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Evolutionary Game Analysis of Medical Waste Disposal in China under Different Reward and Penalty Models

Youqing Lv [1,2], Guojian Ma [1,*] and Juan Ding [1]

1 School of Management, Jiangsu University, Zhenjiang 212013, China; lvyouqing2011@163.com (Y.L.); dj18056201931@163.com (J.D.)
2 School of Economics and Management, Chuzhou University, Chuzhou 239000, China
* Correspondence: profma406@163.com

Abstract: Although local governments have issued relevant reward and penalty policies, there are still problems of medical waste disposal in China, particularly in light of the special situation of the COVID-19 pandemic. Furthermore, these problems are generated in the game between local governments and disposal enterprises. Accordingly, based on the evolutionary game theory, this paper establishes and analyzes the game system between local governments and disposal enterprises under four modes: static reward and static penalty, dynamic reward and static penalty, static reward and dynamic penalty, and dynamic reward and dynamic penalty. The theoretical analysis is verified through numerical simulation of a medical waste disposal case in China. The results showed that when local governments choose the static reward and static penalty mode, the game system hardly always has an evolutionary stable state, and the dynamic reward or dynamic penalty mode can make up for the shortcomings of the static reward and static penalty mode. The static reward and dynamic penalty mode is considerably better than the other two dynamic reward and penalty modes, which has the best effect on improving the quality of medical waste disposal. Additionally, if the reward or penalty increases dynamically, local governments tend to implement a "relaxed supervision" strategy, and disposal enterprises will still improve the disposal quality of medical waste. The suggestions proposed based on the research conclusions offer some enlightenment for policymakers to formulate reasonable reward and penalty measures.

Keywords: medical waste disposal; reward; penalty; evolutionary game

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1. Introduction

As the COVID-19 pandemic continues to spread and rebound, the quantity and quality of medical waste disposal in China is facing new challenges. On the one hand, the challenge in "quantity" is the explosive growth of medical waste production. For example, the medical waste in Wuhan, the first city that suffered from the COVID-19 outbreak, produced from 45 t/d before the outbreak to 155–195 t/d after the outbreak (Yu et al., 2020; Singh et al., 2020) [1,2], whereas the maximum daily disposal capacity is only 49 tons. Meanwhile, Zhenjiang has a relatively low spread of COVID-19, and the number of its confirmed COVID-19 cases only accounts for 0.02% of the confirmed cases in Wuhan. The amount of medical waste produced after the outbreak is shown in Figure 1. Medical waste in Zhenjiang also increased rapidly from 372.42 tons in the first quarter of 2020 to 532.22 tons in the fourth quarter, among which the increased rate of infectious medical waste is particularly prominent. On the other hand, the challenge in "quality" is the higher requirements of medical waste disposal. After the COVID-19 outbreak, the Ministry of Ecology and Environment of China issued the "New Coronavirus -Infected Pneumonia Epidemic Medical Waste Emergency Disposal Management and Technical Guidelines (Trial Implementation)", which requires disposal enterprises to speed up the collection frequency, shorten the residence time of disposal, set up isolation zones, increase cleaning and disinfection, and undertake other measures to carry out the harmless disposal of medical waste according to higher emergency disposal management and technical standards.

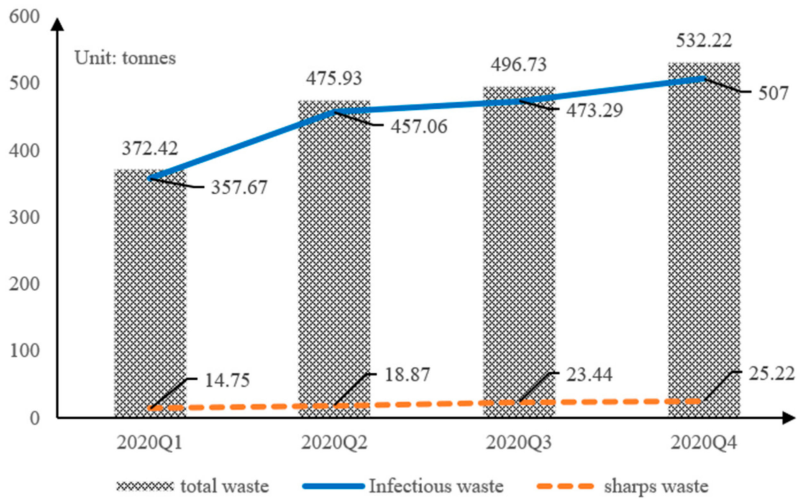


Figure 1. Trend chart of medical waste production in Zhenjiang, Jiangsu Province in 2020.

China has been strengthening its medical waste management system and financial supports. Especially after the outbreak of severe acute respiratory syndrome in 2003, China promulgated a series of laws and regulations to deal with medical waste, such as medical waste management regulations, technical specifications for centralized medical waste disposal, and invested in the construction of medical waste disposal stations and facilities (Wei et al., 2021) [3]. However, due to the dual challenges in "quantity" and "quality" mentioned above, problems in China's medical waste disposal process, such as untimely disposal, simplified disposal procedures, mixed disposal with ordinary household garbage, or illegal reselling of medical waste, have appeared. And these inappropriate disposal measures may cause significant harm to the environment and human health and even exacerbate the spread of diseases, such as typhoid, cholera, acquired immunodeficiency syndrome and 2019 coronavirus disease (COVID-19) (Taslimi et al., 2020; Sarkodie et al., 2021) [4,5].

Considering China's medical waste management system, most of the current medical waste management policies were issued in 2001–2006, and the reward and penalty mechanism for medical waste disposal is not perfect (Cao et al., 2021) [6]. Under the established regional centralized disposal system for medical waste (Chen et al., 2021) [7], Chinese local governments evaluate and select medical waste disposal enterprises, and medical waste from various medical institutions is collected and transferred to the disposal enterprises for centralized disposal (Song et al., 2018) [8]. This system leads to the co-governance dilemma in medical waste management. The fundamental reason lies in the static reward and penalty mode adopted by local governments, which leads to the lack of proactive motivation to dispose medical waste among disposal enterprises (Cao et al., 2021) [6]. Concretely speaking, the medical waste disposal charge labeling of disposal enterprises is subject to the official guide price approved by the local governments once a year. In other words, when disposal enterprises improve the disposal quality, local governments rarely give additional compensation, except a slight increase in the approved price of medical waste. Meanwhile, for violations of medical waste disposal found in daily supervision, local governments usually impose fixed fines, rather than presenting continuous dynamic characteristics with the change of disposal enterprises' behavior. Therefore, optimizing the reward and penalty model to improve the effectiveness of medical waste management is a key measure to break through the co-governance dilemma.

In fact, scholars have explored an endogenous mechanism to overcome social dilemmas by adopting game theory, and the classical metaphor for investigating social problems is the prisoner's dilemma (PD) game (Tanimoto 2015) [9]. Based on the concept proposed by Neumann et al. (1944) [10], Nash (1949) drove game theory forward and made it more applicable in various fields, such as economics, information science, statistical physics, and other social sciences [11]. However, according to the research application of Acevedo et al. (2005) [12], Pothos et al. (2011) [13], Bahbouhi et al. (2017) [14], Babajanyan et al. (2020) [15], a theoretical premise of the prisoner's dilemma is that it is a symmetric game, that is, the two prisoners have equal strength. And this theoretical premise is very different from the current situation of medical waste disposal in China, where local governments are strong and disposal enterprises are weak. Therefore, the asymmetric game model is more suitable for describing the behavioral interaction mechanism of multi-agents in China's medical waste disposal. Furthermore, the developments of evolutionarily stable strategy and Nowak classifications have driven evolutionary game theory to become one of the most exciting fields in science (Tanimoto 2019) [16]. Hofbauer et al. (2003) and Dindo et al. (2011) also proposed that evolutionary game theory is an effective tool to study the influence of institutional evolution through the selection of strategies, such as multi-agent learning adjustment and group imitation [17,18]. Combined with evolutionary game tools, the asymmetric game model has been widely used in drug quality supervision, COVID-19 pandemic control in the medical field, and waste disposal in other fields (Ding et al., 2018; Rong et al., 2020; Wei et al., 2020; Yu et al., 2020) [19–22].

