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Multi-Stakeholder Co-Evolution in Rural Solid Waste Governance in Northern China: Coupled Tripartite Evolutionary Game and System Dynamics Simulation

Li Jia [1], Jing Zhang [2], Xiaoxu Zhang [1] and Guanghua Qiao [1,*]

[1] College of Economics and Management, Inner Mongolia Agricultural University, Hohhot 010010, China; jiali@imau.edu.cn (L.J.); xiaoxu_zhang@emails.imau.edu.cn (X.Z.)
[2] Griffith Sciences, Griffith University, Brisbane 4111, Australia; jing.zhang@griffith.edu.au
* Correspondence: guanghua.qiao@imau.edu.cn

Abstract

Effective rural household waste sorting is essential for improving living conditions and advancing rural revitalization in China. Our study develops a tripartite evolutionary game model involving government, waste collection and disposal enterprises (WCDEs), and rural households, and it integrates the model with system dynamics simulations to examine strategic evolution, equilibrium outcomes, and key influencing factors. The baseline scenario was calibrated using evidence from Inner Mongolia, official data, field interviews, and expert assessments. The results show that system evolution is jointly shaped by government regulation, WCDE implementation, and rural household participation. The government plays a critical coordinating role, while the emergence of cooperative equilibrium depends on appropriate institutional incentives and regulatory conditions. Government strategies are particularly sensitive to regulatory costs, expenditures on public awareness campaigns, and investments in supporting infrastructure. WCDE strategies are primarily influenced by additional operating costs and government-imposed rewards and penalties, with reductions in subsidies exerting a stronger effect than increases in penalties. Rural household participation is constrained by the time and economic costs of waste sorting and is encouraged mainly by government incentives, whereas subsidies provided by WCDE have only a limited effect. Overall, effective governance requires balancing incentives for stakeholder participation against implementation costs, and different subsidy–penalty combinations may generate heterogeneous strategic responses across stakeholders. Our theoretical contributions lie in explicitly modeling the publicity-cost and supporting-facility-cost-sharing mechanisms between governments and WCDEs, identifying asymmetric stakeholder responses toward incentive–penalty instruments, and providing region-calibrated simulation evidence for RSWM multi-agent governance. Practically, it offers a reference for designing differentiated incentive policies for rural solid-waste management in northern China.

Keywords: multi-stakeholder governance; rural solid waste; waste classification; evolutionary game; system dynamics; China

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1. Introduction

Globally, approximately 2 billion tonnes of municipal solid waste are generated annually, at least 33% of which is not managed in an environmentally sustainable manner [1]. Recycling accounted for 19%, waste-to-energy for 13%, and sanitary landfilling for 30% of

total municipal solid-waste output worldwide [2]. Nevertheless, rural solid waste management (RSWM) remains substantially less developed than its urban counterpart, largely because of inadequate collection, transportation, and disposal infrastructure [3]. Rural solid waste (RSW) also differs markedly from urban waste in its composition and spatial distribution. It is generated across dispersed settlements, frequently mixed with agricultural pollutants, and may contain a high proportion of ash. Accordingly, waste treatment practices also differ between rural and urban areas: rural communities rely primarily on local composting and ash backfilling, whereas cities generally employ centralized incineration and industrialized sorting systems. Directly transferring the urban waste-management model to rural areas is therefore difficult. Dispersed settlement patterns can increase transportation costs by threefold to fivefold, while the high ash content of rural waste reduces incineration efficiency. These technical and economic constraints, together with the established waste-disposal practices of rural households, necessitate governance and treatment approaches tailored to rural conditions.

Using national population estimates and a hypothetical per capita rural solid-waste generation rate of 0.8 kg per capita per day in 2017, China's rural solid-waste output is roughly estimated at approximately 175 million tonnes [4]. In response to rising waste production, villages and towns have annually raised their investments in environmental sanitation. By 2021, the number of sanitation vehicles in towns in China had reached 120,000, while township sanitation investment grew from ¥1.46 million in 2015 to ¥2.14 million in 2022 [5]. However, due to inadequate management and limited technical capacity in rural areas, domestic waste collection and treatment remain insufficient, resulting in persistent open-field accumulation and indiscriminate dumping into rivers. In 2022, the harmless treatment rate of rural domestic waste in towns was only 62.30%, substantially lower than the 99.90% in cities and 99.24% in counties [5]. These figures underscore the urgent need to establish a practical and reliable RSWM system.

Recent studies on RSWM have primarily focused on behavioral drivers and management strategies [3,6–10]. However, relatively little attention has been paid to the strategic interactions among multiple stakeholders in waste management. Achieving multi-agent coevolution requires a collaborative system [11], with its success dependent on well-designed incentive policies. Beyond economic incentives, environmental behavior is also influenced by social norms, community expectations, environmental awareness, and individual characteristics. Rural household waste classification decisions are not only determined by direct economic returns but also by perceived social responsibility and collective behavioral expectations. However, these non-economic factors are difficult to quantify and integrate into a dynamic payoff-based framework. Therefore, this study focuses on economic and institutional mechanisms, including subsidies, penalties, governance costs, and benefit allocation, as the principal drivers affecting stakeholder strategy evolution.

The involvement of government, WCDE, and rural households is influenced by the actions of other stakeholders [12,13]. Under the polluter-pays and beneficiary-pays principles, rural households bear primary responsibility for RSWM [14]. Empirical evidence suggests that rural household participation in waste sorting and cost-sharing notably reduces waste accumulation [15]. However, given the public-good nature of waste management, the government plays a crucial role in safeguarding environmental health [10]. Meanwhile, WCDEs are incentivized by government policies to participate in RSW classification systems while ensuring sustainable operations through profit mechanisms [16]. Within this multi-stakeholder framework, dynamic interactions and continuous strategic adaptations among the parties call for further analysis of these complex, non-static relationships.

Inefficiencies in RSWM can be traced back to the conflicting interests and heterogeneous influences among stakeholders, including government, WCDE, and rural households [17].

Despite China's extensive policy and legal framework for urban and rural waste management, achieving effective RSWM remains an ongoing challenge [3]. The tripartite evolutionary-game model offers a robust analytical framework for unpacking strategic interactions within RSWM systems [18]. Rooted in game-theoretic logic, this approach uses mathematical formalisms to describe decision-making processes under bounded rationality. Departing from classical game theory, it captures behavioral evolution within structured groups, including dynamic strategy adaptation and altruistic behavioral patterns [19–21]. Such models have been widely deployed across diverse research domains, ranging from technology adoption [22,23] and environmental regulation [24] to policy evaluation [25,26]. Within solid-waste research specifically, they have been utilized to examine industrial waste disposal [27,28], municipal waste recycling [18], and food-waste treatment [21].

However, tripartite evolutionary game models are limited in their capacity to capture the intricate interactions among participants in complex systems and the dynamic adjustments of decision-makers in response to parameter changes. To address this, they are frequently integrated with system dynamics simulation, which is a mathematical modeling approach [19,20,29] that employs inventories, flows, internal feedback loops, table functions, and time delays to analyze nonlinear system behavior over time [21]. This combinatorial approach has become an important research paradigm for studying the dynamic evolution of complex systems and is increasingly applied in current research.

The three-party dynamic game under bounded rationality conditions in RSWM remains underexplored [30]. To address the above-mentioned research gaps, this paper follows a clear sequential research workflow. First, it clarifies the interest and responsibility boundaries of the three core stakeholders (government, WCDEs, and rural households) within rural solid-waste classification governance and constructs the corresponding game payoff matrix. Second, it derives the replicator dynamic equations to describe stakeholder strategy evolution under bounded rationality. Third, model parameters are calibrated based on official statistics and semi-structured field interview evidence collected from northern rural China. Fourth, the tripartite evolutionary-game model is implemented via system-dynamics numerical simulation to identify how key parameters shape evolutionary trajectories. Finally, simulation outputs are interpreted to draw targeted policy implications for promoting multi-stakeholder collaborative RSWM. The detailed modeling and analysis procedures are presented in Section 2.

The theoretical contributions of this study are threefold: it explicitly models the publicity cost and supporting facility cost-sharing mechanisms between the government and WCDEs, identifies asymmetric stakeholder responses toward incentive–penalty instruments, and provides region-calibrated simulation evidence for RSWM multi-agent governance. This study focuses on exploring behavioral interaction mechanisms rather than statistically estimating causal effects. In addition, it identifies the institutional conditions that facilitate cooperative governance rather than seeking mathematically optimal policy solutions. Furthermore, this study employs Vensim PLE 9.3.5 x64 (Vensim PLE (Personal Learning Edition, Ventana Systems, Inc., Harvard, MA, USA), a free-to-use system-dynamics modeling software for academic purposes; it numerically solves ordinary differential equations via stock-flow structures and generates time-series evolutionary trajectories, which we utilize to implement the tripartite replicator-dynamic model) to simulate evolutionary trajectories, evaluate variable impacts, explore stabilization strategies, and identify key drivers within the RSWM system.

2. Materials and Methods

2.1. Chain of Responsibility for RSWM

The "chain of responsibility" for RSW classification and management is reflected at the institutional level. The key to effective management lies in ensuring that all parties fulfill their responsibilities in accordance with the provisions of urban and rural household waste management regulations, thereby integrating the waste classification system into the broader governance framework [31]. Empirical evidence suggests that enhancing recycling facility accessibility, coupled with formalizing informal recycling markets, notably boosts resident participation in waste recycling, thereby advancing waste reduction goals [32]. The "waste classification" system codifies governmental oversight of waste collection, transportation, and disposal, delineating clear behavioral expectations for all parties. A clear "chain of responsibility" was established among the government, WCDE, and rural households, encompassing the entire process from planning and construction of RSW facilities to waste sorting, collection, transportation, treatment, and ultimately resource recovery, as shown in Figure 1.

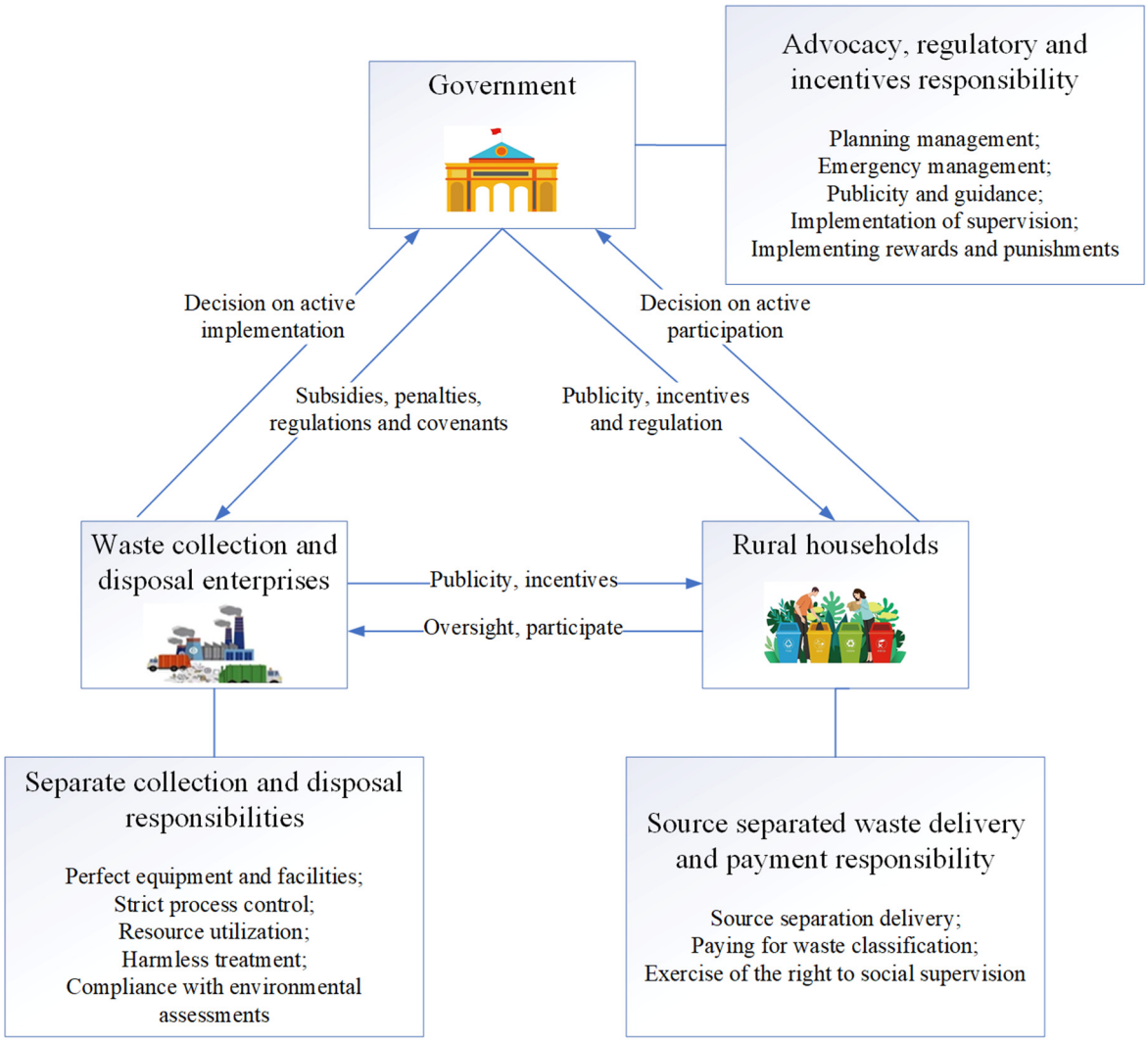

Figure 1. Schematic diagram of the chain of responsibility for rural-household solid waste classification.

