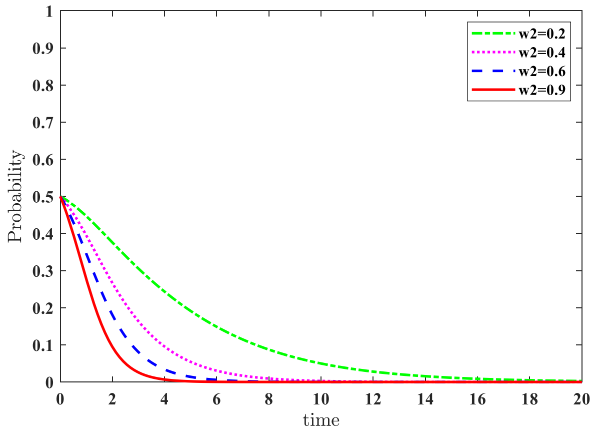

Fig. 30. Influence of w_1 on behavioral strategy of X. (Left).

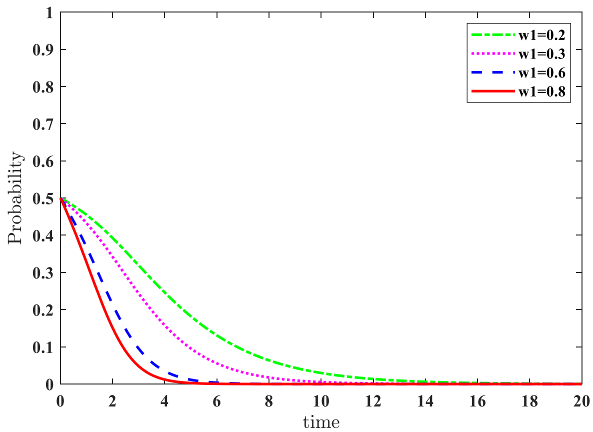

Fig. 31. Influence of w_2 on behavioral strategy of Y. (Right).

Moreover, the fitness of the fraudulent strategy among companies in the same group is low when the system evolves to E_8, corresponding to Scenario I. Therefore, all three actors would give up choosing and emulating the fraudulent strategy. On the contrary, In Scenario IV, where the equilibrium point is E_1, we assume that the intensity of imitation is the same as in Scenario I and refer to Figs. 30–32. According to the analysis of Figs. 30–32, when the level of social co-governance is low, even if the level of emulating fraudulent behavioral among companies in the same group is low, they would still choose and emulate the fraudulent strategy to obtain

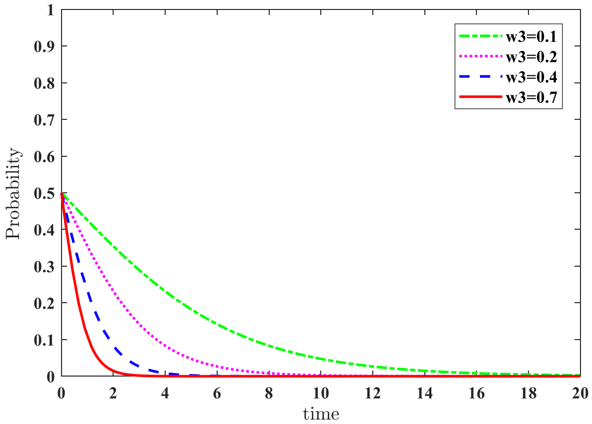

Fig. 32. Influence of w_3 on behavioral strategy of Z.

high profits due to the high fitness of the fraudulent strategy among companies in the same group. This suggests that the effect of emulation level on companies' behavioral strategy choices is based on social co-governance. In other words, Imitation levels simply determine the timing when the subject selects a behavioral strategy, while the level of social co-governance determines companies' choices of behavioral strategies at various levels of emulation.

7. Conclusions and policy implications

This study has created a social co-governance framework involving government regulation, supervision between companies, and consumer reporting based on the reality of China, and developed a three-party evolutionary game model among upstream raw material producers, midstream food producers, and downstream distributors to investigate the behavioral strategy choices of these three parties. Furthermore, it verified the stability conditions of the equilibrium points by numerical simulation, and investigated the effects of government regulation, supervision between companies, consumer reporting, and the level of fraud emulation among companies on fraudulent behavior and fraud emulation among companies in the same group.