Taking the asymmetric model as the starting point of logical analysis, the evolutionary game systems of disposal enterprises and local governments are established under four scenarios: static reward and static penalty, dynamic reward and static penalty, static reward and dynamic penalty, and dynamic reward and dynamic penalty. Then, the evolutionary stability of the game system is analyzed, and the evolutionary trajectory and influencing factors are studied. The main problems to be solved in this paper are as follows:

(1) What are the evolution characteristics of the game system between disposal enterprises and local governments under different reward and penalty modes?
(2) Which reward and penalty model implemented by local governments under the supervision of medical waste disposal has the best effect?
(3) How does reward and penalty affect the evolution of behavioral strategies of disposal enterprises and local governments?

The remainder of this paper is structured as follows. Section 2 summarizes the relevant literature. Section 3 establishes and analyzes the evolutionary game system of disposal enterprises and local governments under the static reward and penalty model. Section 4 establishes and analyzes the evolutionary game system of disposal enterprise and local government behaviors under the dynamic reward and penalty model according to the shortcoming in Section 3. Section 5 provides a case study to simulate and discuss the evolution effect of the game systems under different reward and penalty modes. Section 6 gives the main conclusions and limitations.

2. Literature Review

According to the research purposes of this paper, the related literature can be divided into two categories: medical waste management and the government's reward and penalty for medical waste disposal.

2.1. Research on Medical Waste Management

Medical waste is a special pollutant produced by medical institutions in the process of medical treatment, prevention and related medical activities (Lee et al., 1991) [23]. It includes infectious waste, sharps waste, radioactive waste, chemical waste, etc. (Win et al., 2019) [24]. With the continuous increase of medical waste, scholars have carried out in-depth research on the generation, recovery and disposal of medical waste from the perspective of the management process. Table 1 summarizes the key research content in detail. Especially during the COVID-19 pandemic, medical waste management has become a high priority public health and environmental concern issue (Tsai et al., 2021) [25].

Limited studies have been conducted to assess the amount of infectious medical waste generation (Mihai 2020; Maalouf et al., 2021) [26,27] or to study the design and optimization of reverse logistics networks for medical waste management under specific constraints or requirements, such as disposal capacity, time, and risk (Yu et al., 2020; Kargar et al., 2020; Gao et al., 2021) [1,28,29].

Table 1. Summary of research content related to medical waste management.

Research Field	Research Content	References
The generation of medical waste	Prediction of medical waste generation based on statistical or econometric models	[30–32]
	Horizontal and vertical comparisons of medical waste generation rate	
	Key factors affecting the generation of medical waste	
The recovery of medical waste	The evaluation of medical waste recovery	[1,28,29,33,34]
	The optimization of recovery mode	
	The design of a recovery network path	
The disposal of medical waste	Medical waste disposal technological application and innovation	[35–39]
	Medical waste disposal method assessment	
	Pollution level measurement for medical waste disposal	
	Medical waste disposal behavior	

2.2. *Research on the Government's Reward and Penalty for Medical Waste Disposal*

The positive performance of relevant laws, regulations, and standards on medical waste disposal has been extensively tested by scholars (Perry et al., 2012; Tabrizi et al., 2019) [40,41]. Some scholars further explored the necessity of the government's reward and penalty system for medical waste disposal. For example, Sarker et al. (2014) evaluated the medical waste disposal practices of hospitals with different levels in Bangladesh. They found that 44% of doctors and 56% of cleaning personnel had improper operation and therefore proposed the necessity for the government to increase reward support to solve obstacles, such as the lack of medical waste disposal equipment and personnel training [42]. Niyongabo et al. (2019) investigated the medical waste disposal practices in 12 medical institutions in Bujumbura and found that 92.8% of medical waste is directly buried or incinerated because of the government's failure to provide adequate financial support [43]. Based on the lack of traceability, operational transparency, and safety of medical waste management under the COVID-19 pandemic, Ahmad et al. (2021) defined interaction rules regarding COVID-19 waste disposal and imposed penalty measures [44]. Additionally, scholars have also paid attention to the importance of government supervision in the implementation of the reward and penalty mechanism. Coker et al. (2009) analyzed the medical waste generation situation of 400 medical institutions in 11 regions in Nigeria and proposed that the government should strengthen the monitoring of medical waste disposal [45]. Al-Khatibt et al. (2020) investigated the current situation of medical waste classification and landfill disposal in three hospitals in Palestine and suggested that the government can strengthen the supervision of medical waste classification and disposal through the cooperation of the Ministry of Health, the Bureau of Environmental quality, and non-governmental organizations [46].

In conclusion, the research results related to medical waste management are relatively abundant, which has important reference and informational value for this paper. However, although most scholars have suggested that the government needs to strengthen supervision, reward support, or financial penalize those who incorrectly dispose of medical waste, few scholars have deeply explored the internal mechanism of government's reward and penalty measures on medical waste disposal behavior. Notably, most of the government reward and penalty models involved in the application of the evolutionary game are static, which hardly reflects essential utility. Compared with the existing research results, the main contributions are: (1) Under the special background of the COVID-19 pandemic, research on medical waste disposal and supervision issues has a certain timeliness which not only makes up for the lack of research on medical waste disposal, but also provides theoretical support for local governments to design effective reward and penalty models. (2) This paper puts forward the dynamic reward and punishment mode in government supervision innovatively, compares the evolution law of medical waste disposal and supervision system under one static and three dynamic reward and penalty modes, and clarifies the differences of medical waste disposal enterprise and government behavior strategies and the influence mechanism of key influencing factors under the four reward and penalty modes. (3) The evolutionary game theory is applied to the field of medical waste disposal, and the evolution process of the game behavior of disposal enterprises and local governments is described by computational experiment simulation, which expands the application research of the evolutionary game model.

3. Construction and Analysis of Evolutionary Game Model under Static Reward and Penalty Mode

3.1. Problem Description

In the process of medical waste disposal, local governments and disposal enterprises are the core participants, and their behavior choices have a major impact on the surrounding environmental health and disease prevention and control. Under the premise of market-oriented operation mechanisms, disposal enterprises always take the maximization of interests as the decision-making goal. In comparison, government departments take the environmental management of medical waste as the purpose; they are responsible for the supervision of disposal enterprises and the formulation of corresponding reward and penalty measures. At present, the static reward and penalty model is the main incentive and deterrence method adopted by local governments in China. That is, the reward and penalty set by the government departments are fixed regardless of the changes in the disposal enterprises' medical waste disposal strategy. Therefore, this mode can be called the static reward and static penalty mode.

In addition, according to the actual disposal situation of medical waste, local governments can choose two strategies: "strict supervision" and "relaxed supervision". "Strict supervision" refers to the use of scientific and technological means to strictly control disposal enterprises, including the working conditions of medical waste entrances, incineration plants, and fly ash storage to prevent environmental pollution, disease transmission, and other risk events. "Relaxed supervision" refers to the use of conventional means to supervise the disposal process of medical waste. Correspondingly, the strategies of disposal enterprises are divided into "high-quality disposal" and "low-quality disposal". "High-quality disposal" refers to the recovery and disposal of medical waste with higher standards and specifications, such as raising sterilization temperature and extending sterilization time during the COVID-19 pandemic. "Low-quality disposal" refers to the recovery and disposal of medical waste using conventional standards. Driven by short-term interests, disposal enterprises violate relevant regulations on medical waste disposal or do not take special protective measures in cases of major outbreaks such as the COVID-19 pandemic.