The government serves as the core policymaker in institutionalizing the "chain of responsibility" for rural waste management through comprehensive regulatory measures. For WCDE, the government conducts regular inspections to ensure compliance with classified

transportation and disposal protocols while offering tax incentives to stimulate technological innovations for efficient waste treatment [33]. Regarding residents, the government mandates source segregation through village regulations and smart monitoring systems, implementing reward–penalty mechanisms such as reduced fees for proper sorting. WCDEs perform three critical operational functions. First, they deploy labeled vehicles to prevent mixed waste transport (with penalties up to ¥500,000 for violations) and optimize collection routes. Second, they apply advanced resource recovery technologies, such as pyrolysis, to meet at least 60% recycling targets while ensuring professional treatment of hazardous waste. Third, they balance operational costs through recycled material sales and government subsidies. Rural households, as primary waste generators, must adopt simplified classification categories (e.g., decomposable and non-decomposable) and reduce single-use items under "Clean Farming" policies, while also exercising oversight by reporting violations through hotlines and participating in government-led performance evaluations. This multi-stakeholder framework establishes an integrated system for effective rural waste management.

Rural and urban waste-classification systems share a tri-party governance framework of government supervision, enterprise operation, and resident participation, alongside incentive–penalty mechanisms. However, they differ in sorting implementation: cities can conduct secondary sorting thanks to complete facilities, whereas rural governance largely relies on source-separation by rural households. Rural areas are further constrained by scattered settlements, higher transportation costs, high-ash waste composition, simplified classification requirements, and limited supporting-infrastructure coverage.

2.2. Problem Description and Assumptions of the Three-Party Game

China's RSWM system involves three key stakeholders with distinct behavioral patterns. The government enforces management through either active regulation or passive regulation. WCDE may engage in either active implementation or negative implementation; rural households may choose to either follow the rules or break the rules. All parties operate under bounded rationality, dynamically adjusting strategies based on others' actions within this tripartite game-theoretic framework. The game tree model for RSW classification management is illustrated in Figure 2.

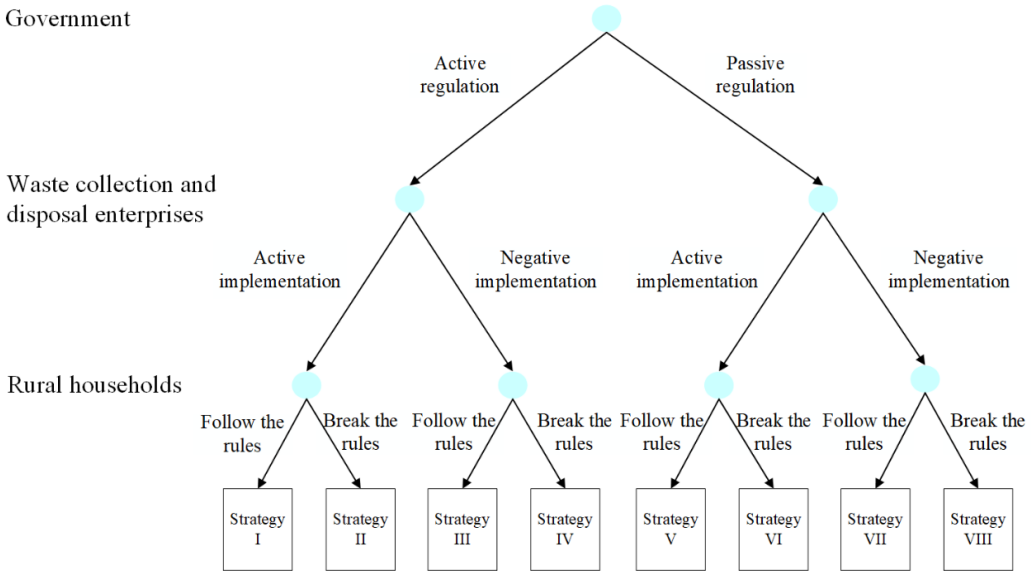

Figure 2. A game tree model for RSW classification management.

Figure 2 illustrates eight pure strategy combinations in the tripartite evolutionary game of RSWM: (1, 1, 1), (1, 1, 0), (1, 0, 1), (1, 0, 0), (0, 1, 1), (0, 1, 0), (0, 0, 1), and (0, 0, 0). Agents pursue payoff improvement via bounded-rational learning and strategy imitation, rather than perfect global utility maximization.

Fieldwork was carried out in June 2024. Villages were selected following purposive sampling logic, and interviewees included government administrative staff, representatives of WCDEs, 18 village-level cadres, and 124 rural households. Semi-structured interviews were conducted with pre-designed interview outlines; each interview lasted an appropriate duration, and participants were recruited through local village authorities. Interview records were processed via qualitative thematic coding. The acquired field insights were used to determine the cost–benefit structure and the relative magnitude range of model parameters, rather than for statistical regression-based parameter estimation. All interviews were anonymous without human-subject experimental interventions. Verbal informed consent was obtained from every participant prior to data collection, and all personally identifiable information was removed from interview materials.

2.3. Parameter Selection and Model Construction

For the government, the benefits of adopting an "active regulation" strategy depend on ecological benefit (E_b), fines levied on WCDE (F_e) and on rural households (F_f); the cost depends on inspection cost (R_c), publicity expense (aP_e), supporting facility cost (bS_f), subsidies for the WCDE (S_e), and economic incentives for rural households (E_f). In addition, if the government adopts the strategy of "passive regulation", but the WCDE implements the waste separation policy out of natural competition, it may also generate ecological benefits (E_b), but the government may face penalties from superiors and reputation loss (C_f).

For WCDE, prior to the enforcement of waste segregation policies, their revenue (R_n) and cost (C_n) are determined by their regular operational capacity. If the government enforces waste segregation and the companies resist, they face penalties (F_e). Conversely, if they actively adopt waste segregation, they incur additional operational costs (A_c) and gain economic benefits (C_r) from their proactive waste segregation efforts. They also receive government subsidies and incentives (S_e) for their compliance. These incentives are designed to offset the additional costs of publicity ($(1-a)P_e$) and supporting facilities ($(1-b)S_f$). Furthermore, to encourage rural household participation in waste segregation, companies may offer active subsidies and incentives (S_h). However, if rural households fail to segregate their waste, it results in increased collection and disposal costs (E_x) for the companies.

For rural households, adopting a "follow the rules" strategy yields subsidies and rewards (E_f) from the government for their proactive engagement, along with additional incentives (S_h) from WCDE. By following the rules, they also enhance their environmental consciousness (E_c), albeit at the cost of time (T_c) and economic expenses (E_i). Conversely, choosing a "break the rules" strategy entails the risk of penalties, specifically government-imposed fines ($-F_f$).

This study simplifies a tri-party evolutionary game model by analyzing the implementation process of RSW classification systems and makes the following assumptions:

Assumption 1. *The implementation of RSW classification is a long-term process. All participants observe and compare the benefits of different strategies and dynamically adjust their behavioral choices accordingly. Consequently, the government, WCDE, and rural households are bound by rationality and seek to maximize their benefits. The "government" refers to local authorities, "WCDE" denotes local third-party enterprises responsible for waste collection, transportation, and disposal, and "rural*

households" refers to rural residents. Each participant chooses between two mutually exclusive pure strategies and decides whether to adjust their strategy based on their perceived total benefits.

Assumption 2. *Parameters such as P_e, S_f, and E_c are quantified as positive values. In the tripartite evolutionary game model, the probability that the government regulates waste classification is denoted by α $(0 \leq \alpha \leq 1)$, the probability that the WCDE implements waste classification is denoted by β $(0 \leq \beta \leq 1)$, and the probability that rural households participate in waste classification is denoted by γ $(0 \leq \gamma \leq 1)$. Figure 2 illustrates the eight pure strategies of the evolutionary game model, where the government, WCDE, and rural households adopt mixed strategies by determining the probability of selecting between two alternatives. To improve the model's realism, this study incorporates additional assumptions grounded in the existing literature [20,34–37].*

Assumption 3. *The publicity costs (P_e) for waste classification are jointly borne by the government and the WCDE. The cost-sharing coefficient for publicity is denoted by a $(0 \leq a \leq 1)$. Consequently, the government bears a cost of aP_e, while the WCDE incurs a cost of $(1-a)P_e$.*

Assumption 4. *The supporting facility costs S_f for waste classification are jointly covered by the government and the WCDE. The allocation coefficient for these costs is represented by b $(0 \leq b \leq 1)$. Thus, the government's share is bS_f, and the WCDE's share is $(1-b)S_f$.*

Assumption 5. *P_e is positively correlated with rural households' environmental concern (E_c). S_f is positively correlated with the ecological benefit (E_b). Additionally, S_f is positively correlated with the economic benefit C_r that WCDE actively derives from waste classification.*

Since the evolutionary game model focuses on relative payoff comparisons rather than absolute economic estimates, all parameters were normalized into dimensionless values. The calibration procedure followed three steps: (1) identifying parameter relationships based on policy documents, previous studies, and stakeholder interviews; (2) converting heterogeneous indicators into comparable normalized metrics via this process; and (3) examining parameter robustness through sensitivity analysis. The parameters are presented in Table 1, and the corresponding payoff matrix is shown in Table 2.

Table 1. The main parameters and implications of the three-party game.

Parameter Symbol	Parameter	Meaning
α	Regulation rate	The probability of the government regulating waste classification.
β	Implementation rate	The probability of WCDE implementing waste classification.
γ	Participation rate	The probability of rural households' participation in waste classification.
R_c	Regulation Cost	The cost is for the government to inspect the implementation of the WCDE and rural households, including the labor cost of supervision and inspection and the cost of purchasing relevant supervision equipment.
C_f	The cost of government failure to regulate	Accountability penalties from superiors and reputation loss.
P_e	Publicity expense	In implementing the waste classification system, the government and WCDE must spend to publicize it to the rural households.
S_f	Supporting facility cost	The government and WCDE should cover the cost of supporting facilities to implement the waste classification system.
a	Publicity expense allocation coefficient	If the publicity expense of the government is aP_e, the expense of the WCDE is $(1\text{-}a)P_e$.
b	Supporting-facility cost allocation coefficient	If the supporting facility cost of the government is bS_f, the cost of the WCDE is $(1\text{-}b)S_f$.

Table 1. *Cont.*

Parameter Symbol	Parameter	Meaning
E_b	Ecological benefit	After implementing the waste classification system, some environmental benefits will be obtained.
F_e	Fine on the WCDE	When the WCDE does not implement the waste classification system, a fine will be paid after being inspected by the government.
F_f	Fine for rural households	When rural households break the waste classification rules, a fine will be paid after being investigated by the government.
S_e	Subsidies for the WCDE	The government will subsidize the WCDE that implements the waste classification system.
E_f	Economic incentives of government for rural households	The government will incentivize rural households who actively participate in waste classification.
S_h	Subsidies for rural households from the WCDE	Economic incentives of WCDE. The WCDE will incentivize rural households that actively participate in waste classification.
A_c	Additional operating cost	The WCDE must spend additional operating costs when implementing the waste classification system.
C_r	Classified recycling economic benefit	The WCDE gains economic benefits by implementing the waste classification system.
E_x	Extra cost for the WCDE	When rural households break the waste classification rules, the WCDE must pay additional fees to deal with solid waste.
T_c	Time cost of classification	Rural households must spend the corresponding time cost when obeying the waste classification rules.
E_i	Economic cost of classification	When rural households obey the waste classification rules, they must incur the corresponding economic cost.
E_c	Environmental Concern	Rural households' understanding of waste classification in ecological protection.
C_n	Former cost of the WCDE	Total cost of the WCDE not implementing waste classification.
R_n	Former revenue of the WCDE	Total revenue of the WCDE not implemented waste classification.

Table 2. Players' payoff matrix.

