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An Evolutionary Game Analysis of Periodical Fluctuation in Food Safety Supervision

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Abstract: Periodical fluctuation is a common phenomenon in food safety supervision. The existing literature on China's food safety supervision mainly analyzes periodical fluctuation by statistical methods. This paper provides a theoretical explanation by building an evolutionary game model between food enterprises and supervision institutions under bounded rationality. The "Sanlu milk powder" food safety incident is taken as a typical example to conduct numerical simulations of the food safety supervision game. Moreover, the determining factors in the periodical fluctuation in food safety supervision are analyzed in detail by numerical simulations, including the initial states and benefit–cost parameters. The results show that the periodical fluctuation and probability of supervision failure are influenced by the initial states. Supervision institutions should discard historical path dependence and adjust their supervision-intensity timing according to its actual effects. In addition, blindly increasing rewards or punishments cannot effectively restrain the fluctuation or reduce food safety incidents. To reduce the occurrence of food safety incidents and decrease periodical fluctuation, supervision institutions should reduce supervision costs by using information technology, establish strict food safety standards to eliminate "small-workshop" enterprises, be more aware of risks and appropriately overestimate the added benefits for food enterprises of becoming involved in illegal production.

Keywords: periodical fluctuation; food safety supervision; evolutionary game theory; food safety incidents

MSC: 91A22

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1. Introduction

Food safety is an important issue across the world, as it is closely related to social stability and economic development. As recorded in history, the first food safety incident involved artificial sweeteners and took place in the ancient Roman Empire [1]. More recently, several foodborne diseases developed in Western countries in the early 19th century. During the second half of the 20th century, a large number of food safety incidents took place [2,3]. Currently, food safety problems still plague governments and people all around the world. For example, the outbreak of "poisonous eggs" in Europe in 2007 affected countries including the Netherlands, Belgium and Germany [4]. Food safety incidents occur throughout the world, and China is no exception. The Chinese government attaches great importance to food safety and has issued a series of relevant laws and regulations, such as the People's Republic of China Food Safety Law, to correctly regulate and guide the development of the food industry. However, food safety incidents still occur frequently and high-profile food safety scandals are often exposed by the media [5,6], from the "SudanI" in 2005 [7], "Sanlu milk powder" incident in 2008 [8], to the subsequent "gutter oil" [9], "clenbuterol" and "industrial gelatin" incidents. Those food safety incidents have caused thousands of people to become sick or even lose their lives. The frequent occurrence of food safety incidents undermines public confidence in current food safety in China [10], which has negative impacts on social stability and economic development [11]. In domestic and foreign food safety incidents, food safety supervision is an effective way to reduce the occurrence of food incidents. Therefore, food safety supervision remains one of the most critical and prominent problems in China, attracting extensive attention from scholars.

In the past decades, China has paid much attention to food safety issues and introduced many food safety policies to strengthen food safety supervision. Especially since the 18th National Congress of the Communist Party of China (CPC), the Party and the state have attached great importance to food safety. In order to establish and improve food safety and ensure "bite safety", new policies for food safety governance have been launched and governance methods have consistently been developed. In 2021, the first year of the 14th Five-Year Plan period, China's overall food safety situation continued to improve. However, in spite of the improving levels of food safety in general, problems and challenges cannot be ignored [12–14]. Many scholars analyzed the causes of food incidents and provided suggestions for supervision. Holtkamp and Liu analyzed the food incident data reported by the media and found that the reported food safety incidents increased with the rate of urbanization [15]. Furthermore, improving food safety laws and management systems was considered to be an effective way to ensure food safety [16,17]. Moreover, other suggested reasons for food safety incidents were also explored by scholars, including the unclear and overlapping responsibilities of different government departments [13], lax supervision [17–19], the lack of effective reward and punishment measures [20], asymmetric information [21] and the contribution of numerous small-scale producers [22]. Although these studies provide a foundation for research, they mainly focus on empirically exploring the factors contributing to food safety and lack an appropriate mathematical model to investigate the interactions between supervision institutions and food enterprises. By contrast, evolutionary game theory is an effective approach to describing the dynamic process of the interplay between stakeholders and can provide a deep insight into food safety supervision [23–26]. Yang et al. built an evolutionary game between food enterprises and governments under different reward and punishment mechanisms [20], which provided a theoretical basis for the establishment of reward and punishment measures. Cao et al. constructed an evolutionary game model of the government and enterprises in the context of new media environments [27]. They believed that the government should not only build and develop new media, but also strengthen the management of new media. Zhang et al. explored the influence of third-party supervision on food safety supervision by establishing an evolutionary game model; they found that third-party supervision had a certain substitution effect on government supervision [28]. Han and Li built a food safety evolutionary game simulation model based on improved prospect theory. The results showed that a stable evolutionary strategy of food safety is difficult to implement in reality [29]. These studies approached food safety supervision from different perspectives, but ignored a common phenomenon in food supervision. Periodical fluctuation in food safety supervision is an interesting phenomenon in China and verified in empirical studies [30], but there is currently research on this topic with theoretical analysis. Evolutionary game theory originated from the biology field and is now applied in many fields, including criminal behavior, large-scale migration, epidemics, environmental challenges, and climate change [31]. It was proven to be an effective tool with which to study the interactions between bounded rational players [32]. It provides a good method for analyzing and solving food safety supervision problems. This paper provides a theoretical explanation for periodical fluctuation by building an evolutionary game model between food enterprises and supervision institutions together with numerical simulations.

This study contributes to the literature in several ways. First, this paper aims to study the periodical fluctuation in food safety supervision using evolutionary game theory. Second, the numerical example of the "Sanlu milk powder" incident is simulated to explain the interactions between food enterprises and supervision institutions. Thirdly, the determining factors of periodical fluctuation in food safety supervision are analyzed in detail. The results of this study should be helpful in understanding periodical fluctuation in food safety supervision and provide directions for effective regulation.

The rest of this paper is organized as follows. Section 2 proposes an evolutionary game model between food enterprises and supervision institutions, from which an analytic solution is obtained. In Section 3, the numerical simulation example of the "Sanlu milk powder" incident is explained. Section 4 discusses the determining factors in the periodical fluctuation in food safety supervision by simulations, including initial states and benefit–cost parameters. Section 5 presents the conclusions and policy implications of this study.