The results show that choices regarding fraudulent behavior and fraud emulation among companies in the same group are related to the level of social co-governance. A higher the co-governance level makes companies more likely to choose a safe strategy and give up emulating fraudulent behavior. The food supply chain system's final stable state thus does not depend on the initial willingness of the three actors to engage in fraud, but only on the level of social co-governance. However, the actors' initial willingness does impact the time needed for system to evolve to a stable state. Moreover, although the level of emulation among companies in the same group does not change the companies' behavioral strategies, it does affect the time they take to make choices. The effect of emulation level on companies' behavioral strategy choices is based on social co-governance. For example, in a system with high social co-governance, the time needed to choose a safe strategy decreases as the level of emulation increases.

Furthermore, companies' behavioral strategy choices also change with the level of government regulation. As government regulation decreases, companies gradually shift from a safe to a fraudulent strategy. This in turn compels more and more companies in the same group to also gradually shift to adopt fraudulent behavior, i.e., engage in emulation. However, company decisions are based on the level of government regulation, i.e., the probability of government sampling inspections and the amount of financial penalties. When the inspection probability or financial penalties alone are reduced, it is still possible for companies to shift to a fraudulent strategy and to cause fraud emulation among companies in the same group. Therefore, financial penalties and government inspection probabilities should be maintained at appropriate levels that reinforce each other; otherwise government failure is still possible.

It was also found that reduced supervision of upstream companies by midstream companies induces upstream companies to choose a fraudulent strategy. Additionally, when downstream companies reduce their supervision of midstream companies, the latter's behavioral strategy choices show cyclical fluctuations. This indicates that financial penalties among upstream, midstream, and downstream companies based on market mechanisms alone cannot effectively curb fraud and emulation among companies in the long term. In other words, market failure is still possible in this case, and participation of additional regulatory forces, such as consumers and other social forces, is needed.

The conclusions of this study have important policy implications. Preventing food fraud and fraud emulation among companies requires the participation of the government, the market (supervision between companies), and social forces. Downstream companies should maintain sampling inspections of upstream companies with a certain probability and impose financial penalties for any breach of contract. As the core force in preventing food fraud, the government should implement an appropriate combination of sampling inspections and financial penalties. Moreover, the government should encourage consumers to participate in social co-governance, and increases the economic cost borne by companies who commit and emulate fraud. This can be done through the market reputation mechanism by disclosing fraud information, thereby reducing companies' willingness to commit and emulate fraud. In short, the prevention of food fraud and fraud emulation among companies should be based on social co-governance to combine and potentiate the respective advantages of the government, market, and society.

This study also has some limitations, which require collaborative efforts from the academic community to overcome. This study did not consider the emulation of fraud across different groups of companies in the food supply chain. Due to the interest relationships between different groups of companies in the supply chain, they may emulate each other due to differences in profit levels. Moreover, as noted above, many social forces are involved in combating food fraud, such as non-governmental organizations and news media. However, only consumers were included in this study. Therefore, future research should include multiple social forces to build a complete social co-governance framework and investigate the emulation of fraud among different groups of companies.

Although this study is based on China, it may provide guidance for other countries, especially developing countries, in the prevention of food fraud. This is because this study uses companies' economic benefits as a basic assumption, which follows the universal laws of the market economy [81]. Moreover, the social co-governance system proposed in this study is a governance system recognized and implemented by many countries. However, the national conditions of China do have quite strong differences from those of other countries. Therefore, the extent to which the conclusions of this study are applicable to other countries requires further research.

Data availability statement

No data was used for the research described in the article.

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CRediT authorship contribution statement

Linhai Wu: Writing – review & editing, Supervision, Investigation. **Hejie Tang:** Writing – original draft, Validation, Software, Formal analysis, Conceptualization. **Xiaoting Dai:** Visualization, Methodology. **Xiujuan Chen:** Writing – review & editing. **Jingxiang Zhang:** Writing – review & editing.

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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References