		Rural Households	**WCDE**	
			Active Implementation ($\boldsymbol{\beta}$)	**Negative Implementation ($\mathbf{1}-\boldsymbol{\beta}$)**
Government	Active regulation (α)	Follow the rules (γ)	$-R_c + E_b - aP_e - bS_f - S_e - E_f$, $-C_n + R_n - A_c + C_r - (1-a)P_e - (1-b)S_f + S_e - S_h$, $E_f - T_c - E_i + E_c + S_h$	$-R_c - P_e - S_f + F_e - E_f$, $-C_n + R_n - F_e$, $E_f - T_c - E_i + E_c$
		Break the rules ($1-\gamma$)	$-R_c + E_b - aP_e - bS_f - S_e + F_f$, $-C_n + R_n - A_c + C_r - (1-a)P_e - (1-b)S_f + S_e - E_x$, $-F_f$	$-R_c - P_e - S_f + F_e + F_f$, $-C_n + R_n - F_e$, $-F_f$
	Passive regulation ($1-\alpha$)	Follow the rules (γ)	E_b, $-C_n + R_n - A_c + C_r - P_e - S_f - S_h$, $-T_c - E_i + E_c + S_h$	$-C_f$, $-C_n + R_n$, $-T_c - E_i + E_c$
		Break the rules ($1-\gamma$)	E_b, $-C_n + R_n - A_c + C_r - P_e - S_f - E_x$, 0	$-C_f$, $-C_n + R_n$, 0

2.4. Game Solution

2.4.1. Stability Analysis

(1) Based on Table 1, the expected payoff of the government when adopting the "active regulation" strategy, "passive regulation" strategy, and average payoff of the government are U_{g1}, U_{g2} and $\overline{U_g}$, respectively:

$$U_{g1} = \beta\left(E_b + (1-a)P_e + (1-\mathrm{b})S_f - S_e - F_e\right) - \gamma\left(E_f + F_f\right) - R_c - P_e - S_f + F_e + F_f \quad (1)$$

$$U_{g2} = \beta\left(E_b + C_f\right) - C_f \quad (2)$$

$$\overline{U_g} = \alpha U_{g1} + (1-\alpha)U_{g2} \quad (3)$$

Therefore, the replicator dynamic equation of the government adopting an "active regulation" strategy is:

$$\begin{aligned} F(\alpha) = \frac{d\alpha}{dt} &= \alpha\left(U_{g1} - \overline{U_g}\right) = \alpha(1-\alpha)\left(U_{g1} - U_{g2}\right) = \alpha(1-\alpha)\left(\beta\left(E_b + (1-a)P_e + (1-b)S_f - S_e - F_e\right)\right. \\ &\left. - \gamma\left(E_f + F_f\right) - R_c - P_e - S_f + F_e + F_f - \beta\left(E_b + C_f\right) + C_f\right) = \alpha(1-\alpha)(\beta((1-a)P_e \\ &+ (1-b)S_f - S_e - F_e - C_f\big) - \gamma\left(E_f + F_f\right) - R_c - P_e - S_f + F_e + F_f + C_f\big) \end{aligned} \quad (4)$$

In evolutionary game theory, an equilibrium state refers to a dynamic steady state in which all stakeholders adjust their strategies in response to opponents' choices and eventually converge to an evolutionarily stable strategy.

To facilitate subsequent analysis, we define three composite constant parameters based on Equation (4): $a_1 = -R_c - P_e - S_f + F_e + F_f + C_f$; $a_2 = (1-a)P_e + (1-b)S_f - S_e - F_e - C_f$; $a_3 = E_f + F_f$. Two scenarios are distinguished for the stability analysis of government strategies:

i. If $\beta = \frac{\gamma a_3 - a_1}{a_2}$, $F(\alpha) \equiv 0$, for all $\alpha \in [0,1]$ constitute stable fixed points, indicating that the government's supervision strategy remains invariant regardless of the initial proportion of active supervision.

ii. If $\beta \neq \frac{\gamma a_3 - a_1}{a_2}$, solving $F(\alpha) = 0$ yields two boundary fixed points: $\alpha = 0$ and $\alpha = 1$. A core criterion for identifying ESS states is that the first-order derivative of the replicator dynamic function evaluated at a fixed point is negative. Differentiate $F(\alpha)$ with respect to α:

$$\frac{dF(\alpha)}{d\alpha} = (1-2\alpha)[\beta a_2 - \gamma a_3 + a_1] \quad (5)$$

Two comparative static cases are further analyzed:

When $\beta < \frac{\gamma a_3 - a_1}{a_2}$, we obtain $\left.\frac{dF(\alpha)}{d\alpha}\right|_{\alpha=0} < 0$ and $\left.\frac{dF(\alpha)}{d\alpha}\right|_{\alpha=1} > 0$. Accordingly, $\alpha = 0$ is the evolutionarily stable strategy.

When $\beta > \frac{\gamma a_3 - a_1}{a_2}$, we obtain $\left.\frac{dF(\alpha)}{d\alpha}\right|_{\alpha=0} > 0$ and $\left.\frac{dF(\alpha)}{d\alpha}\right|_{\alpha=1} < 0$. Hence, $\alpha = 1$ is the evolutionarily stable strategy.

(2) Similarly, the expected payoff of the WCDE when adopting an "active implementation" strategy, "negative implementation" strategy and average payoff of the WCDE are U_{e1}, U_{e2} and $\overline{U_e}$, respectively:

$$U_{e1} = \alpha\left(aP_e + bS_f + S_e\right) + \gamma\left(E_x - S_h\right) - C_n + R_n - A_c + C_r - P_e - S_f - E_x \quad (6)$$

$$U_{e2} = -\alpha F_e - C_n + R_n \quad (7)$$

$$\overline{U_e} = \beta U_{e1} + (1-\beta)U_{e2} \quad (8)$$

Therefore, the replicator dynamic equation of the WCDE adopting the "active implementation" strategy is:

$$\begin{aligned} F(\beta) = \frac{d\beta}{dt} &= \beta\left(U_{e1} - \overline{U_e}\right) = \beta(1-\beta)(U_{e1} - U_{e2}) = \beta(1-\beta)\left(\alpha\left(aP_e + bS_f + S_e\right)\right. \\ &\left. + \gamma\left(E_x - S_h\right) - C_n + R_n - A_c + C_r - P_e - S_f - E_x - (-\alpha F_e - C_n + R_n)\right) \\ &= \beta(1-\beta)\left(\alpha\left(aP_e + bS_f + S_e + F_e\right) + \gamma\left(E_x - S_h\right) - A_c + C_r - P_e - S_f - E_x\right) \end{aligned} \quad (9)$$

We define three composite constant parameters based on Equation (9): $b_1 = aP_e + bS_f + S_e + \mathrm{F_e}$; $\mathrm{b_2} = \mathrm{E_x} - \mathrm{S_h}$; $\mathrm{b_3} = -\mathrm{A_c} + C_r - P_e - S_f - E_x$. Two distinct stability regimes are identified:

i. If $\alpha = \frac{-\gamma b_2 - b_3}{b_1}$, $F(\beta) \equiv 0$, for all $\beta \in [0,1]$ constitute stable fixed points, indicating that the WCDE's strategy remains unchanged at this critical government supervision proportion.

ii. If $\alpha \neq \frac{-\gamma b_2 - b_3}{b_1}$, solving $F(\beta) = 0$ yields two boundary fixed points: $\beta = 0$ and $\beta = 1$. This implies that WCDEs will retain their initial strategic selection (either full passive or full positive implementation) over evolutionary iterations. Differentiate $F(\beta)$ with respect to β:

$$\frac{dF(\beta)}{d\beta} = (1-2\beta)[\alpha b_1 + \gamma b_2 + b_3] \tag{10}$$

Two comparative static cases are further analyzed:

When $\alpha < \frac{-\gamma b_2 - b_3}{b_1}$, we obtain $\left.\frac{dF(\beta)}{d\beta}\right|_{\beta=0} < 0$ and $\left.\frac{dF(\beta)}{d\beta}\right|_{\beta=1} > 0$. Accordingly, $\beta = 0$ is the evolutionarily stable strategy.

When $\alpha > \frac{-\gamma b_2 - b_3}{b_1}$, we obtain $\left.\frac{dF(\beta)}{d\beta}\right|_{\beta=0} > 0$ and $\left.\frac{dF(\beta)}{d\beta}\right|_{\beta=1} < 0$. Hence, $\beta = 1$ is the evolutionarily stable strategy.

(3) Similarly, the expected payoff of the rural households when adopting the "Follow the rules" strategy, "Break the rules" strategy and average payoff of the rural households are U_{f1}, U_{f2} and $\overline{U_f}$, respectively:

$$\begin{aligned} U_{f1} &= \alpha\beta\left(E_f - T_c - E_i + E_c + S_h\right) + \alpha(1-\beta)\left(E_f - T_c - E_i + E_c\right) \\ &+ \beta(1-\alpha)(-T_c - E_i + E_c + S_h) + (1-\alpha)(1-\beta)(-T_c - E_i + E_c)U_{f1} \\ &= \alpha E_f + \beta S_h - T_c - E_i + E_c \end{aligned} \tag{11}$$

$$U_{f2} = \alpha\beta\left(-F_f\right) + \alpha(1-\beta)\left(-F_f\right) = -\alpha F_f \tag{12}$$

$$\overline{U_f} = \gamma U_{f1} + (1-\gamma)U_{f2} \tag{13}$$

Therefore, the replicator dynamic equation of the rural households adopting the "Follow the rules" strategy is:

$$F(\gamma) = \frac{d\gamma}{dt} = \gamma\left(U_{f1} - \overline{U_f}\right) = \gamma(1-\gamma)\left(U_{f1} - U_{f2}\right) = \gamma(1-\gamma)\left(\alpha\left(E_f + F_f\right) + \beta S_h - T_c - E_i + E_c\right) \tag{14}$$

We define three composite constant parameters based on Equation (14): $c_1 = E_f + F_f$, $c_2 = S_h$, $c_3 = -T_c - E_i + E_c$. Two distinct stability regimes are identified:

i. If $\alpha = \frac{-\beta c_2 - c_3}{c_1}$, $F(\gamma) \equiv 0$, for all $\gamma \in [0,1]$ constitute stable fixed points, indicating that the rural households' strategy remains unchanged.

ii. If $\alpha \neq \frac{-\beta c_2 - c_3}{c_1}$, solving $F(\gamma) = 0$ yields two boundary fixed points: $\gamma = 0$ and $\gamma = 1$. This implies that rural households will retain their initial strategic selection over evolutionary iterations. Differentiate $F(\gamma)$ with respect to γ:

$$\frac{dF(\gamma)}{d\gamma} = (1-2\gamma)[\alpha c_1 + \beta c_2 + c_3] \tag{15}$$

Two comparative static cases are further analyzed:

When $\alpha < \frac{-\beta c_2 - c_3}{c_1}$, we obtain $\left.\frac{dF(\gamma)}{d\gamma}\right|_{\gamma=0} < 0$ and $\left.\frac{dF(\gamma)}{d\gamma}\right|_{\gamma=1} > 0$. Accordingly, $\gamma = 0$ is the evolutionarily stable strategy.

When $\alpha > \frac{-\beta c_2 - c_3}{c_1}$, we obtain $\left.\frac{dF(\gamma)}{d\gamma}\right|_{\gamma=0} > 0$ and $\left.\frac{dF(\gamma)}{d\gamma}\right|_{\gamma=1} < 0$. Hence, $\gamma = 1$ is the evolutionarily stable strategy.

The multi-player evolutionary game can be represented by the following set of replicator dynamic equations:

$$\begin{cases} F(\alpha) = \alpha(1-\alpha)\left(\beta\left((1-a)P_e + (1-b)S_f - S_e - F_e - C_f\right) - \gamma\left(E_f + F_f\right) - R_c - P_e - S_f + F_e + F_f + C_f\right) \\ F(\beta) = \beta(1-\beta)\left(\alpha\left(aP_e + bS_f + S_e + F_e\right) + \gamma\left(E_x - S_h\right) - A_c + C_r - P_e - S_f - E_x\right) \\ F(\gamma) = \gamma(1-\gamma)\left(\alpha\left(E_f + F_f\right) + \beta S_h - T_c - E_i + E_c\right) \end{cases} \tag{16}$$

2.4.2. Equilibrium Analysis

The stability of the local equilibrium point can be discriminated using Lyapunov's stability analysis [38]. According to Lyapunov's discrimination method, when all the eigenvalues of the Jacobi matrix are less than 0, the equilibrium point is a locally stable point; otherwise, the equilibrium point is an unstable point. The stability of the equilibrium solution is analyzed according to the basic assumptions.