2. An Evolutionary Game Model of Food Safety Supervision

2.1. Problem Description

As an important aspect of people's livelihood, food safety receives significant attention from both the public and the government. To enable clean governance, China monitors supervision institutions strictly, forbidding collusion between governmental officials and food producers. In particular, due to the rapid development of the Internet and new media, the high level of information transparency reduces the possibility of rent seeking by governmental officials. Thus, when we analyze the game between supervision institutions and food enterprises, collusion is not taken into account. There are two main categories of stakeholder in the field of food safety regulation in China: supervision institutions (G), which are responsible for food safety supervision and inspection; and food enterprises (C), which are responsible for food safety investment and legal production. When food safety incidents occur frequently, supervision institutions strengthen their supervision of food enterprises, in which case, food enterprises are more inclined to comply with food safety standards to avoid punishment. However, when most food enterprises engage in legal production and food safety incidents are reduced, supervision institutions relax supervision to save costs. At this point, food enterprises take opportunities to save on production costs and gain more profits. Therefore, according to the interactions between supervision institutions and food enterprises, we built a regulatory game model between supervision institutions and food enterprises.

2.2. Game Design

The food enterprises were assumed to be bounded and rational and to make decisions based on the principle of maximizing profit. Assuming that the supervision institutions have a strong regulatory ability, once enterprises engaged in illegal production are inspected, their violations are discovered and no food enterprises escape punishment. Furthermore, there is no power rent seeking in the process of supervision.

The payoff matrix of the food safety supervision game is given in Table 1. The strategy space of the supervision institution, including loose (W) or strict (S) supervision, is defined as $S_G = \{W, S\}$ and the strategy space of the food enterprise, including legal production and illegal production, is defined as $S_C = \{I, N\}$. Legal production means that the products produced by the food enterprise are in full compliance with relevant food standards. By contrast, illegal production means the food enterprise producing unsafe food by using substandard ingredients or illegal additives to save costs. Suppose the food enterprise's average cost of producing safe food (legal production) is defined as C_2, and the strict-supervision cost of the supervision institution is C_1. The gain of the supervision institution derived from legal production is R_1, which includes improving the administration's reputation and image, protecting consumers' health, praise or reward by superiors, etc. By contrast, if the food enterprise conducts illegal production when the supervision institution implements a loose supervision strategy, the food enterprise can obtain an added benefit H through illegal production, such as food adulteration. At the same time, under these conditions, food safety incidents are likely to occur, in which case the supervision institution suffers a loss L. However, if the supervision institution adopts a strict supervision strategy, the illegal production of a food enterprise can be discovered, in which case the enterprise has to accept a punishment F, such as a penalty, stopping production for consolidation, rectification, shutdown, compensating consumers, etc. By contrast, food enterprises that adopt legal production strategies to produce safe food in line with all the relevant food safety standards can obtain R_2, which involves, for example, a reward from the supervision institution, an improved corporate reputation, etc. It is obvious that $L + R_1 + F > C_1$. Otherwise, the supervision institution gives up on regulating completely because of the high inspection costs. Under strict supervision, the food enterprise should produce safe food (through legal production) to avoid punishment, that is, $R_2 - C_2 > -F$. In the process of evolution, the players are drawn randomly in pairs from two populations (supervision institutions and food enterprises). Assume that the supervision institution (G) chooses a loose supervision strategy with a probability of $x(0 \le x \le 1)$ in the evolution, where $x = 0$ represents the strict execution of regulation duties and $x = 1$ represents the dereliction of regulation duties. Accordingly, assume that the food enterprise (C) chooses a legal production strategy with a probability of $y(0 \le y \le 1)$, where $y = 0$ represents breaking the regulations and laws and producing food that does not meet the relevant food standards and $y = 1$ represents following the rules and regulations and producing safe food, respectively.

Table 1. Meanings of the variables in the food safety supervision game.

	Variables	Meanings of the Variables	Notes
Supervision institution	C_1	Supervision institution's cost of strict supervision strategy	$C_1 > 0$
	R_1	Supervision institution's benefits derived from legal production	$R_1 > 0$
	L	Expected loss of overall social benefits due to illegal production	$L > 0$
	x	Probability of adopting loose supervision strategy	$0 \le x \le 1$
Food enterprise	C_2	Food enterprise's cost of legal production	$C_2 > 0$
	R_2	Food enterprise's benefits derived from legal production	$R_2 > 0$
	F	Punishment of food enterprise with illegal production when discovered	$F > 0$
	H	Added benefits for food enterprise with illegal production when escaping regulation	$H > 0$
	y	Probability of adopting legal production strategy	$0 \le y \le 1$

The above food safety supervision game model and its corresponding variables are shown in Table 1. It follows that the payoff matrix can be obtained in Table 2, according to the preceding assumptions and analysis. Here, we analyze the unique mixed strategy equilibrium in the supervision game.

Table 2. Payoff matrix of food safety supervision game.

		Food Enterprise (C)	
		Legal Production	**Illegal Production**
Supervision institution (G)	Loose supervision	$(R_1, -C_2)$	$(-L, H)$
	Strict supervision	$(R_1 - C_1, -C_2 + R_2)$	$(R_1 - C_1 + F, -F)$

2.3. Game Solution

As the players are drawn randomly in pairs from two populations in the supervision game, the food enterprise's expected benefits U_{C_1} from adopting a legal production strategy and its expected benefits U_{C_2} from adopting an illegal production strategy can be calculated as follows, respectively:

$$U_{C_1} = (1 - x)(-C_2 + R_2) + x(-C_2) \tag{1}$$

$$U_{C_2} = (1 - x)(-F) + xH \tag{2}$$

where U_{C_1} and U_{C_2} are also the food enterprise's fitness for legal production and illegal production.

Therefore, the food enterprise's expected average benefits $\overline{U}_C$ can be obtained as follows:

$$\overline{U}_C = yU_{C_1} + (1-y)\,U_{C_2} \tag{3}$$

In the same way, the supervision institution's expected average benefits $\overline{U}_G$ can be obtained as follows:

$$\overline{U}_G = xU_{G_1} + (1-x)\,U_{G_2} \tag{4}$$

Therefore, the expected average benefits of the two kinds of player (food enterprises and supervision institutions) can be calculated in detail, as shown below:

$$\begin{cases} |\overline{U}_C = y[(1-x)(-C_2+R_2) + x(-C_2)] + (1-y)[(1-x)(-F) + xH] \\ |\overline{U}_G = x[yR_1 + (1-y)(-L)] + (1-x)[y(R_1-C_1) + (1-y)(R_1-C_1+F)] \end{cases} \tag{5}$$