[1] C. Dima, L. Badea, A. Cristescu, Consumer perception concerning the trade of counterfeit clothing brands in Romania. A pilot study–Southern region and Bucharest, Industria Textila 68 (5) (2017) 380–387, https://doi.org/10.35530/IT.068.05.1366.
[2] C.E. Handford, K. Campbell, C.T. Elliott, Impacts of milk fraud on food safety and nutrition with special emphasis on developing countries, Compr. Rev. Food Sci. Food Saf. 15 (1) (2016) 130–142, https://doi.org/10.1111/1541-4337.12181.
[3] S. Sumar, H. Ismail, Adulteration of foods: past and present, Nutr. Food Sci. 95 (4) (2013) 11–15, https://doi.org/10.1108/00346659510088663.
[4] Y. Guntzburger, J. Théolier, V. Barrere, et al., Food industry perceptions and actions towards food fraud: insights from a pan-Canadian study, Food Control (2020), https://doi.org/10.1016/j.foodcont.2020.107182.
[5] D. Li, M. Zang, S. Wang, et al., Food fraud of rejected imported foods in China in 2009–2019, Food Control 133 (2022) 108619, https://doi.org/10.1016/j.foodcont.2021.108619.
[6] Europol, 320 tonnes of potentially dangerous dairy products taken off the market in operation OPSON IX targeting food fraud, Available at: https://www.europol.europa.eu/media-press/newsroom/news/320-tonnes-of-potentially-dangerous-dairy-products-taken-market-in-operation-opson-ix-targeting-food-fraud, , 2022. (Accessed 20 February 2023).
[7] H. Grundy, D. Kelly, J. Charlton, et al., Food authenticity and food fraud research: achievements and emerging issues, J. Assoc. Public Anal. 40 (1) (2012) 65–68.
[8] C. Moyer, W. DeVries, J. Spink, The economics of a food fraud incident: case studies and examples including Melamine in Wheat Gluten, Food Control 71 (2017) 358–364, https://doi.org/10.1016/j.foodcont.2016.07.015.
[9] C.L. Chen, X. Shang, W.J. Tsaur, et al., An anti-counterfeit and traceable management system for brand clothing with hyperledger fabric framework, Symmetry 13 (11) (2021) 2048, https://doi.org/10.3390/sym13112048.
[10] J. Spink, D.C. Moyer, Defining the public health threat of food fraud, Journal of food science 76 (9) (2011) R157–R163, https://doi.org/10.1111/j.1750-3841.2011.02417.x.
[11] R.S. Hellberg, K. Everstine, S.A. Sklare, Food Fraud: a Global Threat with Public Health and Economic Consequences, Academic Press, 2021, pp. 1–7, https://doi.org/10.1016/j.jneb.2021.06.004.
[12] K. Everstine, E. Abt, D. McColl, et al., Development of a hazard classification scheme for substances used in the fraudulent adulteration of foods, J. Food Protect. 81 (1) (2018) 31–36, https://doi.org/10.4315/0362-028X.JFP-17-173.
[13] P. Danese, R. Mocellin, P. Romano, Designing blockchain systems to prevent counterfeiting in wine supply chains: a multiple-case study, Int. J. Oper. Prod. Manag. (2021), https://doi.org/10.1108/IJOPM-12-2019-0781.
[14] C. Xiu, K.K. Klein, Melamine in milk products in China: examining the factors that led to deliberate use of the contaminant, Food Pol. 35 (5) (2010) 463–470, https://doi.org/10.1016/j.foodpol.2010.05.001.