Solve the partial derivatives of the replicator dynamic equations according to the Equations above. Let:

$$\mathrm{X}(\beta,\gamma) = \beta a_2 - \gamma a_3 + a_1$$

$$\mathrm{Y}(\alpha,\gamma) = \alpha b_1 + \gamma b_2 + b_3$$

$$\mathrm{Z}(\alpha,\beta) = \alpha c_1 + \beta c_2 + c_3$$

The Jacobi matrix can be obtained as follows:

$$J_1 = \begin{pmatrix} \frac{\partial F(\alpha)}{\partial \alpha} & \frac{\partial F(\alpha)}{\partial \beta} & \frac{\partial F(\alpha)}{\partial \gamma} \\ \frac{\partial F(\beta)}{\partial \alpha} & \frac{\partial F(\beta)}{\partial \beta} & \frac{\partial F(\beta)}{\partial \gamma} \\ \frac{\partial F(\gamma)}{\partial \alpha} & \frac{\partial F(\gamma)}{\partial \beta} & \frac{\partial F(\gamma)}{\partial \gamma} \end{pmatrix} = \begin{pmatrix} (1-2\alpha)\mathrm{X}(\beta,\gamma) & \alpha(1-\alpha)a_2 & -\alpha(1-\alpha)a_3 \\ \beta(1-\beta)b_1 & (1-2\beta)\mathrm{Y}(\alpha,\gamma) & \beta(1-\beta)b_2 \\ \gamma(1-\gamma)c_1 & \gamma(1-\gamma)c_2 & (1-2\gamma)\mathrm{Z}(\alpha,\beta) \end{pmatrix} \quad (17)$$

The equilibrium points are obtained by solving using MATLAB Online (R2024b; The MathWorks, Inc., Natick, MA, USA), and their local stability is analyzed; the results are shown in Appendix A.

Upon solving the model, we observe that the stability of the equilibrium point is influenced by numerous parameters and depends on their relative values. The stability of the local equilibrium points cannot be determined from the results presented above. Therefore, in this paper, we simulate the evolutionary dynamics to examine how the uncertainty factor affects the evolution process of the three-party game.

2.5. SD Model Configuration

First, the model's variables are identified. The state variables, representing stocks, include α, β, γ. The rate variables, which are flows, consist of $F(\alpha)$, $F(\beta)$, and $F(\gamma)$. Auxiliary variables facilitate information transfer and total nine, such as U_{g1}, U_{g2}, $(U_{g1}-U_{g2})$, U_{e1}, U_{e2}, $(U_{e1}-U_{e2})$, U_{f1}, U_{f2} and $(U_{f1}-U_{f2})$. The remaining variables are constants, which remain constant or change only marginally over the study period, amounting to a total of 12 variables. The relationships between these variables are then established and equations formulated. All equations are based on the analysis and findings of the tripartite responsibility game involving rural household waste classification and management. Finally, the SD model is constructed as in Figure 3.

For the simulation of the SD model, determining initial parameter values is a critical prerequisite. In our study, the parameters were determined from multiple data sources, including policy documents, official statistics, previous studies, stakeholder interviews, and expert consultation. The participants interviewed included representatives from government departments, WCDEs, and rural households. The purpose of the interviews was not statistical estimation but identifying stakeholder relationships, cost structures, and benefit allocation mechanisms. All parameters were calibrated based on relative magnitudes of costs, benefits, subsidies, and penalties rather than direct monetary estimation. The values represent a baseline scenario reflecting the institutional characteristics of rural waste management in Inner Mongolia, which were further validated and refined through semi-structured expert interviews.

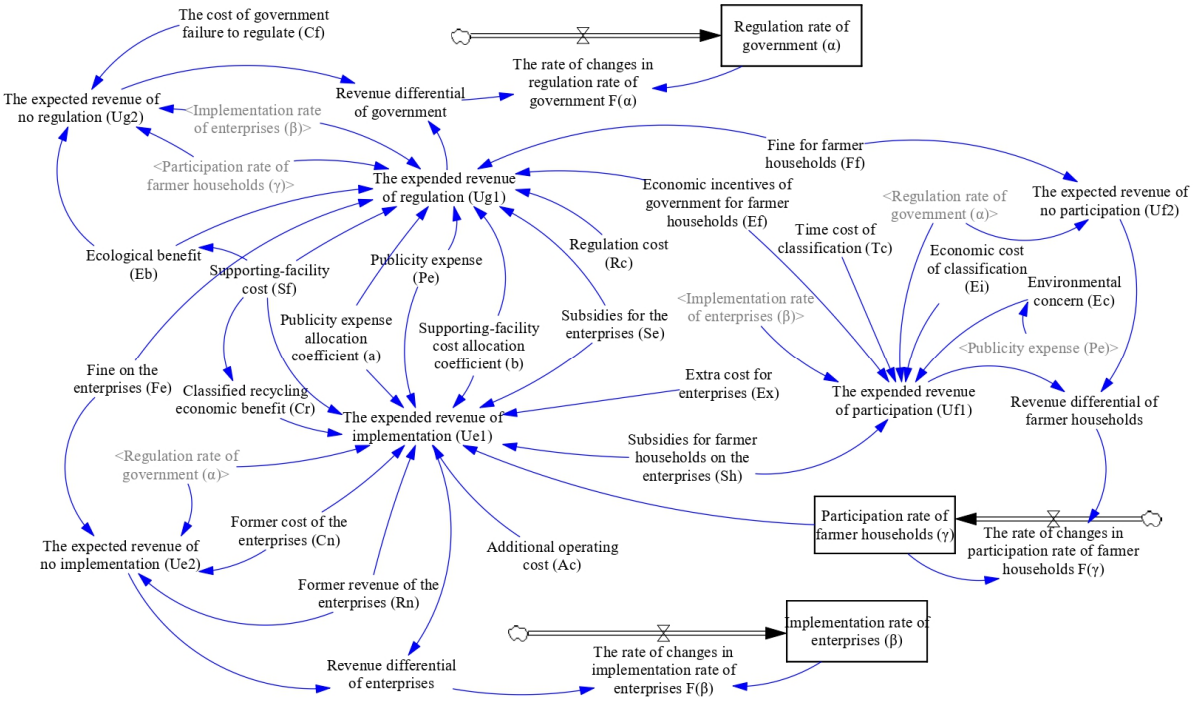

Figure 3. Evolutionary game SD model of the three-party game.

The Inner Mongolia Autonomous Region provides a representative scenario of northern rural areas because of its dispersed settlements, relatively long waste transportation distances, cold climate conditions, and challenges in rural environmental governance. Inner Mongolia can serve as a model case for exploring multi-stakeholder participation mechanisms in rural solid waste (RSW) management in northern China. It was persistently advancing the classified management and treatment of domestic waste in rural and pastoral regions by intensifying regulatory governance and expediting the construction of supporting infrastructure. From a fiscal investment perspective, a total of 254 million yuan was invested in rural domestic waste governance initiatives in 2024, facilitating the completion of targeted waste treatment projects in 102 administrative villages, with each having a permanent population exceeding 1000.

In regard to institutional governance, the region has systematically improved the overall performance of rural domestic waste classification and treatment through a set of integrated measures: strengthening public awareness and promotional campaigns regarding waste sorting, deploying comprehensive specialized infrastructure for waste classification, implementing targeted support and standardized regulation for waste treatment-related enterprises, and fostering the mechanism of villager autonomy and multi-dimensional supervision over rural waste governance practices. To obtain reliable data for model calibration, we conducted field interviews in June 2024. Interviewees included 6 representatives from local government environmental-sanitation and rural-revitalization administrative departments, and 7 managerial representatives from WCDEs (Beijing Huifeng Qingxuan Company: Beijing, China), alongside 18 village-level cadres and 124 rural-household respondents. The semi-structured interview questionnaire covered three core modules targeting different stakeholders: government-related questions involved the implementation status of rural waste classification policies, subsidy standards, supervision and penalty rules, and administrative costs alongside anticipated environmental and social gains; enterprise-focused items surveyed waste collection and disposal firms' operating expenses, facility investment, treatment expenditures, government financial support, expected revenues, and factors restricting their participation; rural household inquiries explored

residents' waste-sorting awareness, participation intentions, perceived time and economic costs, anticipated returns, and the impacts of official incentives, penalties, and village-level environmental norms.

Both qualitative and quantitative data were collected after the interviews. In addition, official statistical data were primarily sourced from the Hohhot municipal government website and relevant departmental documents. S_e represents the relative subsidy intensity provided to WCDE. Its baseline value was selected according to the observed importance of government financial support in promoting enterprise participation. Considering the difficulty of obtaining directly observed ecological and social benefit values, this study adopts a proportional relationship assumption between input variables and benefit variables. Parameters related to costs and investments were obtained from official information and field investigation, while parameters that cannot be directly observed, such as ecological benefits, social benefits, and behavioral conversion efficiency, were determined through expert judgment and previous studies. Specifically, ecological benefits (E_b) and classified recycling economic benefit (C_r) are assumed to increase with supporting facility investment (S_f), while social benefits (E_c) increase with publicity expenditure (P_e). The coefficients (1.82, 0.84, and 0.64) represent relative conversion parameters rather than directly measured economic values, following previous studies [36,39]. These coefficients were determined based on previous studies and expert assessments and were further examined through sensitivity analysis. Ultimately, the initial values of exogenous parameters were detailed in Table 3.

Table 3. The initial values of exogenous parameters.

Parameter Category	Parameters	Initial Values
costs	R_c	4
	C_f	2
	P_e	8
	S_f	6
	A_c	4
	T_c	3
	E_i	2
	C_n	2
	E_x	3
Allocation coefficient	a	0.45
	b	0.65
Subsidies and penalties	F_e	3
	F_f	3
	S_e	14
	E_f	2
	S_h	2
Environmental benefits	E_b	1.82 * S_f
Economic benefits	R_n	2
	C_r	0.84 * S_f
Social benefits	E_c	0.64 * P_e

3. Results

3.1. Initial Data Simulation

This study adopts SD modeling and Vensim PLE software to simulate the dynamic interaction process. The simulation cycle is set to 240 months, with an initial time of 0, a termination time of 240, a time step of 1, and the time unit defined as months. Vensim PLE employs the Euler integration method for solving ordinary differential equations in this model. The initial values of α, β, and γ represent the initial willingness or probability of

government regulation, WCDE implementation, and rural household participation, respectively. As rural waste classification systems are generally at an early stage of development, incomplete participation and bounded rationality are considered. At the same time, we also examined whether different initial states influence the evolutionary results. Firstly, the initial values of α, β, and γ are set to 0.5, 0.2, and 0.05, respectively. As shown in Figure 4, under the baseline parameter configuration, the trajectories evolve toward the neighborhood of the boundary point $(1, 1, 1)$. It should be emphasized that $(1, 1, 1)$ is a saddle-point locally-unstable boundary equilibrium; this near-stationary behavior arises from simplex boundary constraints rather than true asymptotic convergence to a stable attractor. The evolutionary outcome is conditional on the relative payoff differences among strategies and does not represent an inevitable equilibrium under all parameter settings. This result should be interpreted as a scenario-based evolutionary outcome rather than an empirical prediction. The direction of government strategy evolution depends on the balance between regulatory benefits and regulatory costs.

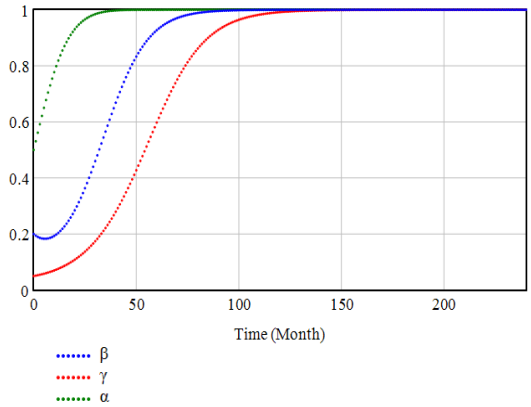

Figure 4. Initial data simulation for the SD model. Note: At the initial state ($t = 0$, $\alpha = 0.5$, $\beta = 0.2$, $\gamma = 0.05$), Equation (16) predicts a brief transient decrease in α and β. Owing to the coupled dynamics, the rapid increase in γ quickly reverses their derivative signs. β exhibits a visible early dip, whereas the transient decrease of α is too small to be visually resolved in Figure 4 but is confirmed by both Vensim and independent Python (3.15.1; Python Software Foundation, Wilmington, DE, USA) simulations.