3.2. Basic Assumptions and Game Model Construction

For the convenience of analysis, the following basic assumptions are given. Table 2 lists definitions of the parameters included in the assumptions.

Table 2. The definitions of parameters.

Parameter	Definition
p	The probability of being discovered when disposal enterprises implement low-quality disposal
q	The probability of risky occurrence when disposal enterprises implement low-quality disposal
e	The reward given by local governments when disposal enterprises implement high-quality disposal
r	The revenue obtained by disposal enterprises
g	The environmental income obtained by local governments
f	The penalty imposed by local governments
s	The remedial cost borne by local governments
w	The cost by disposal enterprises that arise from potential risk loss
c	The supervision cost of strict supervision
αc	The supervision cost of relaxed supervision
d	The disposal cost of high-quality disposal
βd	The disposal cost of low-quality disposal

Assumption 1: According to the basic nature of the evolutionary game (Smith 1974) [47], local governments and disposal enterprises have bounded rationality and take decision-making behaviors based on their own interests. The probability of a "strict supervision" strategy by local governments is x, whereas the probability of a "relaxed supervision" strategy is $1-x$. Similarly, the probability of a "high-quality disposal" strategy by disposal enterprises is y, whereas the probability of a "low-quality disposal" strategy is $1-y$.

Assumption 2: If local governments implement strict supervision, the low-quality or high-quality strategy of medical waste disposal can be accurately identified. Conversely, the probability of a "low-quality disposal" strategy being discovered under local governments' relaxed supervision is p. Furthermore, the supervision costs of the "strict supervision" and "relaxed supervision" strategies are c and αc, respectively.

Assumption 3: From the regional centralized disposal system of medical waste in China (Chen et al., 2021) [7], the revenue obtained by disposal enterprises through collecting medical waste from medical institutions in the region is r. If disposal enterprises implement high-quality disposal, the environmental income obtained by local governments is g, and the reward given by local governments to disposal enterprises is e. Moreover, the penalty imposed by local governments is f. Finally, the disposal costs of the "high-quality disposal" and "low-quality disposal" strategies are d and βd, respectively.

Assumption 4: Compared with general solid waste, medical waste has a higher risk of environmental pollution and disease spread (Chaerul et al., 2008) [48]. Therefore, when similar risk events occur, the remedial cost borne by local governments is s, whereas the cost faced by disposal enterprises that arise from potential risk loss, such as reputation loss and the reduction of the recovery price of medical waste, is w.

Assumption 5: Based on the research of Liu et al. (2018) [49], risk events will occur only in the case of low-quality disposal by disposal enterprises and relaxed supervision by local governments because of the contingencies of risks. We set the probability of risky occurrence as q.

In the assumptions, $x \in [0, 1]$, $y \in [0, 1]$, $\alpha \in (0, 1)$, $\beta \in (0, 1)$, $p \in [0, 1]$, and $q \in [0, 1]$. Risk events, such as environmental pollution and disease transmission, have negative externalities; hence, the local governments' remedial losses are far greater than the cost of strict supervision, that is, $qs > c$. According to the above assumptions, the payment matrix of the game between disposal enterprises and local governments is shown in Table 3.

Table 3. The payment matrix of the evolutionary game model.

Players		Local Governments	
		Strict Supervision	**Relaxed Supervision**
Disposal enterprises	high-quality disposal	$\begin{bmatrix} g-c-e, \\ r+e-d \end{bmatrix}$	$\begin{bmatrix} g-\alpha c-e, \\ r+e-d \end{bmatrix}$
	low-quality disposal	$\begin{bmatrix} f-c, \\ r-f-\beta d \end{bmatrix}$	$\begin{bmatrix} pf-(1-p)e-\alpha c-qs, \\ r+(1-p)e-pf-qw-\beta d \end{bmatrix}$

Combined with the Malthusian dynamic equation theorem, the expected returns of local governments with the two different strategies (strict or relaxed supervision) and the average expected return are as follows:

$$\begin{cases} U_{11} = y(g-c-e) + (1-y)(f-c) \\ U_{12} = y(g-\alpha c-e) + (1-y)[pf-(1-p)e-\alpha c-qs] \\ \overline{U}_1 = xU11 + (1-\mathrm{x})U12 \end{cases} \tag{1}$$

Therefore, the replication dynamic equation $U(x)$ of local governments is:

$$U(x) = \frac{dx}{dt} = x(U11 - \overline{U}1) = x(1-x)\{qs + (1-p)(e+f) - (1-\alpha)c - y[qs + (1-p)(e+f)]\} \tag{2}$$

Similarly, the expected returns of disposal enterprises with the two different strategies (high-quality or low-quality disposal) and the average expected return are:

$$\begin{cases} U_{21} = x(r+e-d) + (1-x)(r+e-d) \\ U_{22} = x(r-f-\beta d) + (1-x)[r+(1-p)e-pf-qw-\beta d] \\ \overline{U}_2 = yU_{21} + (1-\mathrm{y})U_{22} \end{cases} \tag{3}$$

The replication dynamic equation $U(y)$ of disposal enterprises is:

$$U(y) = \frac{dy}{dt} = y(U21 - \overline{U}_2) = y(1-y)\{qw + p(e+f) - (1-\beta)d - x[qw - (1-p)(e+f)]\} \tag{4}$$

3.3. Analysis of the Stability of the Game Model under the Static Reward and Penalty Mode

Let Formula (2), $U(x) = 0$, and Formula (4), $U(y) = 0$, then:

$$x_1 = 0,\ x_2 = 1,\ y_1^* = \tfrac{qs+(1-p)(e+f)-(1-\alpha)c}{qs+(1-p)(e+f)},$$
$$y_1 = 0,\ y_2 = 1,\ x_1^* = \tfrac{qw+p(e+f)-(1-\beta)d}{qw-(1-p)(e+f)}.$$

Thus, the game system always has four fixed equilibrium points, namely, (0, 0), (1, 0), (0, 1), and (1, 1). When $0 \le [qw + p(e+f) - (1-\beta)d]/[qw - (1-p)(e+f)] \le 1$ and $0 \le [qs + (1-p)(e+f) - (1-\alpha)c]/[qs + (1-p)(e+f)] \le 1$, $(x_1^*,\ y_1^*)$ is also an equilibrium point of the game system. Meanwhile, the Jacobian matrix can be obtained by solving Formulas (2) and (4) as shown in Formula (5):

$$J(x,y) = \begin{bmatrix} \frac{\partial U(x)}{\partial x} & \frac{\partial U(x)}{\partial y} \\ \frac{\partial U(y)}{\partial x} & \frac{\partial U(y)}{\partial y} \end{bmatrix}$$
$$= \begin{bmatrix} (1-2x)\begin{Bmatrix} qs + (1-p)(e+f) - (1-\alpha)c \\ -y[qs + (1-p)(e+f)] \end{Bmatrix} & -x(1-x)[qs + (1-p)(e+f)] \\ -y(1-y)[qw - (1-p)(e+f)] & (1-2y)\begin{Bmatrix} qw + p(e+f) - (1-\beta)d \\ -x[qw - (1-p)(e+f)] \end{Bmatrix} \end{bmatrix} \tag{5}$$

According to the research method proposed by Friedman (1998) [50], if the conditions, $Det(J) = \frac{\partial U(x)}{\partial x} * \frac{\partial U(y)}{\partial y} - \frac{\partial U(x)}{\partial y} * \frac{\partial U(y)}{\partial x} > 0$ and $Tr(J) = \frac{\partial U(x)}{\partial x} + \frac{\partial U(y)}{\partial y} < 0$, are met, then the game system will be locally stable. The results of the five equilibrium points of the game system under the static reward and static penalty mode are shown in Table 4, and the results of the stability analysis are shown in Table 5. To simplify the statement in the Tables 4 and 5, we set $H_1 = qs + (1-p)(e+f) - (1-\alpha)c$, $H_2 = qw + p(e+f) - (1-\beta)d$, $H_3 = e + f - (1-\beta)d$, $H_4 = qw - (1-p)(e+f)$ and $H_5 = qs + (1-p)(e+f)$. Obviously, we can know $H_1 > 0$ and $H_5 > 0$ from the condition of $qs > c$.