[15] T.K. Udeigwe, J.M. Teboh, P.N. Eze, et al., Implications of leading crop production practices on environmental quality and human health, J. Environ. Manag. 151 (2015) 267–279, https://doi.org/10.1016/j.jenvman.2014.11.024.
[16] M.T. Law, in: E.H. Net, R. Whaples (Eds.), History of Food and Drug Regulation in the United States, 2004.
[17] D. Harrison, The Oxford Companion to American Food and Drink, Reference Reviews, 2008. https://webofscience.clarivate.cn/wos/alldb/full-record/WOS:000248797400348.
[18] M. Malek, History of the 1st IR, McGraw-Hill Companies, New York MG, 2005.
[19] R. Levi, S. Singhvi, Y. Zheng, Economically motivated adulteration in farming supply chains, Manag. Sci. 66 (1) (2020) 209–226. Available at SSRN, https://doi.org/10.2139/ssrn.3060078.
[20] S. Dani, L. Fassam, The convergence of ethics and fraud: challenges facing procurement functions in food supply chains. 21st Logistics Research Network(LRN) Annual Conference 2016 and PhD (Accepted Version). Workshop: Doing the Right Thing-Ethical Issues in Logistics and Supply Chain, University of Hull, 2016.
[21] W. Zuo, L.S. Xie, Research on behavior of food corporates' social irresponsibility and consumers' willingness to punish, Journal of South China Agricultural University (Social Science Edition) 21 (2) (2022) 110–120.
[22] Shilong Wang, guangMing Xie, Review of research on behavioral contagion in social networks, The Life and Opinions of the People (8) (2016) 164–166, https://doi.org/10.3969/j.issn.1004-3381.2016.08.053.
[23] L. Wenjing, Qingyun Jiang, L.I.U. Ting, Literature review and prospect on social contagion research: from the perspective of behavioral economics, Modernization of Management 40 (4) (2020) 105–109.
[24] Linhai Wu, Liu Yanding, The intrinsic mechanisms and risk prevention of the Chinese food safety governance system, Jiangsu Soc. Sci. (4) (2023) 104–113+243, https://doi.org/10.13858/j.cnki.cn32-1312/c.20230719.010.
[25] J.J. Argo, D.W. Dahl, A.C. Morales, Consumer contamination: how consumers react to products touched by others, J. Market. 70 (2) (2006) 81–94, https://doi.org/10.1509/jmkg.70.2.81.
[26] J.J. Argo, D.W. Dahl, A.C. Morales, Positive consumer contagion: responses to attractive others in a retail context, J. Market. Res. 45 (6) (2008) 690–701, https://doi.org/10.1509/jmkr.45.6.690.
[27] G.E. Newman, P. Bloom, Physical contact influences how much people pay at celebrity auctions, Proc. Natl. Acad. Sci. USA 111 (10) (2014) 3705–3708, https://doi.org/10.1073/pnas.1313637111.
[28] J.I. Hyun, L. Jia, J.P. Young, Policy uncertainty and peer effects:evidence from corporate investment in China, Int. Rev. Financ. Anal. 77 (2021) 101834, https://doi.org/10.1016/j.irfa.2021.101834.
[29] M. Michael, G. Daniel, N. Collins, Do peer firms influence innovation? Br. Account. Rev. 53 (5) (2021) 100988 https://doi.org/10.1016/j.bar.2021.100988.
[30] C. Dougal, C.A. Parsons, S. Titman, Urban vibrancy and corporate growth, J. Finance 70 (1) (2015) 163–210, https://doi.org/10.1111/jofi.12215.
[31] J.L. Brown, K.D. Drake, Network ties among low-tax firms, Account. Rev. 89 (2) (2014) 483–510, https://doi.org/10.2308/accr-50648.
[32] T. Staake, F. Thiesse, E. Fleisch, Business strategies in the counterfeit market, J. Bus. Res. 65 (5) (2012) 658–665, https://doi.org/10.1016/j.jbusres.2011.03.008.
[33] Li Zheng, Convergence of enterprise technology innovation-from the perspective of innovation gap, Journal of Shanxi University of Finance and Economics 44 (10) (2022) 85–97.
[34] Z. Wu, R. Salomon, Does imitation reduce the liability of foreignness? L inking distance, isomorphism, and performance, Strat. Manag. J. 37 (12) (2016) 2441–2462, https://doi.org/10.1002/smj.2462.
[35] J. Romley, T. Shih, Product safety spillovers and market viability for biologic drugs, International Journal of Health Economics and Management 17 (2017) 135–158, https://doi.org/10.1007/s10754-016-9208-2.
[36] H. Kendall, S. Kuznesof, M. Dean, et al., Chinese consumer's attitudes, perceptions and behavioural responses towards food fraud, Food Control 95 (2019) 339–351, https://doi.org/10.1016/j.foodcont.2018.08.006.