When the initial values of the three stakeholders are pure strategies, the choice set is either 0 or 1. There are eight possible strategy combinations: $(0, 0, 0)$, $(0, 1, 0)$, $(0, 0, 1)$, $(0, 1, 1)$, $(1, 1, 1)$, $(1, 0, 0)$, $(1, 1, 0)$, and $(1, 0, 1)$. It should be noted that exact pure-strategy initial states constitute trivial boundary fixed points of replicator dynamics. They yield zero flow irrespective of payoff functions. Therefore, strictly setting initial values to 0 or 1 cannot reflect real-world strategic adaptation behaviors. For numerical simulation, small perturbed starting values are adopted to escape this mathematical boundary condition. To investigate the changes in the strategies adopted by the three stakeholders, we fine-tuned the initial values of the strategy combinations based on relevant research [19]. For instance, $(0.99, 0.99, 0.99)$ was used instead of $(1, 1, 1)$ as the initial value for the simulation, and $(0.01, 0.01, 0.01)$ was used instead of $(0, 0, 0)$. Based on the government's initial strategy, the evolutionary strategies and steady states of different stakeholders are examined.

1. Government's initial strategy is passive regulation

When the government's initial strategy is non-regulation, four possible strategy combinations emerge for the stakeholders. The simulation results are shown in Figure 5a–d.

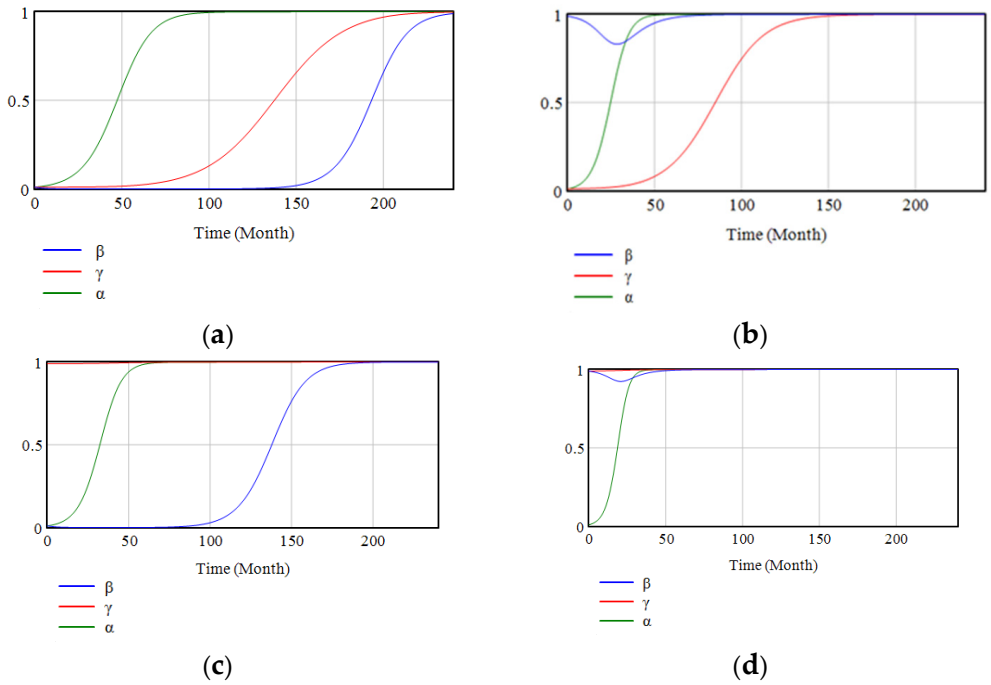

Figure 5. Simulation results when the government's initial strategy is non-regulation. (**a**) Strategy combination is (0, 0, 0). (**b**) Strategy combination is (0, 1, 0). (**c**) Strategy combination is (0, 0, 1). (**d**) Strategy combination is (0, 1, 1).

Comparing Figure 5a,b, it is evident that when rural households initially do not follow the rules but WCDEs initially implement actively, the government stabilizes in the regulation strategy more quickly, and rural households stabilize in following the rules more rapidly. Simultaneously, when WCDEs initially implement actively, their implementation rate exhibits a decline at a certain stage; however, as the government's regulatory intensity increases, WCDEs resume waste classification implementation and gradually attain a steady state. Similarly, when WCDEs and rural households initially choose a positive strategy, the government reaches a steady state of positive regulation more quickly. Furthermore, when WCDEs initially implement waste classification, their implementation rate decreases at a certain stage. As the government's regulatory rate increases, WCDEs resume the implementation of waste classification and gradually return to a steady state. However, comparing Figure 5b,d, it is clear that when rural households initially participate in waste classification, the WCDE's reduction in the implementation rate at the beginning is substantially smaller. Additionally, comparing Figure 5a,c, it is evident that when rural households initially participate in waste classification, the government stabilizes in positive regulation more quickly, and WCDE stabilize in the positive implementation more rapidly.

2. Government's initial strategy is active regulation

When the government's initial strategy is regulation, four possible strategy combinations emerge for the stakeholders. The simulation results are shown in Figure 6a–d.

Comparing Figure 6a,b, it is evident that when rural households initially break the rules, but WCDEs initially implement waste classification, rural households stabilize in following the rules more quickly. Furthermore, as shown in Figure 6b,c, the initial participation of rural households in waste classification has minimal impact on the decisions made by WCDEs.

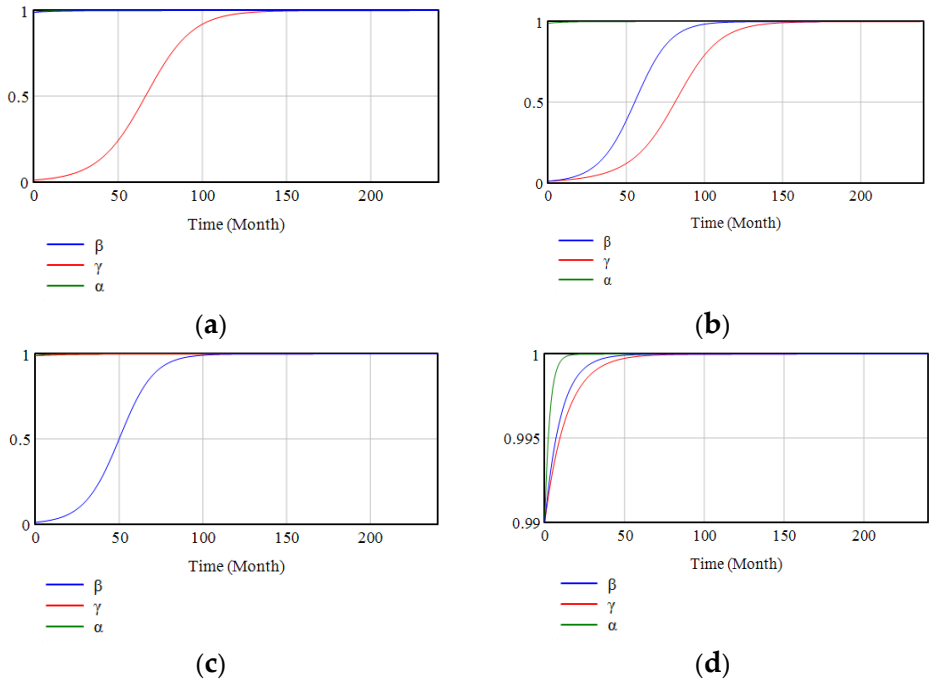

Figure 6. Simulation results when the government's initial strategy is regulation. (**a**) Strategy combination is (1, 1, 0). (**b**) Strategy combination is (1, 0, 0). (**c**) Strategy combination is (1, 0, 1). (**d**) Strategy combination is (1, 1, 1).

In summary, when the government's initial strategy is regulation, (1, 1, 1) is a policy-desirable corner-point equilibrium, which is dynamically locally unstable under baseline parameters. The simulation results also suggest that WCDEs are more responsive to the government's strategy than rural households. The government plays a crucial guiding role for both WCDEs and rural households, while WCDEs substantially influence rural households. Effective guidance from both the government and WCDEs can expedite rural households' transition to following the rules.

3.2. Simulation Analysis of the Main Influencing Factors

To further analyze the influence of exogenous variables on stakeholders' strategy choices, the primary factors affecting the evolutionary game were identified by altering each parameter's initial value and observing its evolutionary path. It should be noted that the analysis in this section does not aim to identify an optimal policy combination. Instead, it examines how variations in key parameters affect stakeholder strategy evolution and identifies favorable conditions for achieving cooperative outcomes.

1. For government

Firstly, the increase in the cost of active government regulation (R_c) slows down the evolution rate of the active regulation strategy (shown in Figure 7). Higher R_c weakens the government's incentive to adopt the regulatory strategy, and the system requires more time to reach the stable state.

Secondly, the cost of publicity and supporting facilities (P_e, S_f) will also influence government strategies. When the government implements higher-cost publicity efforts and makes greater investments in supporting facilities, the government may increase regulation accordingly. Static partial derivatives only reflect instantaneous direct effects under fixed system states, while our sensitivity simulations capture the net long-term dynamic outcome, in which positive indirect feedbacks from evolving WCDE and household strategies can outweigh negative direct effects and reverse the final response of government strategy.

As shown in Figure 8, as P_e and S_f increase, the government is more likely to adopt the regulatory strategy more quickly. Additionally, the simulation results indicate that the allocation coefficients of P_e and S_f have minimal influence on government strategy.

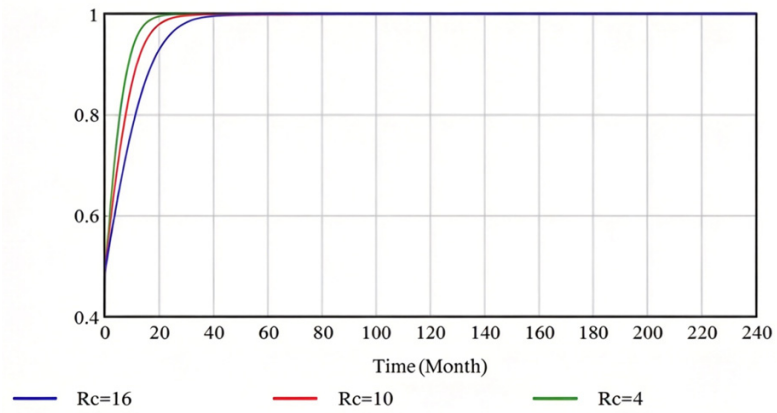

Figure 7. Impact of the cost of active government regulation on government strategy.

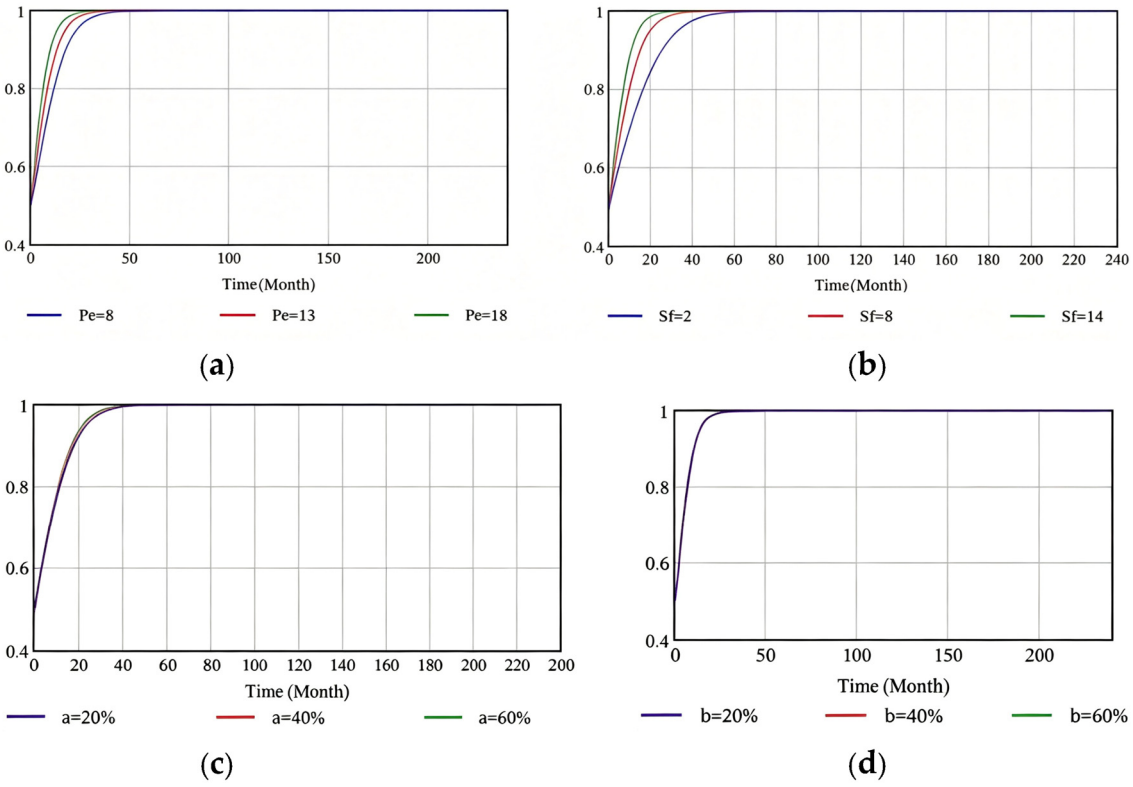

Figure 8. Impact of P_e and S_f on government strategy (**a**) Impact of P_e. (**b**) Impact of S_f . (**c**) Impact of a. (**d**) Impact of b.