Table 4. Results of *Det*(*J*) and *Tr*(*J*) under the static reward and static penalty mode.

Equilibrium Point	*Det*(*J*)	*Tr*(*J*)
(0, 0)	$H_1 * H_2$	$H_1 + H_2$
(1, 0)	$-H_1 * H_3$	$-H_1 + H_3$
(0, 1)	$(1-\alpha)c * H_2$	$-(1-\alpha)c - H_2$
(1, 1)	$-(1-\alpha)c * H_3$	$(1-\alpha)c - H_3$
(x_1^*, y_1^*)	$-H_1 * H_2 * (1 - \frac{H_2}{H_4}) * (1 - \frac{H_1}{H_5})$	0

Table 5. Results of stability analysis under the static reward and static penalty mode.

Equilibrium Point	$H_3 > 0$								
	$0 < H_4 < H_2$			$H_4 < 0 < H_2$			$H_4 < H_2 < 0$		
	Det(*J*)	*Tr*(*J*)	Stability	*Det*(*J*)	*Tr*(*J*)	Stability	*Det*(*J*)	*Tr*(*J*)	Stability
(0, 0)	+	+	Unstable point	+	+	Unstable point	−	+/−	Saddle point
(1, 0)	−	+/−	Saddle point	−	+/−	Saddle point	−	+/−	Saddle point
(0, 1)	+	−	ESS	+	−	ESS	−	+/−	Saddle point
(1, 1)	−	+/−	Saddle point	−	+/−	Saddle point	−	+/−	Saddle point
(x_1^*, y_1^*)		Meaningless			Meaningless		+	0	Center point
Equilibrium point	$H_3 < 0$								
	$0 < H_2 < H_4$			$H_2 < 0 < H_4$			$H_2 < H_4 < 0$		
	Det (*J*)	*Tr* (*J*)	Stability	*Det* (*J*)	*Tr* (*J*)	Stability	*Det* (*J*)	*Tr* (*J*)	Stability
(0, 0)	+	+	Unstable point	−	+/−	Saddle point	−	+/−	Saddle point
(1, 0)	+	−	ESS	+	−	ESS	+	−	ESS
(0, 1)	+	−	ESS	−	+/−	Saddle point	−	+/−	Saddle point
(1, 1)	+	+	Unstable point	+	+	Unstable point	+	+	Unstable point
(x_1^*, y_1^*)	−	0	Center point		Meaningless			Meaningless	

Note: ESS (Evolutionary Stable Strategy).

According to the results in Table 5, the game system has no asymptotic stability point when $H_3 > 0$ and $H_4 < H_2 < 0$, but at least one asymptotic stability point is found in all other situations. Furthermore, when the game system has no asymptotic stability point, the evolution trajectory of the system is a closed-loop orbit around the central point (Taylor et al., 1978) [51], (x_1^*, y_1^*), as shown in Figure 2. Thinking in terms of economics, disposal enterprises can obtain the maximum expected benefits by adopting the "low-quality disposal" strategy under the above conditions of $H_3 > 0$ and $H_4 < H_2 < 0$, but this behavior is contrary to the original intention of local governments to dispose of medical waste. Therefore, local governments will take more strict regulatory measures, and disposal enterprises will adopt the "high-quality disposal" strategy under the pressure of government supervision. However, the high cost of long-term strict supervision makes local governments face financial difficulties to a certain extent. After disposal enterprises implement the "high-quality disposal" strategy, local governments will transition from strict supervision to relaxed supervision. Finally, disposal enterprises will gradually return to the "low-quality disposal" strategy, and the strategic choice of both game players will enter a vicious circle.

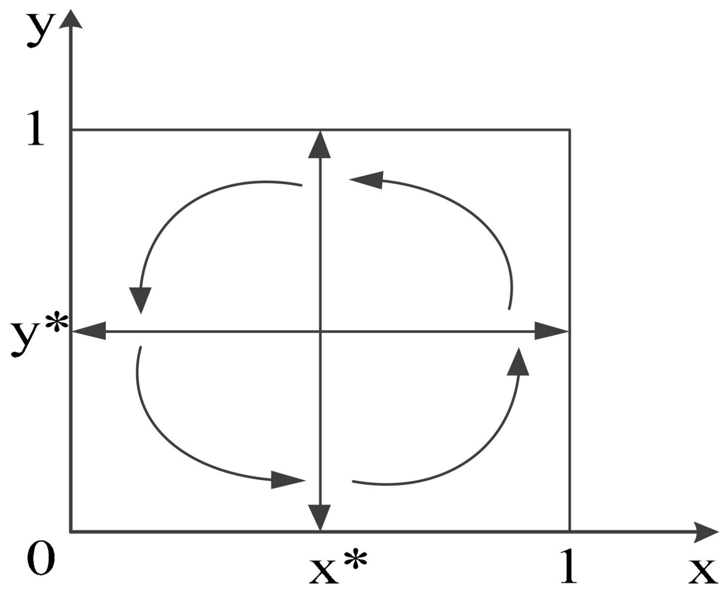


Figure 2. The evolution path of the game system without asymptotically stability points.

4. Construction and Analysis of the Evolutionary Game Model under Dynamic Reward and Penalty Mode

Meng et al. (2021) [52] and Liu et al. (2021) [53] proved that the dynamic reward and penalty mechanism is an effective way to relieve the burden of government financial expenditure. Specifically, the rewards or penalties set by local governments are continuously dynamic, and the amount of reward or penalty is related to the behavioral strategies of disposal enterprises. For example, the higher the probability of the disposal enterprises choosing the "low-quality disposal" strategy, the more likely the upper limit of the reward and penalty can be appropriately increased so as to produce a more effective incentive and deterrent effect. On the contrary, the upper limit of reward and penalty can be reduced, so as to avoid the failure of reward and penalty mode and the consumption of additional financial expenditure caused by the inflexible and unrealistic static reward and penalty policies. Therefore, we assume that government rewards and penalties are a linear function of the probability of the disposal enterprise's behavioral strategy. That is, the reward is $E(y) = ye$, and the penalty is $F(y) = (1 - y)f$.

According to the change of reward or penalty, the dynamic reward and penalty mode can be further divided into dynamic reward mode, dynamic penalty mode, and dynamic reward and dynamic penalty mode. Among them, the dynamic reward mode means that the reward is set as a dynamic parameter with the change of disposal enterprise behavior strategy while the penalty is set as a fixed parameter; therefore, it is also called the dynamic reward and static penalty mode. The dynamic penalty mode means that the penalty is set as a dynamic parameter while the reward is set as a fixed parameter; therefore, it is also called the static reward and dynamic penalty mode. Similarly, the dynamic reward and dynamic penalty mode means that reward and penalty are set as dynamic parameters.