The food enterprise and the supervision institution choose y and x to maximize $\overline{U}_C$ and $\overline{U}_G$ in Equation (5), respectively. Therefore, the first-order conditions are:

$$\begin{cases} |\frac{\partial \overline{U}_G}{\partial x} = R_1 y - L + Ly - R_1 + C_1 - F + Fy = 0 \\ |\frac{\partial \overline{U}_C}{\partial y} = -C_2 + R_2 - R_2 x - Hx + F - Fx = 0 \end{cases} \tag{6}$$

The mixed strategy equilibrium can be derived by solving Equation (6). The results are as follows:

$$(x^*, y^*) = \left(\frac{-C_2 + R_2 + F}{H + R_2 + F}, \frac{L - C_1 + F + R_1}{L + F + R_1} \right) \tag{7}$$

From the equilibrium solution, we can determine that the supervision institution will select a loose supervision strategy with a probability of $x^* = \frac{-C_2+R_2+F}{H+R_2+F}$, while the food enterprise will select legal production with a probability of $y^* = \frac{L-C_1+F+R_1}{L+F+R_1}$ under mixed equilibrium conditions. When the food enterprise fails to engage in legal production as required by laws and regulations while, at the same time, the supervision institution implements a loose supervision strategy, food incidents may occur, which, in other words, is tantamount to the failure of food safety supervision. Therefore, the probability of supervision failure is

$$P^* = x^*(1-y^*) = \frac{C_1}{L + F + R_1}\left(\frac{-C_2 + R_2 + F}{H + R_2 + F}\right) \tag{8}$$

Therefore, the following conclusions can be reached easily by analyzing the equilibrium solution and the supervision failure probability P^*. Firstly, an increase in the food enterprise's cost of legal production C_2 or a decrease in the food enterprise's benefit derived from legal production R_2 lead to an increasing probability of supervision failure. As a "rational economic person", the food enterprise will measure the input–output ratio, allocate resources to more efficient areas and reduce investment in legal production when the cost of legal production increases. Therefore, supervision institutions can use the increase in food enterprises' legal production costs as a signal to adjust their supervision strategy. When legal production costs rise, or are about to rise, supervision institutions can adopt strict supervision strategies to correctly guide food enterprises to produce safe food. Secondly, the probability of supervision failure decreases with the increase in the legal production gain of supervision institutions R_1, the expected loss of overall social benefits due to illegal production L and the food enterprise's excess returns derived from illegal production H. Lower returns from illegal production weaken the opportunistic behavior of food enterprises, while the higher return from legal production incentivizes supervision institutions to intensify supervision. In this situation, supervision institutions strengthen supervision to regulate food enterprises and the supervision failure probability decreases. It is also worth mentioning that with the increase in supervision costs C_1, the probability of supervision failure rises as higher costs discourage supervision institutions from regulating food enterprises strictly.

2.4. Theoretical Explanation for Periodical Fluctuation by Evolutionary Game

We introduce the evolutionary game to analyze the dynamic process of the interactions between supervision institutions and food enterprises, which can overcome the disadvantages of traditional game theory, in which the players are of bounded rationality [33]. In the process of supervision, the players (supervision institutions and food enterprises) can adjust their strategies dynamically by learning from others. Replicator dynamics were introduced to present the learning and evolution mechanism of the players in the evolution of supervision [34]. According to the Malthusian dynamic equation, the payoffs of the players are proportional to the reproduction rate of each player. Therefore, the replicator dynamics model of the food safety supervision game can be obtained as follows:

$$\begin{cases} |\frac{dx}{dt} = x(1-x)[-L-R_1+C_1-F+(L+F+R_1)y] \\ |\frac{dy}{dt} = y(1-y)[F+R_2-C_2-(F+R_2+H)x] \end{cases} \tag{9}$$

Making $\frac{dx}{dt} = 0$ and $\frac{dy}{dt} = 0$, we can obtain five solutions to the differential equations: (1,0), (0,1), (1,1), (0,0), (x^*, y^*). Here, we apply the Jacobi matrix defined by Daniel Firedman [35] to analyze the stability of the five fixed points of the evolutionary game. We can obtain the Jacobi matrix J and the corresponding eigenvalues, $\lambda_i (i = 1, 2)$:

$$J = \begin{bmatrix} \partial\dot{x}/\partial x & \partial\dot{x}/\partial y \\ \partial\dot{y}/\partial x & \partial\dot{y}/\partial y \end{bmatrix} \tag{10}$$

The eigenvalues of the Jacobi matrix J at the fixed point (0,1) can be obtained as follows: $\lambda_1 = C_1$ and $\lambda_2 = -(F + R_2 - C_2)$. Obviously, the value of $\lambda_1 > 0$, so the fixed point (0,1) is unstable. Similarly, we can also evaluate the eigenvalues of the Jacobi matrix J at the fixed points (1,0), (0,0), (1,1) and (x_0^*, y_0^*); the results are shown in Table 3. The fixed points (1,0), (0,0) and (1,1) are also unstable. However, for the fixed point $(x^*, y^*) = \left(\frac{-C_2+R_2+F}{H+R_2+F}, \frac{L-C_1+F+R_1}{L+F+R_1}\right)$, the Jacobi matrix J is evaluated as

$$J = \begin{bmatrix} 0 & \frac{(-C_2+R_2+F)(H+C_2)(L+F+R_1)}{(H+R_2+F)^2} \\ -\frac{C_1(L-C_1+F+R_1)(H+R_2+F)}{(L+F+R_1)^2} & 0 \end{bmatrix} \tag{11}$$

where $\frac{(-C_2+R_2+F)(H+C_2)(L+F+R_1)}{(H+R_2+F)^2} > 0, -\frac{C_1(L-C_1+F+R_1)(H+R_2+F)}{(L+F+R_1)^2} < 0$. Subsequently, the eigenvalues of the Jacobi matrix J at fixed point (x^*, y^*) can be calculated as:

$$m_{1,2} = \pm i \cdot \sqrt{\frac{C_1(R_1 - C_1 + F + L)(F + R_2 - C_2)(H + C_2)}{(F + H + R_2)(L + F + R_1)}} \tag{12}$$