Thirdly, as illustrated in Figure 9, government incentives and penalties for WCDEs and rural households have a minor impact on the government's strategy. Both rewards and punishments for WCDEs can promote the evolution of the government's strategy. Compared with penalties, higher subsidies and incentives are more effective in accelerating the government's adoption of an active regulation strategy.

2. For WCDE

Firstly, A_c is the main factor influencing WCDE strategy. If the additional operating costs exceed the revenue, the WCDE will reassess its strategy. As shown in Figure 10, an increase in A_c is associated with the negative implementation strategy of WCDEs.

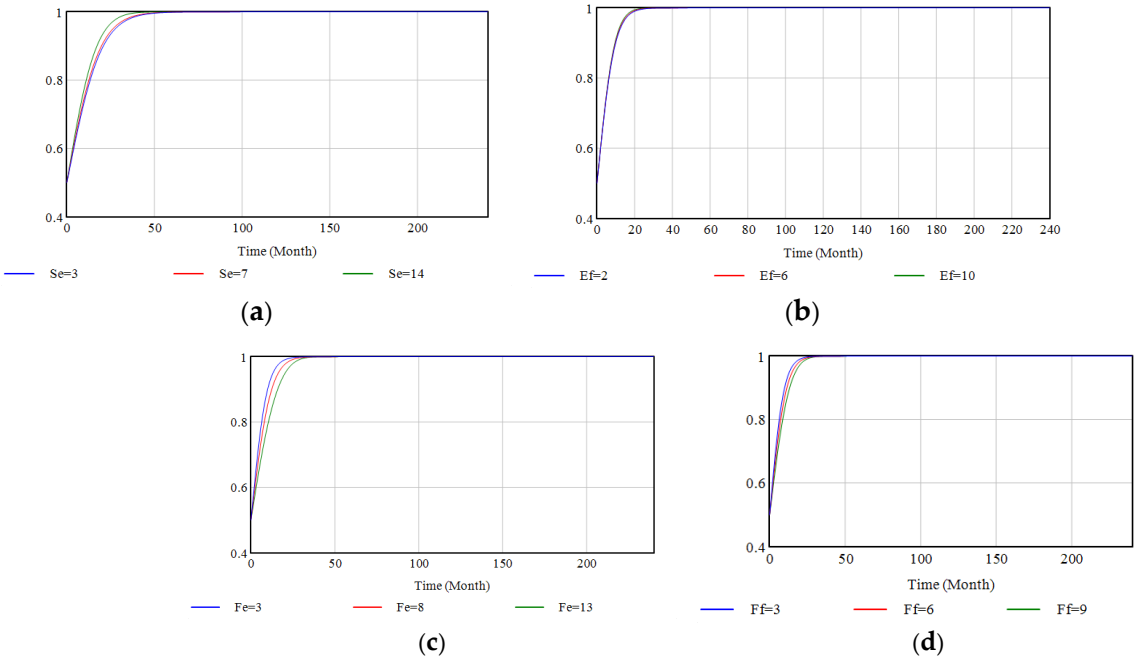

Figure 9. Impact of F_e, F_f, S_e, and E_f on government strategy.(**a**) Impact of S_e. (**b**) Impact of E_f . (**c**) Impact of F_e. (**d**) Impact of F_f.

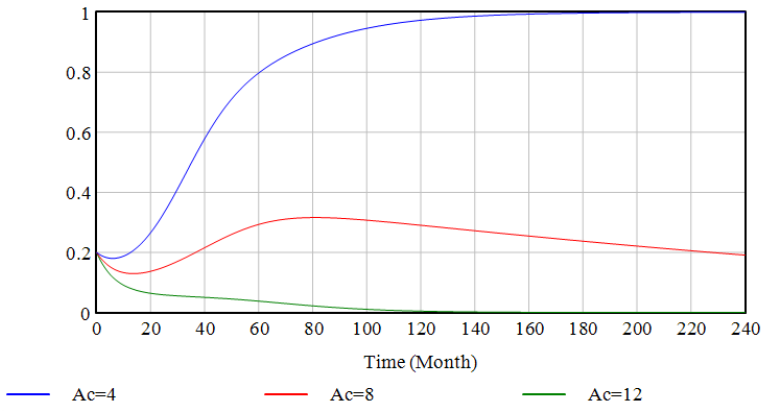

Figure 10. Impact of A_c on WCDE strategies.

Secondly, F_e and S_e exert notable impacts on the strategic choices of WCDEs. As depicted in Figure 11, a higher value of S_e accelerates the evolutionary trajectory of WCDEs toward the active implementation strategy. By contrast, when S_e is sufficiently low, WCDEs may even evolve toward a state of non-implementation. Similarly, an increase in F_e also promotes a WCDE shift toward active implementation. E_f and F_f impose relatively weak effects on the strategic decisions of WCDEs. It is clear that government subsidies and incentives substantially modify the strategic evolution of WCDEs, and their impact is notably greater than that of penalties. The correlation between government rewards and penalties for rural households and the strategic evolution of WCDEs is weak.

P_e and S_f also exert notable impacts on the strategic choices of WCDEs. As illustrated in Figure 12, a rise in P_e prolongs the time required for WCDEs to reach the active implementation strategy, whereas an increase in S_f accelerates the adoption of the active implementation strategy. Furthermore, the allocation coefficients (a, b) of P_e and S_f notably influence the

strategic evolution of WCDEs. P_e and S_f constitute a considerable share of WCDEs' total operational costs. Higher allocation coefficients for government-funded publicity and supporting facility costs effectively reduce the total cost burden of WCDEs, thereby promoting a faster shift to the proactive implementation strategy.

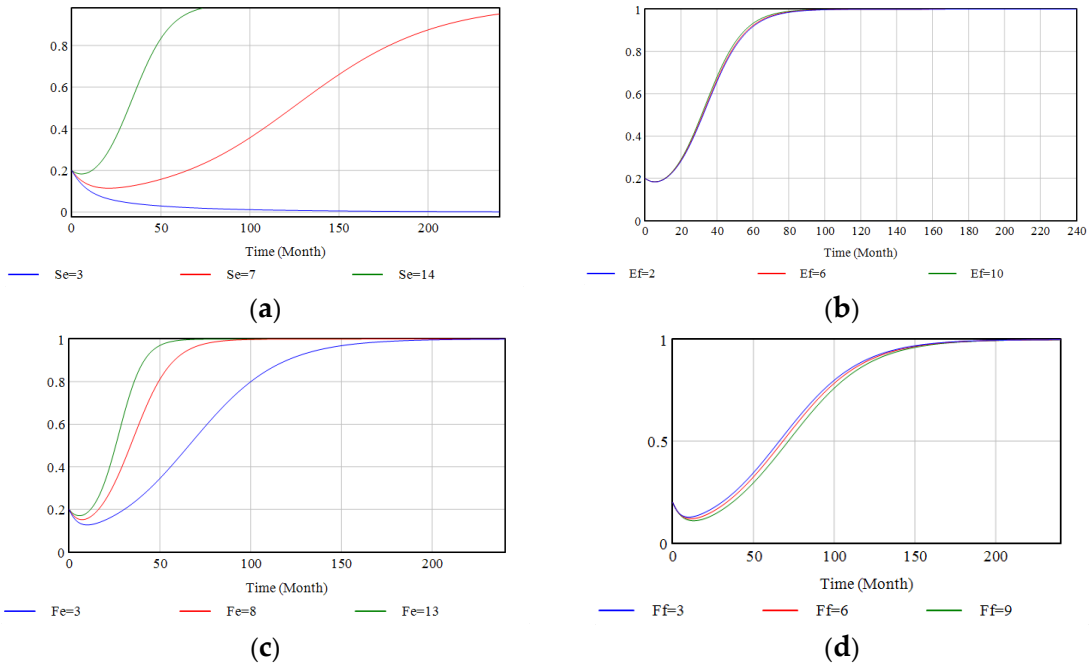

Figure 11. Impact of F_e, S_e, E_f and F_f on WCDE strategies.(**a**) Impact of S_e. (**b**) Impact of E_f . (**c**) Impact of F_e. (**d**) Impact of F_f.

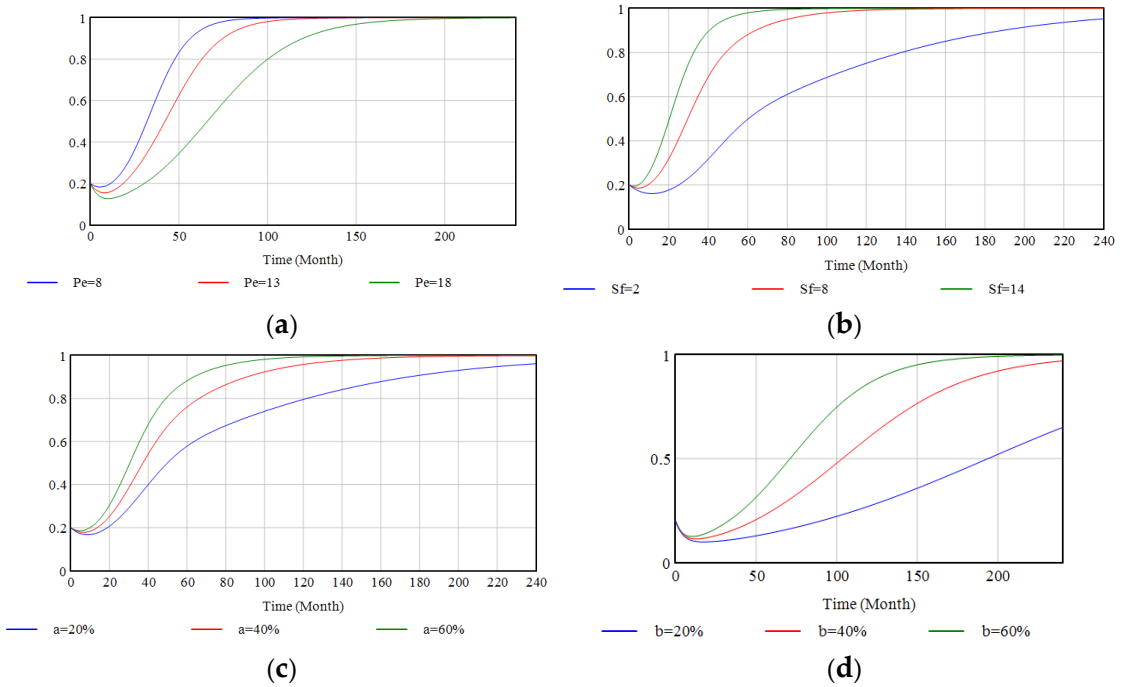

Figure 12. Impact of P_e and S_f on WCDE strategies.(**a**) Impact of P_e. (**b**) Impact of S_f . (**c**) Impact of a. (**d**) Impact of b.

S_h also exerts a notable influence on the strategic choices of WCDEs. As depicted in Figure 13, an increase in S_h delays WCDE implementation strategies. It is evident that

achieving consistent waste classification implementation remains difficult without targeted economic incentives and support from the government. As rational economic entities, WCDEs are unable to independently resolve the externalities generated by their operational activities, and their sustainable operation and long-term survival depend critically on government financial and policy support.

3. For rural households

Firstly, T_c and E_i exert notable impacts on the strategic choices of rural households. As depicted in Figure 14, high costs associated with following the rules in waste classification will deter them from participating in relevant proactive activities.

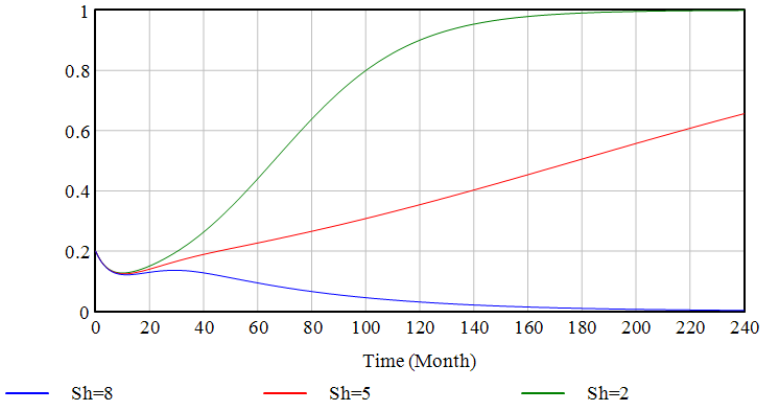

Figure 13. Impact of S_h on WCDE strategies.