4.1. Game Model Construction and Stability Analysis under Dynamic Reward and Static Penalty Mode

We replace e in Formulas (2) and (4) with $E(y) = ye$, and obtain the replication dynamic equation of local governments and disposal enterprises under dynamic reward and static penalty mode as follows:

$$\begin{cases} U(x) = \frac{dx}{dt} = x(1-x)\{qs + (1-p)(ye+f) - (1-\alpha)c - y[qs + (1-p)(ye+f)]\} \\ U(y) = \frac{dy}{dt} = y(1-y)\{qw + p(ye+f) - (1-\beta)d - x[qw - (1-p)(ye+f)]\} \end{cases} \quad (6)$$

According to Formula (6), the four fixed equilibrium points are (0, 0), (1, 0), (0, 1), and (1, 1). When $0 \leq [qw + p(E(y)+f) - (1-\beta)d]/[qw - (1-p)(E(y)+f)] \leq 1$ and

$0 \leq [qs + (1-p)(E(y)+f) - (1-\alpha)c]/[qs + (1-p)(E(y)+f)] \leq 1$, $(x_2^*,\ y_2^*)$ is another system equilibrium point, where $x_2^* = \frac{qw+p(E(y)+f)-(1-\beta)d}{qw-(1-p)(E(y)+f)}$ and $y_2^* = \frac{qs+(1-p)(E(y)+f)-(1-\alpha)c}{qs+(1-p)(E(y)+f)}$.

The Jacobian matrix of the game system under the dynamic reward and static penalty mode is given in Formula (7):

$$J(x,y) = \begin{bmatrix} (1-2x)\begin{Bmatrix} qs+(1-p)(ye+f)-(1-\alpha)c \\ -y[qs+(1-p)(ye+f)] \end{Bmatrix} & x(1-x)[(1-p)(e-f-2ye)-qs] \\ -y(1-y)[qw-(1-p)(ye+f)] & \begin{matrix} (1-2y)\begin{Bmatrix} qw+p(ye+f)-(1-\beta)d \\ -x[qw-(1-p)(ye+f)] \end{Bmatrix}+ \\ y(1-y)[pe+(1-p)ex] \end{matrix} \end{bmatrix} \tag{7}$$

Based on the above Jacobian matrix, the stability of equilibrium point (1, 0) is also affected by the relationship between f and $(1-\beta)d$. If $f < (1-\beta)d$ is met, the equilibrium point (1, 0) is the asymptotic stability point of the game system, but the stability of other equilibrium points is not affected, as shown in Table 6.

Table 6. Results of stability analysis under the dynamic reward and static penalty mode.

Equilibrium Point	*Det(J)*	*Tr(J)*	Stability
(0, 0)	−	+/−	Saddle point
(1, 0)	+	−	ESS
(0, 1)	−	+/−	Saddle point
(1, 1)	−	+/−	Saddle point
$(x_2^*,\ y_2^*)$	+/−	0	Unstable point

4.2. Game Model Construction and Stability Analysis under Static Reward and Dynamic Penalty Mode

We replace f in Formulas (2) and (4) with $F(y) = (1-y)f$ and obtain the replication dynamic equation of local governments and disposal enterprises under static reward and dynamic penalty mode as follows:

$$\begin{cases} U(x) = \frac{dx}{dt} = x(1-x)\{qs+(1-p)(e+(1-y)f)-(1-\alpha)c-y[qs+(1-p)(e+(1-y)f)]\} \\ U(y) = \frac{dy}{dt} = y(1-y)\{qw+p(e+(1-y)f)-(1-\beta)d-x[qw-(1-p)(e+(1-y)f)]\} \end{cases} \tag{8}$$

According to Formula (8), the four fixed equilibrium points are (0, 0), (1, 0), (0, 1), and (1, 1). When $0 \leq [qw + p(e+F(y)) - (1-\beta)d]/[qw - (1-p)(e+F(y))] \leq 1$ and $0 \leq [qs + (1-p)(e+F(y)) - (1-\alpha)c]/[qs + (1-p)(e+F(y))] \leq 1$, $(x_3^*,\ y_3^*)$ is another system equilibrium point, where $x_3^* = \frac{qw+p(e+F(y))-(1-\beta)d}{qw-(1-p)(e+F(y))}$ and $y_3^* = \frac{qs+(1-p)(e+F(y))-(1-\alpha)c}{qs+(1-p)(e+F(y))}$.

The Jacobian matrix of the game system under the static reward and dynamic penalty mode is given in Formula (9):

$$J(x,y) = \begin{bmatrix} (1-2x)\begin{Bmatrix} qs+(1-p)(e+(1-y)f)-(1-\alpha)c \\ -y[qs+(1-p)(e+(1-y)f)] \end{Bmatrix} & x(1-x)[(1-p)(2yf-2f-e)-qs] \\ -y(1-y)[qw-(1-p)(e+(1-y)f)] & \begin{matrix} (1-2y)\begin{Bmatrix} qw+p(e+(1-y)f)-(1-\beta)d \\ -x[qw-(1-p)(e+(1-y)f)] \end{Bmatrix}- \\ y(1-y)[pf+(1-p)fx] \end{matrix} \end{bmatrix} \tag{9}$$

Based on the above Jacobian matrix, the $Det(J)$ and $Tr(J)$ symbols of equilibrium point (1, 1) are affected by the relationship between e and $(1-\beta)d$. However, regardless of whether the relationship between e and $(1-\beta)d$ changes, (1, 0) cannot evolve into a stability point. The stability results of the five equilibrium points of the game system are shown in Table 7 with $e > (1-\beta)d$ as the example. The results showed that (0, 0), (1, 0), (0, 1), and (1, 1) are all saddle points or unstable points, whereas $(x_3^*,\ y_3^*)$ has asymptotic stability. Therefore, the game system remains stable at $(x_3^*,\ y_3^*)$.

Table 7. Results of stability analysis under the static reward and dynamic penalty mode.

Equilibrium Point	*Det(J)*	*Tr(J)*	Stability
(0, 0)	−	+	Unstable point
(1, 0)	−	+/−	Saddle point
(0, 1)	−	+/−	Saddle point
(1, 1)	−	+/−	Saddle point
(x_3^*, y_3^*)	+	−	ESS

4.3. Game Model Construction and Stability Analysis under Dynamic Reward and Dynamic Penalty Mode

Similarly, we replace e and f with $E(y) = ye$ and $F(y) = (1-y)f$, respectively, in Formulas (2) and (4) and obtain the replication dynamic equation of local governments and disposal enterprises under dynamic reward and dynamic penalty mode as follows:

$$\begin{cases} U(x) = \frac{dx}{dt} = x(1-x)\{qs + (1-p)(ye + (1-y)f) - (1-\alpha)c - y[qs + (1-p)(ye + (1-y)f)]\} \\ U(y) = \frac{dy}{dt} = y(1-y)\{qw + p(ye + (1-y)f) - (1-\beta)d - x[qw - (1-p)(ye + (1-y)f)]\} \end{cases} \tag{10}$$

According to Formula (10), the four fixed equilibrium points are (0, 0), (1, 0), (0, 1), and (1, 1). When $0 \leq [qw + p(E(y) + F(y)) - (1-\beta)d]/[qw - (1-p)(E(y) + F(y))] \leq 1$ and $0 \leq [qs + (1-p)(E(y) + F(y)) - (1-\alpha)c]/[qs + (1-p)(E(y) + F(y))] \leq 1$, (x_4^*, y_4^*) is another system equilibrium point, where $x_4^* = \frac{qw+p(E(y)+F(y))-(1-\beta)d}{qw-(1-p)(E(y)+F(y))}$ and $y_4^* = \frac{qs+(1-p)(E(y)+F(y))-(1-\alpha)c}{qs+(1-p)(E(y)+F(y))}$.