Clearly, the eigenvalues of the Jacobi matrix J at the equilibrium point (x^*, y^*) in Equation (12) are complex numbers with zero real parts. Thus, the trajectories of the replicator dynamics equations in Equation (9) at the equilibrium points are stable limit circles but are not asymptotically stable. They can be described as:

$$\begin{cases} |x = x^* + x(0) \cdot \cos \alpha t - y(0) \cdot \sin \alpha t \\ |y = y^* + x(0) \cdot \sin \alpha t + y(0) \cdot \cos \alpha t \end{cases} \tag{13}$$

where $\alpha = \sqrt{\frac{C_1(R_1-C_1+F+L)(F+R_2-C_2)(H+C_2)}{(F+H+R_2)(L+F+R_1)}}$, representing the wave frequency of the trajectories. Furthermore, when $t = 0$, the initial state of the replicator dynamics equations can be defined as:

$$\begin{cases} |x_0 = x^* + x(0) \\ |y_0 = y^* + y(0) \end{cases} \tag{14}$$

So the Equation (16) can be written as:

$$\begin{cases} x = x^* + A\cdot\cos(\alpha t + \varphi) \\ y = y^* + A\cdot\sin(\alpha t + \varphi) \end{cases} \tag{15}$$

where $A = \sqrt{x(0)^2 + y(0)^2}$ and $\varphi = \begin{cases} |arctan\frac{y(0)}{x(0)},\ y(0)/x(0) \geq 0 \\ |arctan\frac{y(0)}{x(0)} + \pi,\ y(0)/x(0) < 0 \end{cases}$.

Therefore, the trajectories of x (the probability of the food enterprise adopting legal production strategy and y (the probability of the supervision institution adopting a loose supervision strategy) are closed-orbit circles, fluctuating around the equilibrium point (x^*, y^*) with amplitude A.

$$(x - x^*)^2 + (y - y^*)^2 = A^2 \tag{16}$$

In the case of periodical fluctuation solution, the probability of supervision failure can be defined as $P = x(1-y)$. As x and y fluctuate around the equilibrium point, the probability of supervision failure P may show the characteristics of periodical fluctuation, which is proven by numerical simulations in the next section. Therefore, compared with the mixed solution in Equation (8), the maximum value of the probability of supervision failure cannot be calculated accurately. Here, we amplify the probability of supervision failure by taking the maximum value of x and y at the same time, regardless of the phase delay between x and y. In this way, we obtain the upper limit of the supervision failure probability to define the supervision failure in the case of periodical fluctuation solution. The expression of the upper limit of the supervision failure probability is given as follows:

$$P_h^* = (x^* + A)(1 - y^* + A) \tag{17}$$

From the above, it is clear that the probability of supervision failure P_h^* is affected by the amplitude A and the mixed equilibrium point (x^*, y^*). According to the equation $A = \sqrt{(x_0 - x^*)^2 + (y_0 - y^*)^2}$, the amplitude A is affected by the initial state $x(0)$ and $y(0)$ of the food safety supervision game. According to Equation (7), the mixed equilibrium point (x^*, y^*) is affected by the parameters related to the payoffs of both players in the evolutionary game. In the following sections, we use numerical simulations to further analyze the probability of food safety supervision failure and the determining factors in the periodical fluctuation.

Table 3. The eigenvalues of Jacobi matrix J and stability.

Fixed Points	Eigenvalues		Stability
(0,0)	$-C_1$	$C_2 + H$	unstable
(0,1)	C_1	$-(F + R_2 - C_2)$	unstable
(1,0)	$L + F + R_1 - C_1$	$-(C_2 + H)$	unstable
(1,1)	$-L - R_1 + C_1 - F$	$F + R_2 - C_2$	unstable
(x_0^*, y_0^*)	m_1	m_2	stable

3. Numerical Simulation Example: The Case of the "Sanlu Milk Powder" Incident

The shocking "Sanlu milk powder" incident in 2008 is a typical food safety incident, which aroused wide concern from society and had a significant negative impact. The State Council of PRC launched a national security incident level I (the highest level) response mechanism to deal with the "Sanlu milk powder" incident. Therefore, in order to analyze the probability of food safety supervision failure and the determining factors in the periodical fluctuation, we take the "Sanlu milk powder" incident as an example to conduct a numerical simulation. In this major food safety incident, hundreds of thousands of infants and children were sick and four infants were even killed after drinking milk powder with the illegal addition of melamine. Sanlu Group was fined more than CNY 49.37 million and had to pay for the treatment of the victims. Moreover, this food incident was a huge blow to China's dairy exports. Since significant amounts of real data are not available and some parameters cannot be quantified directly, the values of some of the parameters in this paper are roughly estimated according to the actual situation. Assume that the punishment F is about CNY 85 million, including fines, compensation, and shutdown losses. If Sanlu Group had conducted rectification in time and invested in food safety when the problems were discovered, it would have avoided losses and fines and would even have obtained a corresponding investment income. The food safety input C_2 is assumed to be CNY 20 million and the corresponding investment income R_2 is about CNY 10 million. For the government, the cost of conducting strict supervision C_1 is assumed to be CNY 20 million, while $R_1 = 40$ million CNY if food enterprises produce safe food. The Sanlu milk powder incident not only had a negative impact on the image and reputation of the regulator, but also sapped people's trust in domestic milk powder and seriously affected China's milk powder exports. Therefore, L is assumed to be CNY 90 million. The above estimations of other parameters meet the following conditions: $L + R_1 + F > C_1$ and $R_2 - C_2 > -F$. Otherwise, the supervision institution gives up on regulating completely because of the high inspection costs, or the food enterprise engages in illegal production due to the weak punishment. Therefore, the values of the relevant parameters are: $C_1 = 20$, $R_1 = 40$, $H = 50$, $F = 85$, $C_2 = 20$, $R_2 = 10$ (unit: CNY million).

Around 2007, China gradually improved its laws and regulations related to food safety and strengthened its supervision of food safety issues. In this context, most food enterprises increased food safety investment and tended to engage in legal production, so the initial state can be set to $(x_0, y_0) = (0.35, 0.9)$. From the above model and equations, the probability of supervision institutions and food enterprises choosing a strategy fluctuates around the equilibrium point $(x^*, y^*) = (0.52, 0.91)$ and the amplitude of the fluctuation A = 0.1674. The evolution of the interval is set to be $\pi/180$ and t represents the time step of the evolution. The periodical fluctuation in the proportions of strategy x and y are shown in Figure 1 left panel. The evolution of the strategy of the supervision institutions and food enterprises involves a bargaining process. When supervision institutions are lax in their supervision, food enterprises take opportunities to produce substandard products through illegal production in order to maximize their profits. However, the opportunistic behavior of food enterprises triggers more safety incidents, forcing supervision institutions to strengthen their supervision, thereby reducing the occurrence of incidents. When food enterprises abide by the regulations, supervision institutions reduce supervision to save costs and allocate resources to more efficient areas. Therefore, the evolution of the strategy of supervision institutions and food enterprises periodically fluctuates around the equilibrium point $(x^*, y^*) = (0.52, 0.91)$. The periodical fluctuation in the probability of supervision failure is shown in Figure 1 right panel. Based on the given values of the parameters and the initial state, the probability of supervision failure P^* =0.0481 and the upper limit of the probability of supervision failure $P_h^* = 0.1783$ at the equilibrium point $(x^*, y^*) = (0.52, 0.91)$. It is clear that the upper limit of the supervision failure probability P_h^* is slightly higher than the maximum value of P^*, due to the inconsistency between the oscillation trajectories of x and y (x and y cannot reach peaks or troughs at the same time). From the results, the small value of the probability of supervision failure means that the probability of food safety incidents is relatively low. These results are consistent with the data on food safety incidents in 2007 [33].