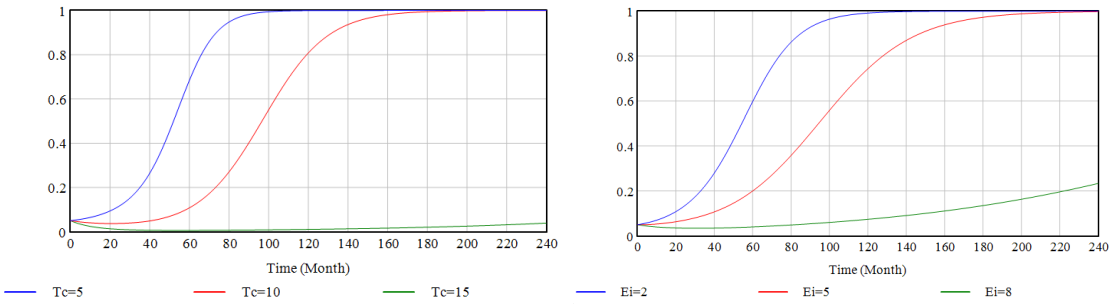

Figure 14. Impact of T_c and E_i on rural households' strategies.

Secondly, P_e and S_f influence the strategies of rural households. As depicted in Figure 15, higher P_e and S_f can effectively incentivize rural households to follow the rules. Furthermore, the simulation results reveal that the allocation coefficients exert a negligible impact on rural household strategies. This finding suggests that the specific cost allocation structure for P_e and S_f does not notably alter the evolutionary trajectory of rural household strategies.

Furthermore, government incentives and penalties for both WCDEs and rural households (F_e, F_f, S_e, and E_f) also influence rural households' strategies. As illustrated in Figure 16, stronger subsidy incentives and penalties for rural households can motivate them to follow the rules. Government subsidies and incentives for WCDEs indirectly affect rural households' strategies. Increased S_e can encourage WCDE implementation, which in turn enables them to reward rural households, whereas F_e imposed on WCDEs has a weaker effect on rural households' strategies.

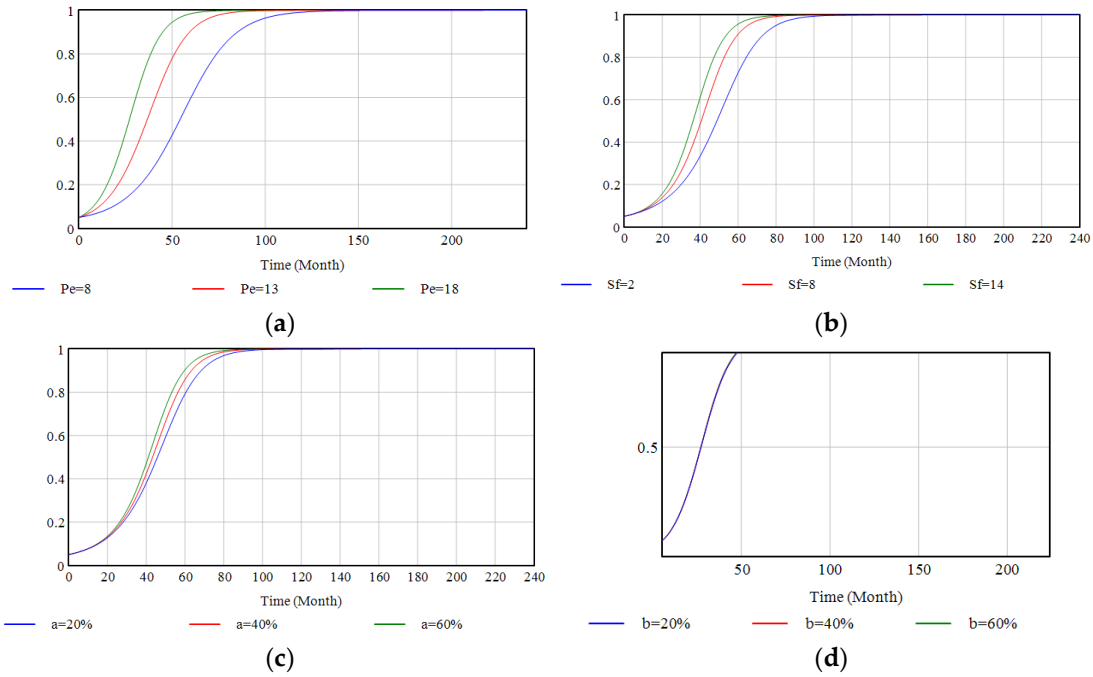

Figure 15. Impact of P_e and S_f and their allocation coefficients on rural households' strategies. (**a**) Impact of P_e. (**b**) Impact of S_f . (**c**) Impact of a. (**d**) Impact of b.

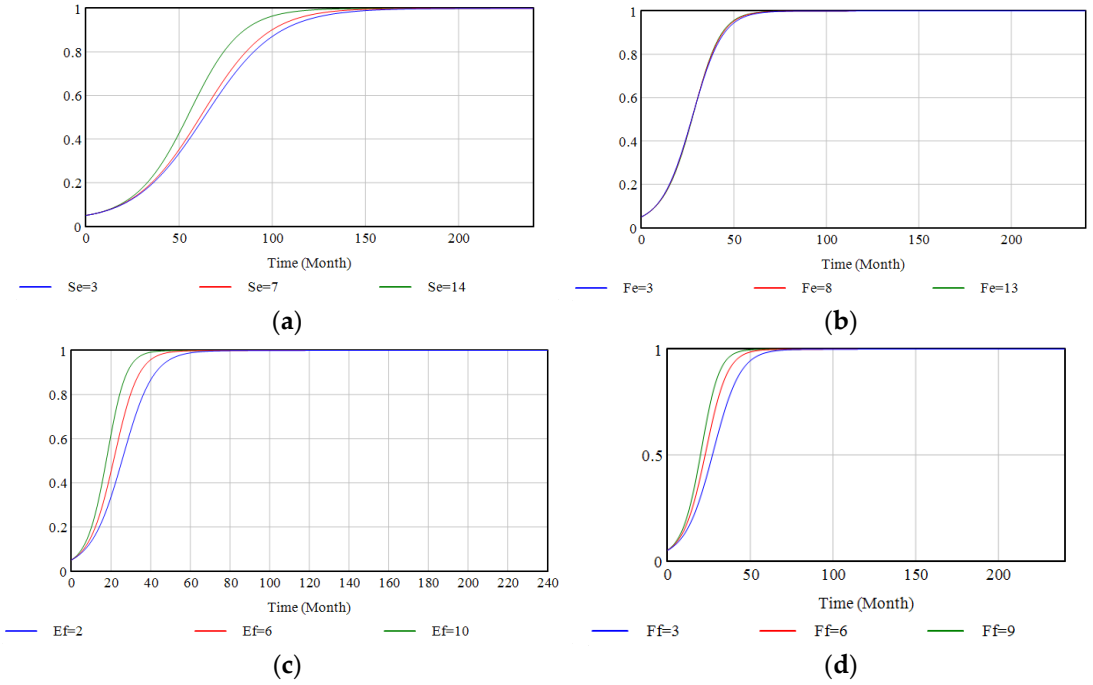

Figure 16. Impact of F_e, F_f, S_e and E_f on rural households' strategies.(**a**) Impact of S_e. (**b**) Impact of F_e. (**c**) Impact of E_f. (**d**) Impact of F_f.

3.3. Impact of Different Subsidy and Penalty Portfolios on Tri-Party Strategies

The impact of various combinations of government subsidies and penalties on the evolution of strategies was further examined. By adjusting the parameter values of subsidies and penalties, we examined the effects of four distinct combinations—low subsidies with low penalties, high subsidies with high penalties, low subsidies with high penalties, and high subsidies with low penalties—on the evolution of strategies (the four combinations are shown in Table 4).

Table 4. Parameter settings of four subsidy–penalty policy portfolios.

Scenario ID	Policy Portfolio	S_e	F_e	E_f	F_f
S1	High subsidies with high penalties	14	13	10	9
S2	Low subsidies with low penalties	3	3	2	3
S3	High subsidies with low penalties	14	3	10	3
S4	Low subsidies with high penalties	3	13	2	9

As illustrated in Figure 17, the four strategy combinations that most strongly drive the government toward active regulation in waste sorting are, in order, low subsidies with low penalties, high subsidies with low penalties, high subsidies with high penalties, and low subsidies with high penalties. Evidently, the government prefers the combination of low subsidies and low penalties. Similarly, for WCDEs and rural households, the four strategy combinations that most effectively promote active implementation rank as follows: high subsidies with high penalties, high subsidies with low penalties, low subsidies with high penalties, and low subsidies with low penalties.

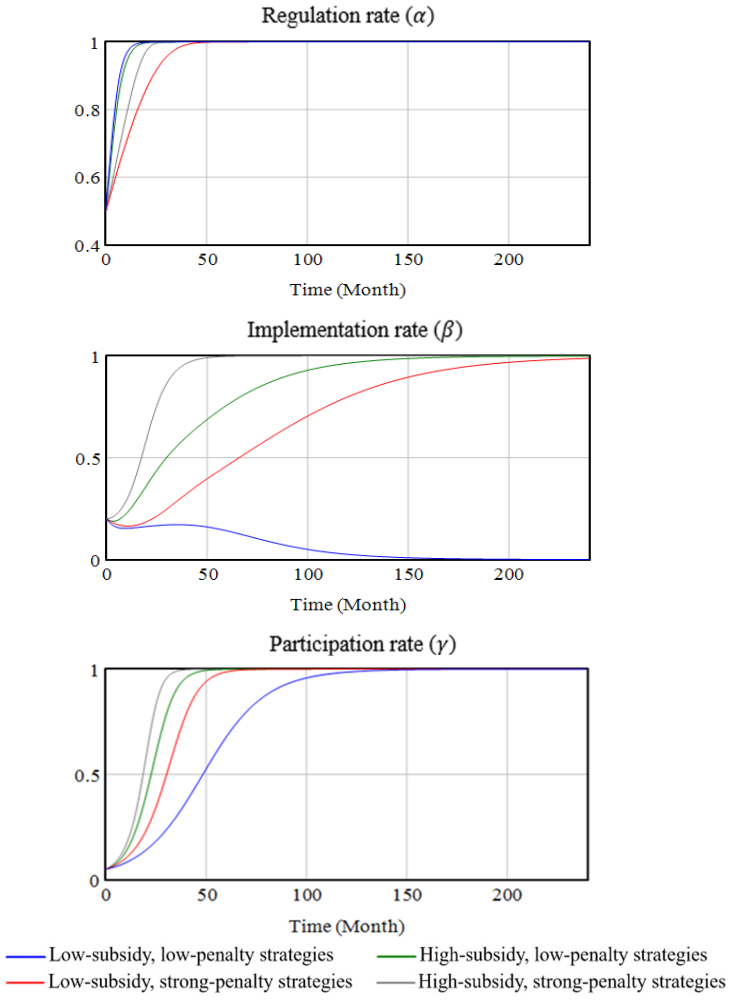

Figure 17. Impact of different subsidy and penalty portfolios on tri-party strategies.

To quantitatively compare the relative influence of the four core parameters, we calculated the normalized sensitivity elasticity index $E = (\Delta T/T_{baseline})/(\Delta p/p_{baseline})$ under ±50% relative perturbation, as shown in Figure 18 (T is the evolution time and p is the parameter). Convergence time T is defined as the earliest simulation time point at which all three state variables α, β, and γ simultaneously reach the threshold value of 0.99. Con-

vergence is only recognized when all three variables continuously stay at or above this 0.99 threshold for all subsequent time steps until the full simulation horizon terminates. A single transient crossing above 0.99 without sustained maintenance does not count as convergence. Negative elasticity means that a percentage increase in the corresponding parameter shortens convergence time and accelerates the evolutionary transition of the whole system. Larger absolute elasticity magnitudes indicate stronger influence on convergence speed. By contrast, positive elasticity values indicate that raising the parameter prolongs convergence time and delays the system's evolutionary progress. These findings support prioritizing subsidy instruments.