[37] P. Steinberg, S. Engert, A daring task: the battle against food crime, Journal of Consumer Protection and Food Safety 14 (2019) 317–318, https://doi.org/10.1007/s00003-019-01259-9.
[38] J. Wang, T. Chen, J. Wang, Research on cooperation strategy of enterprises' quality and safety in food supply chain, Discrete Dynam Nat. Soc. (2015) 2015, https://doi.org/10.1155/2015/301245.
[39] C.B. Lee, Risk management strategies for global food supply chain, Korean J Logist 19 (3) (2011) 105–124.
[40] N. Hirschauer, M. Bavorová, G. Martino, An analytical framework for a behavioural analysis of non-compliance in food supply chains, Br. Food J. 114 (9) (2012) 1212–1227. https://webofscience.clarivate.cn/wos/alldb/full-record/KJD:ART001623519.
[41] G. Migliore, G. Schifani, L. Cembalo, Opening the black box of food quality in the short supply chain: effects of conventions of quality on consumer choice, Food Qual. Prefer. 39 (2015) 141–146, https://doi.org/10.1016/j.foodqual.2014.07.006.
[42] G.K. Abebe, A. Chalak, M.G. Abiad, The effect of governance mechanisms on food safety in the supply chain: evidence from the Lebanese dairy sector, J. Sci. Food Agric. 97 (9) (2017) 2908–2918, https://doi.org/10.1002/jsfa.8128.
[43] H. Ma, G. Shen, Do new mayors bring fresh air? Some evidence of regulatory capture in China, Rev. Econ. Des. 25 (4) (2021) 227–249, https://doi.org/10.1007/s10058-021-00248-5.
[44] B. Steiner, Governance reform of German food safety regulation: cosmetic or real? What's the Beef. https://www.researchgate.net/publication/47629297, 2006.
[45] J. Fewsmith, X. Gao, Local governance in China: incentives & tensions, Daedalus 143 (2) (2014) 170–183. https://www.jstor.org/stable/43297325.
[46] Y. Kang, Food safety governance in China: change and continuity, Food Control 106 (2019) 106752, https://doi.org/10.1016/j.foodcont.2019.106752.
[47] D. Kadjo, J. Ricker-Gilbert, G. Shively, et al., Food safety and adverse selection in rural maize markets, J. Agric. Econ. 71 (2) (2020) 412–438, https://doi.org/10.1111/1477-9552.12350.
[48] G. M, A. Fearne, J.A. Caswell, et al., Co-regulation as a possible model for food safety governance: opportunities for public–private partnerships, Food Pol. 32 (3) (2007) 299–314, https://doi.org/10.1016/j.foodpol.2006.07.005.
[49] M. Garcia Martinez, P. Verbruggen, A. Fearne, Risk-based approaches to food safety regulation: what role for co-regulation? J. Risk Res. 16 (9) (2013) 1101–1121, https://doi.org/10.1080/13669877.2012.743157.
[50] S. Boatemaa, M.K. Barney, S. Drimie, et al., Awakening from the listeriosis crisis: food safety challenges, practices and governance in the food retail sector in South Africa, Food Control 104 (2019) 333–342.
[51] A. Mutshewa, The use of information by environmental planners: a qualitative study using Grounded Theory methodology, Inf. Process. Manag. 46 (2) (2010) 212–232, https://doi.org/10.1016/j.ipm.2009.09.006.
[52] L.M. Salamon, S.W. Sokolowski, Beyond nonprofits: Re-conceptualizing the third sector, Voluntas Int. J. Voluntary Nonprofit Organ. 27 (2016) 1515–1545, https://doi.org/10.1007/s11266-016-9726-z.
[53] I. Ayres, J. Braithwaite, Responsive Regulation: Transcending the Deregulation Debate, Oxford University Press, New York, 1992, https://doi.org/10.1093/oso/9780195070705.001.0001.
[54] C. Coglianese, D. Lazer, Management-based regulation: prescribing private management to achieve public goals, Law Soc. Rev. (4) (2003), https://doi.org/10.1046/j.0023-9216.2003.03703001.x.
[55] B. Cadieux, L.D. Goodridge, J. Spink, Gap analysis of the Canadian food fraud regulatory oversight and recommendations for improvement, Food Control 102 (2019) 46–55, https://doi.org/10.1016/j.foodcont.2019.03.012.
[56] H.V. Pham, T.L. Dinh, The Vietnam's food control system: achievements and remaining issues, Food Control 108 (2020) 106862, https://doi.org/10.1016/j.foodcont.2019.106862.
[57] L.H. Wu, Z.Y. Ling, X.J. Chen, Research on the behavioral strategy choices regarding quality investment in food supply chain based on a social co-governance framework, Journal of Macro-Quality Research 1–20 (March 20, 2024). http://kns.cnki.net/kcms/detail/42.1848.C.20240314.1617.004.html.
[58] Yilin Zhang, Liheng Lei, Gong Qiang, Trust crisis, regulatory burden and food safety, World Economic Papers (6) (2017) 56–71.