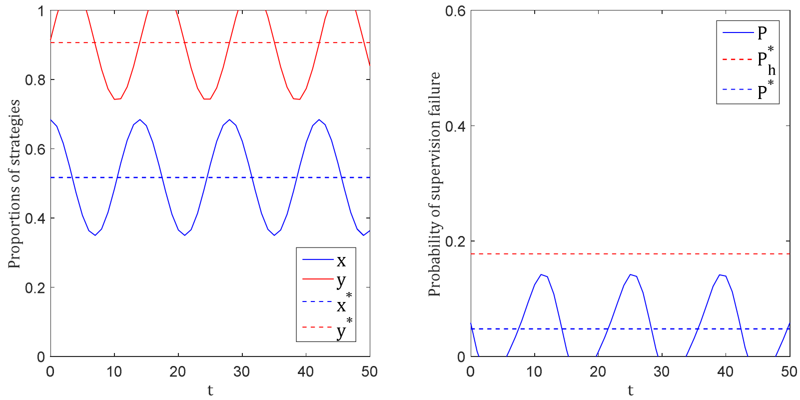

Figure 1. Periodical fluctuation in proportions of strategies (**left panel**) and probability of supervision failure (**right panel**) in initial state $(x_0, y_0) = (0.35, 0.9)$.

4. Determining Factors of Periodical Fluctuation in Food Safety Supervision

Based on the above analysis, the probability of supervision failure is determined by the amplitude A and the equilibrium point (x^*, y^*). However, the amplitude A depends on the initial state of the system and the equilibrium point (x^*, y^*) is determined by the values of the parameters related to the costs and payoffs. In order to further study the determining factors of the periodical fluctuation and supervision failure probability in the food safety supervision game, the following numerical simulations were conducted.

4.1. Initial State of the Food Safety Supervision Game

Before 2007, although the Chinese government had gradually regulated the behavior of food enterprises, food safety incidents still occurred frequently. Thus, the initial state was set to $(x_0, y_0) = (0.65, 0.7)$ in this situation, which means that most food enterprises produce safe food, even though most regulators perform loose supervision. The fluctuating amplitude $A = 0.2459$ and the periodical fluctuation in the proportion of the strategies is shown in Figure 2a. After 2007, the government issued a large number of working documents on the food industry and strengthened supervision. Under strict supervision, food enterprises tended to engage in legal production to produce safe food. To reflect this situation, the initial state of the food safety supervision was set to $(x_0, y_0) = (0.35, 0.9)$. The fluctuating amplitude $A = 0.1674$ and the periodical fluctuation in the proportion of the strategies is shown in Figure 2b. Based on the given values of the parameters, the equilibrium point $(x^*, y^*) = (0.52, 0.91)$. According to the equation $A = \sqrt{(x_0 - x^*)^2 + (y_0 - y^*)^2}$, the amplitude A is determined by the distance between the initial point and the equilibrium point. When other parameters are given, the longer the distance, the greater the amplitude, as illustrated by Figure 2. The initial state $(x_0, y_0) = (0.65, 0.7)$ is further from the equilibrium point, so the amplitude A in the left picture is greater than in the right. The probability of supervision failure in different initial states $(0.65, 0.7)$ and $(0.35, 0.9)$ was also analyzed; the results are shown in Figure 3. Obviously, the upper limit of the supervision failure probability P_h^* is also affected by the initial state. Compared with the initial state $(x_0, y_0) = (0.65, 0.7)$, the supervision is stricter and food enterprises pay more attention to producing safe food in the initial state $(x_0, y_0) = (0.35, 0.9)$, leading to fewer food incidents. Therefore, the initial state has an influence on food safety supervision. In order to avoid the influence of initial states and historical path dependence, supervision institutions should investigate the current effects of food safety supervision and adjust their supervision-intensity timing according to its actual effects. In this way, the occurrence of food safety incidents can be reduced. Except for the initial states, the benefit–cost parameters of the different strategies adopted by regulators and food enterprises is another determining factor in the periodical fluctuation, which is discussed in the next section.

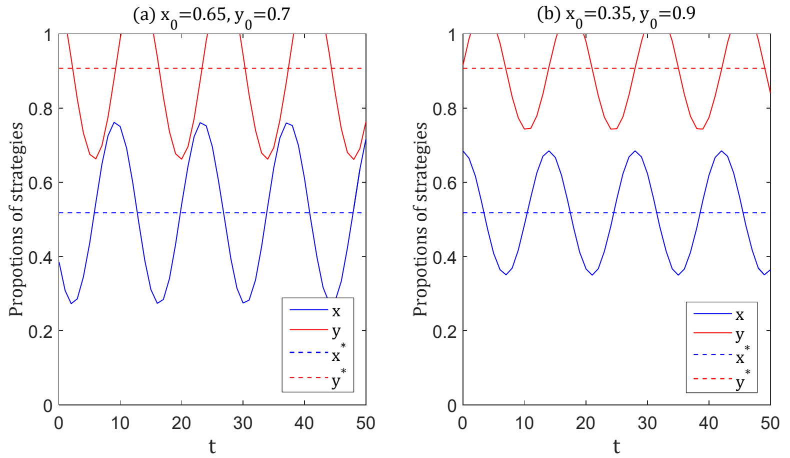

Figure 2. Effects of different initial states on the evolution of supervision. (**a**) Periodical fluctuation in proportions of strategies x and y in initial states $(0.65,\ 0.7)$. (**b**) Periodical fluctuation in proportions of strategies x and y in initial states $(0.35,\ 0.9)$.