The Jacobian matrix of the game system under the dynamic reward and dynamic penalty mode is given in Formula (11):

$$J(x,y) = \begin{bmatrix} (1-2x)\begin{Bmatrix} qs + (1-p)(ye + (1-y)f) - (1-\alpha)c \\ -y[qs + (1-p)(ye + (1-y)f)] \end{Bmatrix} & \begin{matrix} x(1-x)[(1-p)(e-f)(1-2y) \\ -(1-p)f - qs] \end{matrix} \\ -y(1-y)[qw - (1-p)(ye + (1-y)f)] & \begin{matrix} (1-2y)\begin{Bmatrix} qw + p(ye + (1-y)f) - (1-\beta)d \\ -x[qw - (1-p)(ye + (1-y)f)] \end{Bmatrix} + \\ y(1-y)(e-f)[p + (1-p)x] \end{matrix} \end{bmatrix} \tag{11}$$

The results of stability analysis showed that the stability of equilibrium point (1, 0) is consistent with that of the dynamic reward and static penalty mode, whereas the $Det(J)$ and $Tr(J)$ symbols of equilibrium point (1, 1) are consistent with the changes of the static reward and dynamic penalty. Therefore, we made $e > (1-\beta)d$ and $f > (1-\beta)d$ as the analysis conditions. The stability results of the five equilibrium points of the game system are shown in Table 8. Obviously, (0, 0), (1, 0), (0, 1), and (1, 1) are all saddle points, whereas (x_4^*, y_4^*) evolves ultimately into an asymptotic stability point.

Table 8. Results of stability analysis under the dynamic reward and dynamic penalty mode.

Equilibrium Point	*Det(J)*	*Tr(J)*	Stability
(0, 0)	−	+/−	Saddle point
(1, 0)	−	+/−	Saddle point
(0, 1)	−	+/−	Saddle point
(1, 1)	−	+/−	Saddle point
(x_4^*, y_4^*)	+	−	ESS

5. Case and Simulation Analysis

Medical waste disposal in Zhenjiang City, Jiangsu Province, China is used in the case study. We simulate the evolution process of the behavioral strategies of local governments and disposal enterprises under different reward and penalty modes. The simulation results have a certain reference importance for the formulation of the reward and penalty model of medical waste disposal in other areas.

5.1. A Case Study of Medical Waste Disposal in China

Zhenjiang New Universe Solid Waste Disposal Co., Ltd. is a medical waste disposal enterprise designated by the Zhenjiang municipal government in Jiangsu Province, China and holds a hazardous waste operation license issued by the provincial and municipal environmental protection departments. This disposal enterprise is responsible for the collection, disposal and comprehensive utilization of medical waste from more than 190 medical institutions. According to the operating situation, the regulatory cost savings of Zhenjiang's local government under "relaxed supervision" may reach 50% ($\alpha = 0.5$), and the disposal cost savings of Zhenjiang New Universe Solid Waste Disposal Co., Ltd. can reach about 70% ($\beta = 0.3$) when it reduces the disposal standard. For the convenience of calculation, we worked with the relevant personnel of the Zhenjiang local government and Zhenjiang New Universe Solid Waste Disposal Co., Ltd. and set strict supervision costs to $c = 20$, high-quality disposal costs to $d = 40$, government rewards to $e = 30$, government penalties to $f = 40$, risk costs to $w = 10$, and remediation costs for risk events to $s = 80$. In addition, the discovery probability of low-quality disposal and the occurrence probability of risk events are set as $p = 0.3$ and $q = 0.3$, respectively, because of the formalism of relaxed supervision and the contingency of risk events.

5.2. Numerical Simulation

In this section, we use the MATLAB software to perform numerical simulation and compare the evolution trajectory of the game system under the four reward and penalty modes. Finally, we identify the optimal reward and penalty mode and analyze the influence of rewards and penalties on the behavior strategies of disposal enterprises and local governments.

5.2.1. Evolution Trajectory of Game System under Different Modes

Based on the initial assignment of parameters, the evolution trajectory of the game system under the static reward and static penalty mode, static reward and dynamic penalty mode, and dynamic reward and dynamic penalty mode are simulated, as shown in Figure 3a,c,d, respectively. Parameter $f = 40$ is adjusted to $f = 20$ to satisfy the analysis condition of $f < (1 - \beta)d$ under the dynamic reward and static penalty mode, and the evolution trajectory of this game system is shown in Figure 3b. The comparison of the evolution trajectories of the game systems under the four reward and penalty modes reveals the following: (1) Under the static reward and static penalty mode (Figure 3a), the evolution trajectory of the game system is a closed-loop orbit that oscillates around the equilibrium point (x_1^*, y_1^*). Both game players keep learning and adjusting their behavioral strategies according to the benefits, but they cannot evolve to a stable state; (2) Under the dynamic reward and static penalty mode (Figure 3b), the equilibrium point $(1, 0)$ evolves into a stable point after repeated games between local governments and disposal enterprises. At this point, local governments choose the "strict supervision" strategy, but disposal enterprises still choose the "low-quality disposal" strategy; (3) Under the static reward and dynamic penalty mode (Figure 3c) and the dynamic reward and dynamic penalty mode (Figure 3d), the evolution trajectories of the game system show a spiral state and gradually converge after a short-term shock. Although the game system hardly evolves to a stable state, it tends to be close to the equilibrium point (x_3^*, y_3^*) or (x_4^*, y_4^*). That is, under a certain probability, local governments choose the "strict supervision" strategy and disposal enterprises choose the "high-quality disposal" strategy.