[59] H. Kendall, S. Kuznesof, M. Dean, et al., Chinese consumer's attitudes, perceptions and behavioural responses towards food fraud, Food Control 95 (2019) 339–351, https://doi.org/10.1016/j.foodcont.2018.08.006.

[60] E. Strayer, K. Everstine, S. Kennedy, Economically motivated adulteration of honey: quality control vulnerabilities in the international honey market, Food Protect. Trends 34 (1) (2014) 8–14. https://webofscience.clarivate.cn/wos/alldb/full-record/FSTA:2014-07-Lg1597.

[61] Hanjiang Zhang, Wei Xiao, Weina Ge, Hailun Zhang, The transmit mechanism of harmful matter in food supply chain and its hybrid strategy static game model, Syst. Eng. (1) (2008) 62–67. https://webofscience.clarivate.cn/wos/alldb/full-record/CSCD:3224803.

[62] W.A.N. Chun-dong, Q.I.N. Zhi-bing, W.U. Ji-xin, Study on food safety risk control from the perspective of supply chain, China Soft Science (10) (2018) 184–192.

[63] A. Banterle, S. Stranieri, The consequences of voluntary traceability system for supply chain relationships. An application of transaction cost economics, Food Pol. 33 (6) (2008) 560–569, https://doi.org/10.1016/j.foodpol.2008.06.002.

[64] H.T. Thames, Sukumaran A. Theradiyil, A review of Salmonella and Campylobacter in broiler meat: emerging challenges and food safety measures, Foods 9 (6) (2020) 776, https://doi.org/10.3390/foods9060776.

[65] S. Jagtap, F. Bader, G. Garcia-Garcia, et al., Food logistics 4.0: opportunities and challenges, Logistics 5 (1) (2020) 2, https://doi.org/10.3390/logistics5010002.

[66] F. Fung, H.S. Wang, S. Menon, Food safety in the 21st century, Biomed. J. 41 (2) (2018) 88–95, https://doi.org/10.1016/j.bj.2018.03.003.

[67] J. Luo, T. Chen, J. Pan, Evolutionary dynamics of health food safety regulatory information disclosure from the perspective of consumer participation, Food Sci. Nutr. 7 (12) (2019) 3958–3968, https://doi.org/10.1002/fsn3.1257.

[68] Hui Ma, Guo Manlun, Research on ten fold punitive damages system in food safety cases, China Health Law 31 (2) (2023) 6–10, https://doi.org/10.19752/j.cnki.1004-6607.2023.02.002.

[69] Peihua Zhao, Liuqin Zhang, Saiqiang Hu, Study on the behavior of counterfeiter and regulators based on evolutionary game, Economy and Management 32 (4) (2018) 76–82.

[70] C. Eckert, Risk and risk management of spillover effects: evidence from the literature, Risk Manag. Insur. Rev. 23 (1) (2020) 75–104.

[71] T.M. Ha, S. Shakur, K.H.P. Do, Linkages among food safety risk perception, trust and information: evidence from Hanoi consumers, Food Control 110 (2020) 106965, https://doi.org/10.1016/j.foodcont.2019.106965.

[72] K. Singh, M. Misra, Linking corporate social responsibility (CSR) and organizational performance: the moderating effect of corporate reputation, European Research on Management and Business Economics 27 (1) (2021) 100139, https://doi.org/10.1016/j.iedeen.2020.100139.

[73] X. Peng, F. Wang, J. Wang, et al., Research on food safety control based on evolutionary game method from the perspective of the food supply chain, Sustainability 14 (13) (2022) 8122, https://doi.org/10.3390/su14138122.

[74] Linhai Wu, Shijiu Yin, Liangyun Niu, China's Approach to Food Safety Risk Management, vol. 12, China Agriculture Press, 2021, p. 238.

[75] G. Huanyu, D. Xiaoting, W. Linhai, Food safety risk behavior and social Co-governance in the food supply chain, Food Control 152 (2023), https://doi.org/10.1016/j.foodcont.2023.109832.

[76] M.E. Warner, A.M. Aldag, Y. Kim, Privatization and intermunicipal cooperation in US local government services: balancing fiscal stress, need and political interests, Publ. Manag. Rev. 23 (9) (2021) 1359–1376.

[77] W.Q. Judge, R. Dooley, Strategic alliance outcomes: a transaction-cost economics perspective, Br. J. Manag. 17 (1) (2006) 23–37, https://doi.org/10.1111/j.1467-8551.2005.00441.x.

[78] P.C. Parks, AM Lyapunov's stability theory—100 years on, IMA J. Math. Control Inf. 9 (4) (1992) 275–303, https://doi.org/10.1093/imamci/9.4.275.

[79] H.K. Khalil, Lyapunov stability. Control systems, Robotics and AutomatioN 12 (2009) 115, https://doi.org/10.1201/b10384-98.

[80] H.U. Chun-hua, S.U.N. Si-yuan, Z.H.O.U. Xin-min, Cong Chen, Research on food security in online ordering based on evolutionary game, Consum. Econ. 37 (3) (2021) 80–87.

[81] World Health Organization, Meeting report: the second global meeting of the, FAO/WHO International Food Safety Authorities Network (INFOSAN), 9-11 December (2020) 2019. https://www.who.int/publications/i/item/9789240003934.