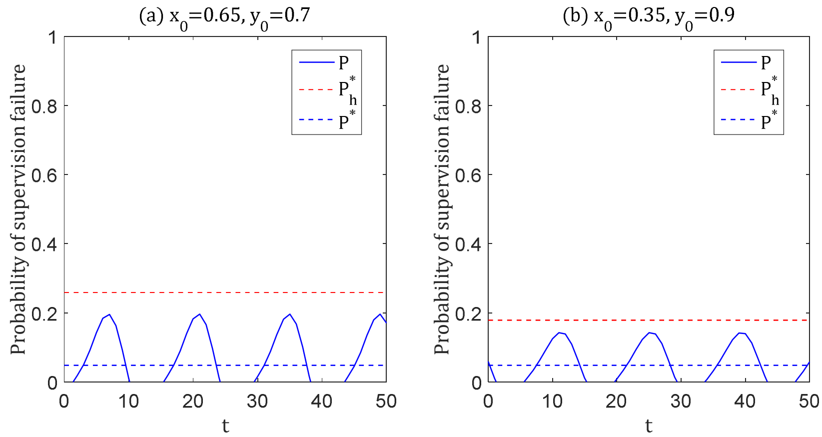

Figure 3. Effects of different initial states on the probability of supervision failure. (**a**) The periodical fluctuation in the probability of supervision failure P in initial state $(0.65,\ 0.7)$, (**b**) The periodical fluctuation in the probability of supervision failure P in initial state $(0.35,\ 0.9)$. The upper limit of the probability of supervision failure P_h^* is also affected by the initial states.

4.2. Benefit–Cost Parameters of the Food Safety Supervision Game

According to Equations (7) and (8), the equilibrium point (x^*, y^*) and the probability of supervision failure are affected by the benefit–cost parameters: C_1, R_1, L, C_2, R_2, F and H. For regulators, it is difficult to calculate the gains and losses derived from enterprises' legal production, which depend on public health, reputation, social stability and other aspects that cannot be quantified. Therefore, only the benefit–cost parameters C_1, C_2, R_2, F and H in the initial state $(x_0, y_0) = (0.35, 0.9)$ are discussed.

(1) Strict-supervision cost C_1.

The supervision cost has an effect on the evolution of the food safety supervision game. Intuitively, given the high cost of the strict supervision strategy, supervision institutions are more likely to adopt loose supervision strategies. In fact, the supervision cost is more likely to directly affect the strategies of food enterprises. In order to investigate the influence of the supervision cost in detail, the simulations were conducted considering the different supervision cost $C_1 = 10$ and $C_1 = 30$. The results are shown in Figure 4. From the results in Figure 4, we can see clearly that the equilibrium proportion of the legal production strategy y^* decreases to 0.8605, and the equilibrium position of the supervision failure probability P^* increases to 0.0722, with the strict-supervision cost C_1 increasing to 30. Furthermore, both the fluctuating frequency ω and the amplitude A grow higher with the increasing C_1. A comparison between the results of the different supervision costs C_1 illustrates that if the cost of a strict supervision strategy is high, food enterprises are more likely to engage in speculative behavior to obtain added profits. Therefore, the probability of supervision failure and the food safety incident rate are higher with the higher strict-supervision cost C_1. The results indicate that reducing the cost of strict supervision can stimulate the enthusiasm of supervision institutions, which can promote legal production among food enterprises and reduce periodical fluctuations in supervision.

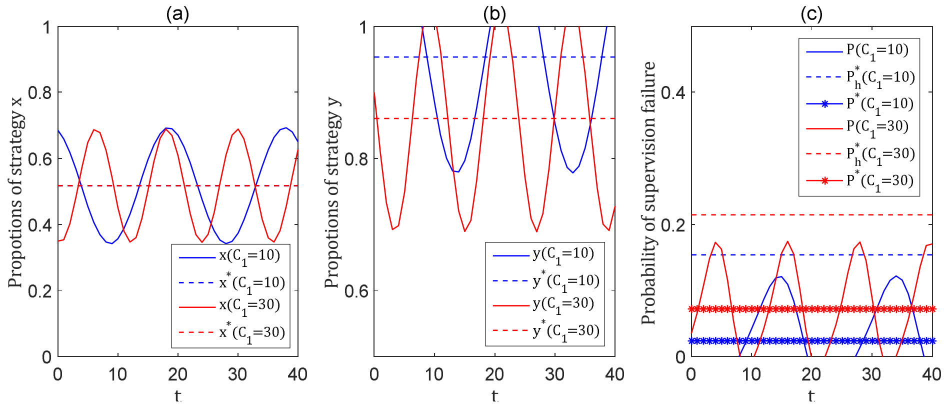

Figure 4. The influence of strict-supervision cost C_1 on periodical fluctuation. (**a**) The periodical fluctuation in proportions of strategy x with different strict-supervision costs $C_1 = 10$ and $C_1 = 30$. (**b**) The periodical fluctuation in proportions of strategy y with different strict-supervision costs $C_1 = 10$ and $C_1 = 30$. (**c**) The periodical fluctuation in the probability of supervision failure P with different strict-supervision costs $C_1 = 10$ and $C_1 = 30$.

(2) Legal production cost C_2.

The legal production cost C_2 directly affects the payoff of food enterprises. To investigate the effects of the legal production cost C_2 in detail, the simulations were conducted with different values of $C_2 = 20$ and $C_2 = 40$. The results in Figure 5 show that the equilibrium proportion of the strict supervision strategy x^* decreases to 0.3793 and the equilibrium proportion of the supervision failure probability P^* decreases to 0.0353, with the legal production cost C_2 increasing to 40. We can infer that supervision failure probability decreases with the increasing C_2. In other words, the occurrence of food safety incidents decreases with the increase in the legal production cost C_2. Consider that food standards are lax and food enterprises can pay low costs to produce food legally. With the premise that the supervision strength remains the same, most food enterprises, especially small ones, are more likely to adopt legal production strategies to avoid punishment. As a result, the qualification rate of food enterprises becomes higher, which in turn causes supervision institutions to relax their supervision. With the relaxation of supervision, food enterprises are inclined to take opportunities to save on costs and adopt illegal production strategies. Therefore, the equilibrium proportion of legal production strategies y^* remains the same. However, food produced by qualified enterprises is not necessarily safe compared with that produced to high standards. Thus, low legal production costs C_2 lead to high rates of supervision failure and more food safety incidents indirectly. By contrast, with high food standards, food enterprises have to pay more to engage in legal production. In this case, many food enterprises, especially small ones, are more likely to take opportunities to save on costs. The low qualification rate instead urges supervision institutions to adopt strict supervision strategies. These results indicate that improving food standards properly can eliminate some "small-workshop" food enterprises, thus reducing the difficulties involved in food safety supervision and helps to lower the probability of supervision failure probability and prevent food safety incidents.