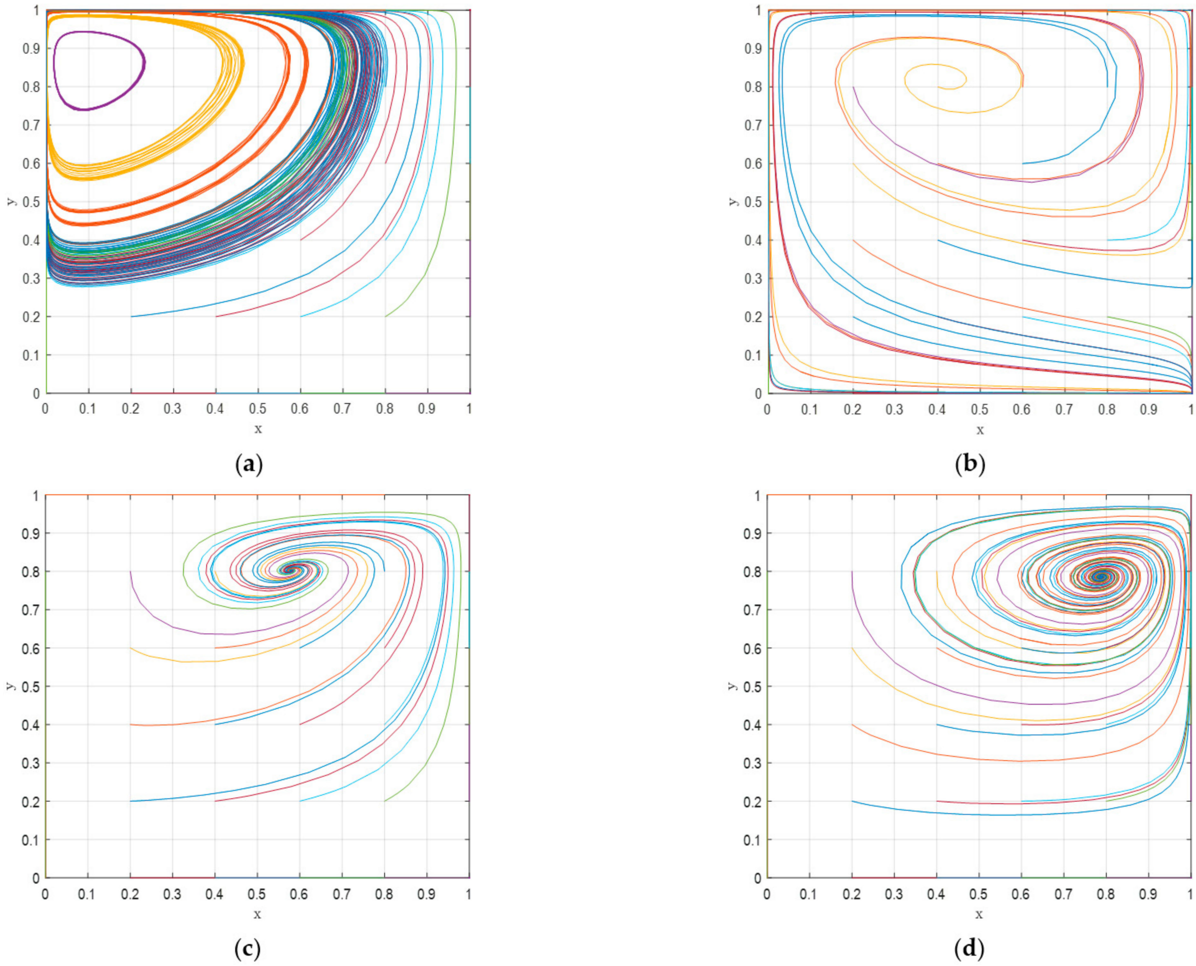
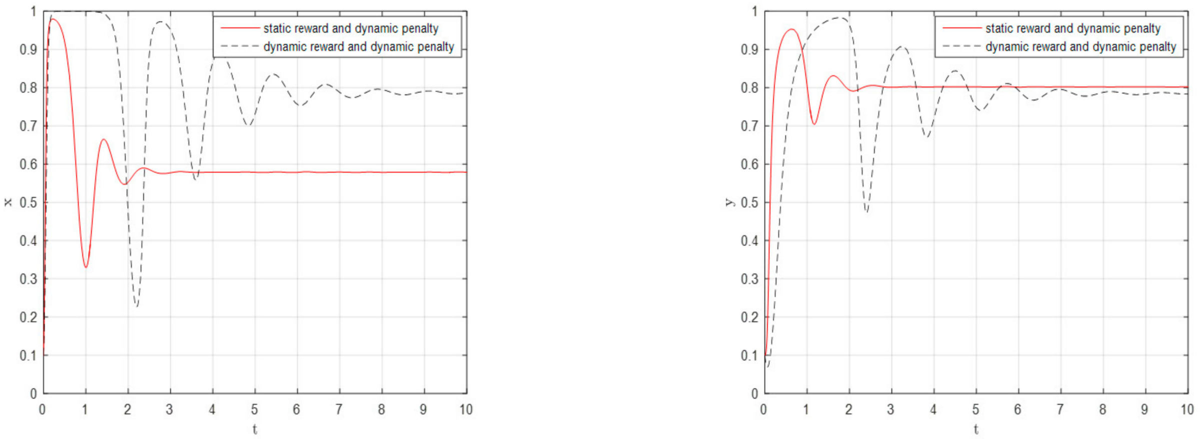


Figure 3. System evolutionary path under different reward and penalty modes. (**a**) static reward and static penalty mode. (**b**) dynamic reward and static penalty mode. (**c**) static reward and dynamic penalty mode. (**d**) dynamic reward and dynamic penalty mode.

5.2.2. Behavior of Game Players under Different Modes

The simulation results show that the reward and penalty models have a remarkable impact on the evolution trajectory of the game system. However, the evolution direction under the dynamic reward and static penalty mode does not conform to the social benefits of medical waste disposal. Therefore, the improved models, namely, the static reward and dynamic penalty mode and the dynamic reward and dynamic penalty mode, are more reasonable and conform to actual needs. We simulate the evolution law of behavior to further compare the effects of the two improved models on the behavior of local governments and disposal enterprises, and the results are shown in Figure 4a,b, respectively. The behavior of local governments and disposal enterprises tend to be stable after experiencing short-term shocks under both reward and penalty modes, and the amplitude of shocks under the dynamic reward and dynamic penalty mode is considerably higher than that under static reward and dynamic penalty mode. Furthermore, compared with the dynamic reward and dynamic penalty model, the period for local governments and disposal enterprises to stabilize is shorter, the probability that the disposal enterprises will choose the "high-quality disposal" strategy is slightly higher, and the probability of local governments to implement the "strict supervision" strategy is substantially lower under the static reward and dynamic penalty mode. Generally speaking, the static reward and dynamic penalty mode is better than the dynamic reward and dynamic penalty mode.

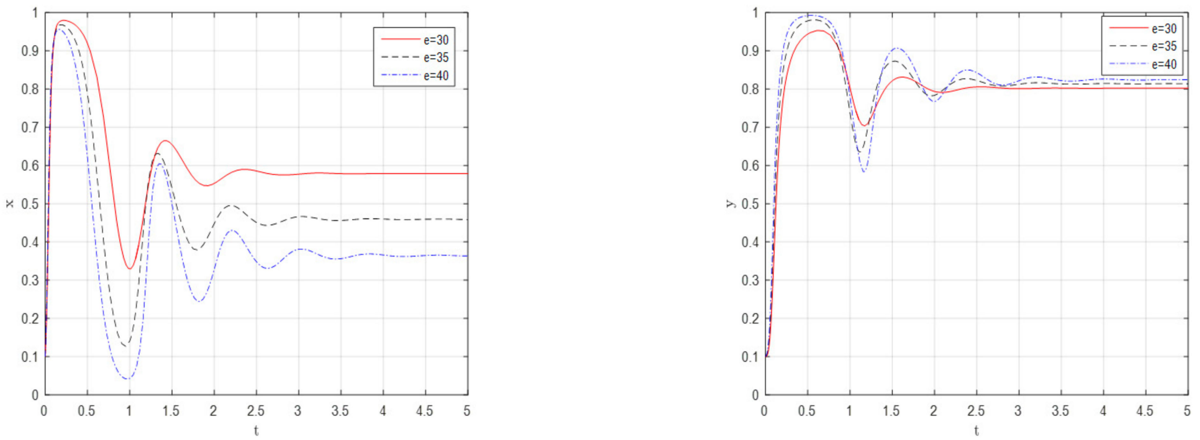


(**a**) (**b**)

Figure 4. Behavior of game players under different reward and penalty modes. (**a**) local governments. (**b**) disposal enterprises.

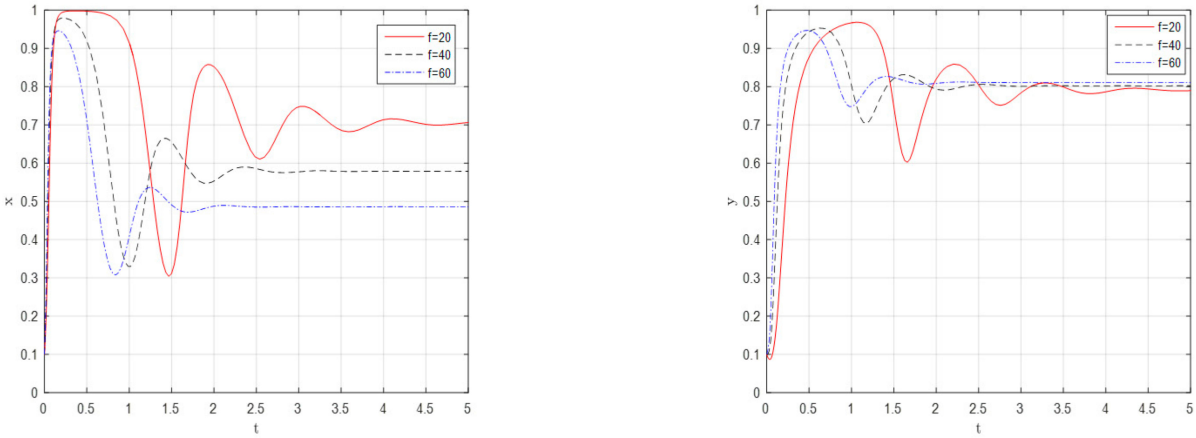
5.2.3. Impact of Reward and Penalty on the Behavior of Game Players