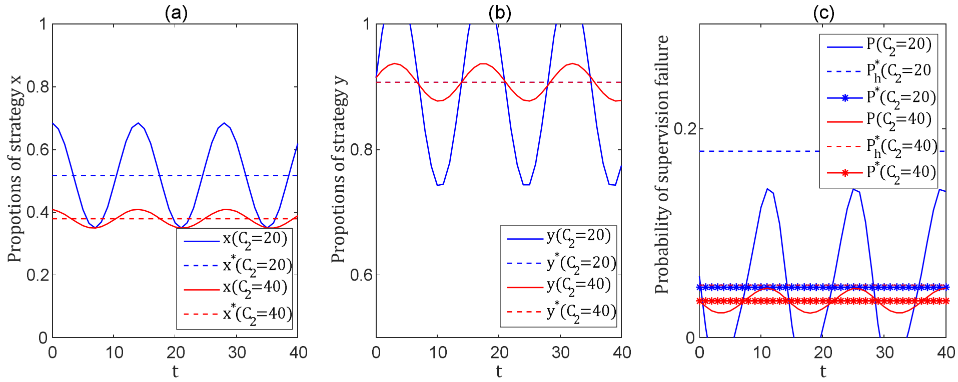

Figure 5. The influence of legal production cost C_2 on the periodical fluctuation. (**a**) The periodical fluctuation in the proportions of strategies x with different legal production costs $C_2 = 20$ and $C_2 = 40$. (**b**) The periodical fluctuation in proportions of strategies y with different legal production costs $C_2 = 20$ and $C_2 = 40$. (**c**) The periodical fluctuation in the probability of supervision failure P with different legal production costs $C_2 = 20$ and $C_2 = 40$.

(3) Food enterprises' added gains from legal production R_2.

If the food produced by a food enterprise meets all the relevant standards, the food enterprise receives added gains R_2, including an improved reputation, rewards from the government, etc. In order to analyze the effects of the added gains R_2 on the evolution of the food safety supervision game, simulations were conducted with different $R_2 = 10$ and $R_2 = 30$, while the values of other parameters were the same. The results are shown in Figure 6. Obviously, with the increase in R_2, the equilibrium proportion of loose supervision strategies x^* becomes higher and the amplitude A becomes larger, as seen in Figure 6a,b. Motivated by the higher added gains, food enterprises are more inclined to invest in producing safe food. With high food-enterprise qualification rates, supervision institutions begin to loosen their supervision to save on costs. Although the supervision institution relaxed its supervision, the equilibrium point of y^* remained the same. The reason for this is that high added gains R_2 promote legal production among food enterprises, while the loose supervision of regulators induces opportunistic behavior among food enterprises at the same time. Therefore, incentive measures can encourage food enterprises to engage in legal production, although this is not an effective way to avoid food safety incidents. Blindly increasing the reward cannot effectively reduce the occurrence of food safety incidents.

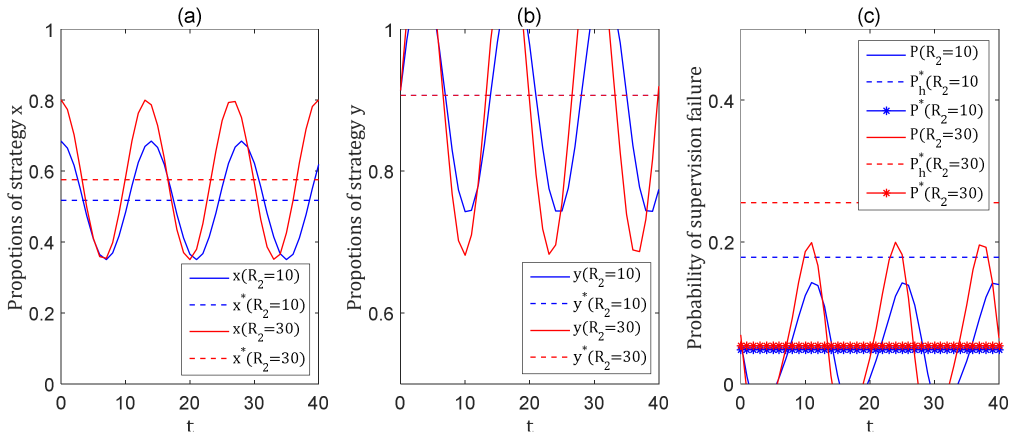

Figure 6. The influence of added gains R_2 on the periodical fluctuation. (**a**) The periodical fluctuation in the proportions of strategies x with different added gains $R_2 = 10$ and $R_2 = 30$. (**b**) The periodical fluctuation in proportions of strategies y with different added gains $R_2 = 10$ and $R_2 = 30$. (**c**) The periodical fluctuation in the probability of supervision failure P with different added gains $R_2 = 10$ and $R_2 = 30$.

(4) Punishment for illegal production F.

Enterprises engaged in illegal production have to pay a punishment F under strict supervision. The punishment F includes penalties, stopping production for consolidation, closure, compensation for victims, etc. To investigate the effects of punishment F on the periodical fluctuation in the supervision game, the simulations were conducted with different values of $F = 85$ and $F = 100$, while the other parameters remained unchanged. The results in Figure 7 show that the equilibrium proportions of loose supervision strategies x^* and legal production strategies y^* increase to $x^* = 0.5625$ and $y^* = 0.913$ with the higher punishment $F = 100$. Furthermore, the equilibrium supervision failure probability P^* increases to 0.0489 and the amplitude A increases to 0.2129 with the punishment F increase to 100. According to the results, the severe punishment $F = 100$ indeed forces food enterprises to engage in legal production, but the punitive measures are not particularly effective at reducing the probability of supervision failure. The reason for this is that severe punishment $F = 100$ brings the supervision institution an added income, which may lead the supervision institution to rely on penalties excessively. Therefore, from the perspective of supervision failure and amplitude, the supervision institution cannot only rely on punitive measures to regulate food enterprises.

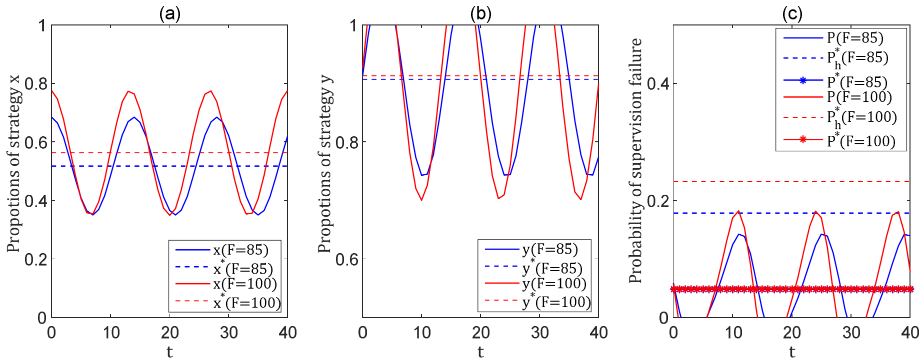

Figure 7. The influence of punishment F on the periodical fluctuation. (**a**) The periodical fluctuation in proportions of strategies x with different punishments $F = 85$ and $F = 100$. (**b**) The periodical fluctuation in proportions of strategies y with different punishments $F = 85$ and $F = 100$. (**c**) The periodical fluctuation in the probability of supervision failure P with different punishments $F = 85$ and $F = 100$.

(5) Added benefits of illegal production H for food enterprises.

A food enterprise can obtain added benefits H by engaging in illegal production when the supervision institution implements a loose supervision strategy. To investigate the effects of added benefits H in detail, the simulations were conducted with different values of $H = 20$ and $H = 40$, while the other parameters remained unchanged. Intuitively, the high benefit of H can tempt food enterprises to adulterate their food; the equilibrium position of legal production y^* should increase with the higher H. However, the simulation results contradicted this intuitive judgment. The results in Figure 8 show that the equilibrium position of loose supervision strategies x^* decreases to 0.3846, but the equilibrium position of legal production strategies y^* remains the same. The reason for this is that when the food enterprise tries to engage in illegal production with the temptation of high added benefits, the supervision institution strengthens its supervision. Consequently, the equilibrium point of supervision failure probability P^* decreases, which is consistent with the results in Figure 8c, in which the P^* decreases to 0.0358 with the higher $H = 100$. Furthermore, with the higher H, the amplitude A also becomes smaller. The results in Figure 8 indicate that the supervision institution can properly overestimate the added benefits H of illegal production to circumvent the high rate of food safety incidents.

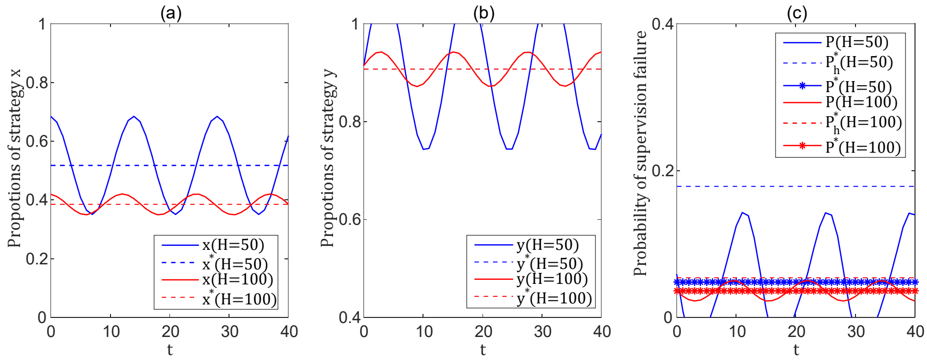

Figure 8. The influences of added benefits H on the periodical fluctuation. (**a**) The periodical fluctuation in proportions of strategies x with different added benefits $H = 50$ and $H = 100$. (**b**) The periodical fluctuation in proportions of strategies y with different added benefits $H = 50$ and $H = 100$. (**c**) The periodical fluctuation in the probability of supervision failure P with different added benefits $H = 50$ and $H = 100$. Through the above simulation results, the initial states and benefit–cost parameters are proven to be influential in food safety supervision. In order to improve the effectiveness of regulation and reduce the fluctuation in supervision, supervision institutions should discard historical path dependence and improve food safety standards appropriately. According to the actual implementation effects, supervision institutions should take corresponding reward and punishment measures appropriately. By investigating the current situation of food safety, possible risks involved in food safety supervision can be hedged in advance.

5. Conclusions and Policy Implications

5.1. Main Conclusions

The recurrence of food safety incidents not only arouses public concern, but also damages the international reputation of China's food industry. Food safety supervision is an important approach to ensuring the legal production of the food industry and reducing the occurrence of food safety incidents. The periodical fluctuation in food safety supervision in China was verified by the quantitative analysis based on the statistical data from recent years. To explain the periodical fluctuation in food safety supervision in detail, we built an evolutionary game model between supervision institutions and food enterprises to describe the dynamic process of food safety supervision under bounded rationality. Based on the evolutionary game model, the determining factors of the periodical fluctuation were discussed using numerical simulations, including the initial states and benefit–cost parameters. As a result, we arrived at the following conclusions:

First, it was observed that under different initial states, there were great differences in the amplitude of the periodical fluctuation in supervision, which suggests that the effectiveness of food regulation can be improved by changing the historical path.

Second, the simulation results from the analysis of the benefit–cost parameters revealed that blindly increasing the reward or punishment cannot effectively reduce the occurrence of food safety incidents.

Moreover, we found that reducing government supervision costs and improving food safety standards are effective ways to decrease the fluctuation in the supervision game and reduce food safety incidents.

Finally, supervision institutions can improve implementation efficacy by raising awareness of the risks involved and appropriately overestimating the added benefits for food enterprises of becoming involved in illegal production.

5.2. Policy Implications

Based on the conclusions above, this paper puts forward some policy implications:

(1) Supervision institutions should discard historical path dependence in food safety supervision. Considering that the probability of supervision failure is affected by the initial states, supervision institutions should investigate the current effects of food safety

supervision and adjust their supervision-intensity timing according to its actual effects. In this way, food safety supervision can become immune to the influence of initial states and avoid historical path dependence, so as to reduce the occurrence of food safety incidents. In addition, this would also be an effective way to form a multi-governing model by reasonably involving new media and public power in food supervision.

(2) The supervision cost dampens supervision institutions' enthusiasm for implementing strict supervision. Supervision institutions should make full use of information technology to trim down supervision costs.

(3) Government departments should properly improve food safety standards, so as to lessen the occurrence of food safety incidents and restrain the fluctuations in food safety supervision to a certain degree. Relatively high food safety standards can also eliminate some "small-workshop" food enterprises, thus reducing the difficulties involved in food safety supervision.

(4) Instead of blindly increasing rewards or punishments, supervision institutions should adopt appropriate incentives and punishments according to the actual effects of their implementation.

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