The static reward and dynamic penalty model is used as an example to further simulate the influence of reward (e) and penalty (f) on the behavior of local governments and disposal enterprises. The assignment of e and f is changed, whereas the assignment of the other parameters is consistent with the original assignment. The simulation results are shown in Figure 5a,b, and Figure 6a,b. Figure 5a,b show that with the increase in the amount of reward, the oscillation range of the behavior choice of local governments and disposal enterprises becomes larger, the period for the game process to be stable becomes longer, and the influence degree of the behavior of local governments is remarkably greater than that of disposal enterprises. Although the probability of disposal enterprises choosing the "high-quality disposal" strategy has a small increase, the trend of local governments favoring the "relaxed supervision" strategy is more remarkable. Similarly, Figure 6a,b show that with the increase in the amount of penalty, the oscillation range of the behavior choice becomes smaller, the period toward stability becomes shorter, and the influence degree of the behavior of local governments is also greater than that of disposal enterprises. In addition, the probability of disposal enterprises choosing the "high-quality disposal" strategy increases slightly, but not remarkably, whereas local governments choose the "relaxed supervision" strategy with a higher probability.



(**a**) (**b**)

Figure 5. The effect of reward on behavior of game players. (**a**) local governments. (**b**) disposal enterprises.



(a) (b)

Figure 6. The effect of penalty on behavior of game players. (**a**) local governments. (**b**) disposal enterprises.

5.3. Results Discussion

The stability analysis and simulation results show that the behavioral interaction mechanism between local governments and disposal enterprises is complex and diverse. In the given realistic assumptions, when the conditions, "$H_3 > 0$ and $H_4 < H_2 < 0$", are met, the game system between local governments and disposal enterprises has no ESS under the static reward and static penalty mode. This is consistent with the research conclusions of Meng et al. (2021) [52] and Liu et al. (2021) [53] in other fields. On the contrary, if the above conditions are not met, the game system under the static reward and static penalty mode will at least have one ESS. Particularly, the stable point $(0, 1)$ indicates that local governments choose the "relaxed supervision" strategy and disposal enterprises choose the "high-quality disposal" strategy, which is the most ideal state.

The optimization results show an ESS in the game system under the dynamic reward or dynamic penalty mode, and the optimization effect is remarkable. However, under the dynamic reward and static penalty mode, although local governments choose the "strict supervision" strategy, disposal enterprises still choose the "low-quality disposal" strategy, which does not meet the realistic needs of local governments. Meanwhile, under the other two modes (static reward and dynamic penalty or dynamic reward and dynamic penalty), the probability of disposal enterprises choosing the "high-quality disposal" strategy is consistent with 0.8, but the probability of local governments choosing the "strict supervision" strategy is about 0.6 and 0.8, respectively. In summary, the static reward and dynamic penalty mode is the most effective scheme to reduce the supervision pressure of local governments and to promote the disposal quality of medical waste to realize the ideal state, in which local governments do not need to strictly supervise all the time and disposal enterprises will also dispose medical waste with high standards.

Reward and penalty have an important influence on the interaction mechanism between local governments and disposal enterprises, and the degree of influence on the behavior of local governments is more obvious. On the one hand, long-term high reward makes local governments bear greater financial pressure, which may lead to management dilemmas (Wang et al., 2020) [54]. Therefore, the probability of local governments turning to relaxed supervision may increase. Furthermore, after receiving a government reward, disposal enterprises may have an opportunistic tendency and use the reward for other risk projects instead of improving the disposal quality of medical waste, which results in the invalidation of the government reward. On the other hand, when the increase in government penalty and the cost of disposal enterprises to improve the disposal quality of medical waste are not obvious, the deterrent force of penalty faced by disposal enterprises is not remarkable, and the disposal quality of medical waste becomes difficult to be remarkably improved. Nevertheless, with the favorable corporate phenomenon and public reputation brought by high-quality disposal behavior, disposal enterprises begin to pursue the excess return of long-term development. In summary, the dynamic reward and penalty model could be a useful tool for capacity-limited regulators to achieve an effective regulation of an enterprise's environmental behavior, and government should pay attention to the transitions from campaign-style enforcement to normal enforcement in China (Jin et al., 2017) [55]. That is, even if local governments no longer strictly supervise them, disposal enterprises will continue to improve the disposal quality of medical waste.

6. Conclusions

Based on evolutionary game theory, this paper constructs a game system between medical waste disposal enterprises and local governments and then analyses and compares the stability of the game system under four modes, namely, the static reward and static penalty mode, dynamic reward and static penalty mode, static reward and dynamic penalty mode, and dynamic reward and dynamic penalty mode. Compared with existing cases or investigation research in medical waste disposal (Sarker et al., 2014; Niyongabo et al., 2019; Ahmad et al., 2021) [1,42,43], this study reveals the internal evolution mechanism of the behavioral strategies of disposal enterprises and local governments under the influence of rewards and penalties and verifies the game system through numerical simulations. The main research conclusions and related suggestions are as follows.

First, the static reward and static penalty model implemented by local governments is not universal. Especially for some specific circumstances, the choice of behavior strategies between medical waste disposal enterprises and local governments enters a vicious circle, and the game system cannot evolve to a stable strategy combination point, which is not conducive to the improvement of the disposal quality of medical waste. Therefore, local governments need to optimize the static reward and penalty mode and make dynamic adjustments according to the behavior of medical waste disposal enterprises to achieve the best reward and penalty effect.

Second, among the three optimized dynamic reward and penalty models, the static reward and dynamic penalty model has the best effect. This mode can minimize the financial burden of local governments and improve the disposal quality of medical waste. Medical waste disposal enterprises and local governments have information asymmetry, that is, disposal enterprises deliberately hide medical waste disposal information in pursuit of high profits; therefore, the penalty policy of local governments cannot achieve the deterrent effect. Accordingly, local governments should broaden the channels of information feedback, improve the transparency of the behavior of medical waste disposal enterprises with the help of third-party forces, such as the public and the media, and implement the dynamic adjustment of penalties.

Finally, local governments play a leading role in medical waste disposal, and their reward and penalty policies and supervision measures have a remarkable impact on the behavior strategies of medical waste disposal enterprises. Particularly, disposal enterprises tend to implement a high-quality disposal strategy with the increase in reward and penalty. However, although excessive rewards put pressure on government finances, they also further reduce the marginal effect of incentives. Consequently, local governments should set different reward and penalty levels for different types of medical waste disposal enterprises. For example, if the disposal capacity of disposal enterprises is insufficient, local governments can increase the reward and reduce the penalty; if the strength of disposal enterprises is strong, local governments can give priority to supervision and penalty, and take reward as the secondary means.

This paper has some limitations. The research will be further expanded in two aspects in the future. First, the basic nature of evolutionary game theory determines the incompleteness of information between game players, which may lead to moral hazards and adverse selection. The design of a co-governance mechanism with the participation of other stakeholders (such as the media and the public) is worthy of further discussion in order to standardize the disposal of medical waste more effectively. Second, the choice of behavioral strategy of medical waste disposal enterprises does not completely depend on government rewards and penalties and is also disturbed by random external factors. We will draw lessons from the viewpoint of stochastically stable equilibrium (Foster et al., 1990) [56] and expand the game model accordingly

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