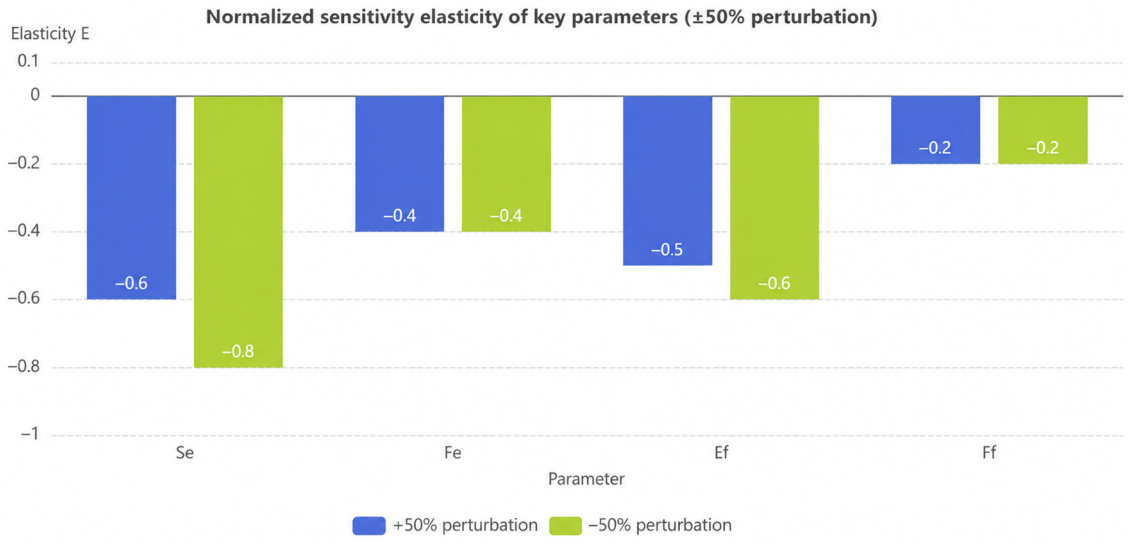

Figure 18. Normalized sensitivity elasticity of parameters under ±50% relative perturbation.

4. Discussion

Rural household waste sorting is a systemic governance issue involving strategic interactions among the government, waste collection and disposal enterprises (WCDEs), and rural households [40]. Unlike traditional game theory, which generally assumes fully rational decision-makers, evolutionary game theory incorporates bounded rationality and allows stakeholders to continuously learn, imitate, and adjust their strategies in response to others [21,41]. Given the strong public-good attributes of RSWM, government policy instruments are critical for system sustainability [42]. Policy design must balance fiscal burdens on public authorities while encouraging private-sector participation and investment [43,44]. In the early stages of multi-party collaboration, governments may deploy subsidies, regulatory sanctions and administrative penalties, and mobilize technical and fiscal support for rural waste governance. As stakeholder collaboration matures and supply-chain profitability improves, a ratchet effect may emerge, enabling governments to introduce market-competition mechanisms to filter out under-performing enterprises and optimize the overall rural solid-waste management supply chain [40].

Our findings confirm the dominant guiding function of government supervision reported in the existing rural-waste-governance literature. Prior studies emphasize that government supervision, incentive design and infrastructure investment are preconditions for effective rural waste management, and weak supervision may break the whole governance chain [11,12,19]. Similar conclusions have been documented in municipal solid-waste recycling research [18]. The present simulations provide further support for this argument: under passive government regulation, the strategies of WCDEs and rural households evolve

slowly toward cooperation, whereas active regulation accelerates trajectories toward the neighborhood of the boundary cooperative state (1, 1, 1).

Nevertheless, (1, 1, 1) is a policy-desirable corner-point equilibrium that remains dynamically locally unstable under our baseline parameters. System evolution cannot converge to this state unconditionally; the cooperative outcome depends on reasonable institutional incentive and regulatory conditions. While the government plays a top-level coordinating role for both WCDEs and rural households, WCDEs in turn exert substantial influence on rural-household behavioral choices. Joint guidance from governments and WCDEs can promote rural households to adopt rule-compliant sorting behavior.

Consistent with the existing literature, our simulation demonstrates that additional operating costs constitute a primary constraint discouraging WCDEs from proactive waste-classification implementation [16,30,45]. Rural waste-management contexts feature geographically dispersed collection points and high marginal transportation costs; without sufficient compensatory financial support, higher incremental operational costs reduce enterprises' willingness for active implementation. Our SD-simulation quantifies this effect: rising additional operating costs decrease the probability of WCDEs choosing active-implementation strategies, whereas government subsidies and cost-sharing arrangements can effectively reverse such negative trends, confirming that financial support alleviates enterprise-level cost pressure [46].

Notably, WCDEs in our Inner-Mongolia rural setting exhibit asymmetric responses to incentive–penalty instruments. Several urban-context studies report that penalties exert stronger disciplinary effects on enterprises than subsidies [25,26]. By contrast, our simulation indicates that the WCDE strategy is more sensitive to subsidy reductions than to penalty increases. Cutting subsidies rapidly pushes WCDEs toward passive implementation, while increasing penalties alone generates only limited improvement in active-implementation performance. This divergence may stem from contextual differences: urban waste-treatment enterprises generally possess stronger revenue-generating capacity and higher penalty affordability, whereas rural-oriented WCDEs operate on narrow profit margins and rely heavily on government fiscal support. This finding therefore cautions against the direct transfer of urban-oriented policy conclusions to rural contexts.

Cost-sharing arrangements for publicity expenditure and supporting-facility investment further shape strategic enterprise choices. A higher government cost-sharing ratio reduces the financial burden borne by WCDEs and encourages active implementation, while cost-allocation coefficients exert negligible influence over rural-household behavior. This result highlights the practical value of well-designed cost-sharing mechanisms to balance multi-stakeholder cost burdens. As rational economic entities, WCDEs cannot independently resolve the externalities generated by waste-classification services and remain dependent on government fiscal and policy backing to achieve long-term sustainable operation.

Rural-household sorting behavior is negatively associated with time and economic costs of classification and is positively driven by economic incentives, which aligns with the empirical survey-based evidence on rural residents' waste-sorting intentions [7,10]. Our results further distinguish incentive sources: incentives provided directly by governments exert stronger effects on household participation, whereas subsidies originating from WCDEs show only limited influence over rural-household behavior, consistent with findings from municipal solid-waste-recycling research [18].

Different subsidy–penalty portfolios produce heterogeneous responses across stakeholders, indicating potential incentive incompatibility within rural waste-governance systems [47]. A low-subsidy and low-penalty portfolio favors sustained government active regulation under tight grassroots-fiscal constraints, whereas high-subsidy together with

high-penalty measures are more effective at motivating active WCDE implementation and rural-household participation. No single policy combination optimizes outcomes for all three stakeholders simultaneously. This observation reflects the real-world fiscal trade-offs that local grassroots governments face when designing rural-waste-governance instruments.

This study has yielded simulation results consistent with core multi-stakeholder-governance logic documented in the existing literature, yet differences remain regarding the magnitude of the reward–penalty effects and evolutionary paths, which can be attributed to variations in research contexts, modeling assumptions and parameter specifications.

First, the relative effects of government subsidies and penalties on WCDE strategies differ from those reported in some previous studies. Existing research has generally suggested that penalties exert a stronger disciplinary effect on enterprise behavior than subsidies [25,26]. In contrast, the present simulations indicate that WCDE strategies are more sensitive to reductions in subsidies than to increases in penalties. Reducing subsidies rapidly shifts WCDEs toward passive implementation, whereas increasing penalties alone produces only a limited improvement in active implementation. This difference may partly reflect variations in research context. Previous studies have primarily examined urban waste management enterprises with relatively stronger revenue-generating capacity and greater ability to absorb regulatory penalties, whereas WCDEs operating in rural areas often face narrow profit margins, high service costs, and greater dependence on government financial support. The present findings therefore extend the discussion of subsidy–penalty mechanisms to rural waste management contexts and caution against directly generalizing conclusions derived from urban settings.

Second, the effects of different subsidy–penalty combinations vary across stakeholders. Previous studies have frequently regarded a combination of high subsidies and high penalties as an effective means of promoting collaborative governance [11,21]. The present study, however, shows that no single combination is equally favorable for all three stakeholders. A low-subsidy and low-penalty combination is more conducive to maintaining the government's active regulatory strategy over the long term, whereas a high-subsidy and high-penalty combination more strongly encourages active implementation by WCDEs and participation by rural households. These results demonstrate the potential for incentive incompatibility among stakeholders in waste management governance [47]. One possible explanation is that grassroots governments in rural areas operate under relatively tight fiscal constraints. Although high subsidies and penalties may strengthen the behavioral responses of WCDEs and rural households, maintaining such a policy combination may impose a substantial and potentially unsustainable fiscal burden on local governments. This stakeholder-specific finding provides a more context-sensitive basis for designing subsidy–penalty policies in rural China.

Third, this study examines cost sharing for public awareness campaigns and supporting infrastructure between the government and WCDEs. The simulations show that a higher government cost-sharing ratio reduces WCDEs' financial burden and encourages active implementation, but has little effect on rural household participation. These findings highlight the value of well-designed cost-sharing arrangements in balancing stakeholder burdens.

Our study also yielded some interesting findings. The strategy of WCDEs was predominantly shaped by two core dimensions: additional operational costs and government reward and punishment mechanisms, with cost differentials acting as the fundamental constraint driving their decision-making. Developing automated waste classification systems could reduce manual labor input for sorting and recycling activities [48]. As rational economic entities, WCDEs cannot unilaterally solve the externalities of their operations. They depend heavily on government support, which must provide economic incentives

and public awareness initiatives to ensure effective waste management [49]. Therefore, the government should subsidize and invest in facilities and equipment dedicated to separate disposal.

This study assumes relatively homogeneous rural households to simplify the evolutionary analysis. However, rural households may differ in environmental awareness, economic conditions, and acceptance of waste classification policies. Future studies could introduce heterogeneous rural household groups and social network effects to improve behavioral realism.

5. Conclusions

This study constructs a tripartite evolutionary game model involving the government, WCDE, and rural households. The SD model is utilized for numerical integration of the tripartite replicator-dynamic ordinary differential equations derived from evolutionary game theory and for visualizing solution trajectories. Based on the model deduction and multi-scenario simulation analysis, the core conclusions are drawn as follows.

Firstly, under the specified model assumptions and the verified baseline parameterisation, simulated trajectories evolve toward the neighborhood of the boundary point (1, 1, 1), representing the scenario of active government regulation, positive WCDE implementation, and rule-compliant rural households. Pure strategy game simulation further verifies the core guiding role of the government in the entire governance chain, which directly dominates the strategic choice of WCDE and indirectly affects rural households' participation. Meanwhile, WCDEs also exert a notable regulatory and driving effect on rural households' behavior, forming a relationship of mutual restraint and collaborative evolution among the three stakeholders.

Secondly, the strategic decisions of each stakeholder are constrained by distinct key factors, showing obvious cost–benefit orientation characteristics. For the government, the supervision cost, publicity cost and supporting facility investment cost are the core factors affecting its strategy, and the government prefers the low-subsidy and low-penalty portfolio to maintain long-term stable regulation. For WCDE, the additional operating costs generated by waste classification implementation, as well as government subsidies and penalties, are the key influencing factors; notably, the impact of subsidy reduction on enterprise strategies is far greater than that of penalty increase, and enterprises are highly dependent on government financial support. For rural households, the time cost and economic cost of waste classification are the main barriers to participation; their economic incentives mainly come from government support, and the subsidies provided by WCDEs have a minimal driving effect on their behavior.

Thirdly, the combination of government subsidies and penalties presents differentiated effects on different stakeholders. The low-subsidy and low-penalty combination is the most conducive to sustaining the government's active regulation strategy, while the high-subsidy and high-penalty combination can maximally mobilize the active implementation of WCDEs and the active participation of rural households. In addition, the cost allocation coefficient of publicity and supporting facilities between the government and WCDEs notably affects the cost burden of enterprises, but has no obvious impact on rural households' strategic choices. The government should design appropriate combinations of subsidies and penalties according to local governance conditions, considering the trade-off between stakeholder participation and implementation costs. The results provide policy insights for rural waste classification governance under the institutional context of China. Although the specific parameter settings may vary across regions, the evolutionary framework developed in this study can provide a theoretical reference for analyzing multi-agent coordination problems in other rural waste management systems.

This study makes three key theoretical contributions. First, it formally constructs and integrates cost-sharing mechanisms for publicity expenditures and supporting-facility investments between governments and WCDEs into the tripartite evolutionary-game framework. Second, it identifies heterogeneous stakeholder responses to incentive–penalty instruments and uncovers underlying incentive incompatibilities among actors. Third, it establishes a theoretical basis for governments to design and roll out incentive policies supporting the sustainable development of the WCDE industry.

6. Policy Implications and Future Prospects

Based on these findings, this paper proposes targeted policy recommendations to address the current dilemmas of weak multi-agent coordination, unclear responsibilities, and governance inefficiency in China's RSW classification management—specifically, by optimizing the responsibility chain, improving incentive and restraint mechanisms, and reducing cost burdens, thereby promoting the long-term stability of the RSW classification governance system.

First, governments should optimize incentive and restraint mechanisms for WCDEs and balance their cost–benefit structure. Given that high extra operating costs discourage enterprises' active adoption of waste classification, the government may establish a dynamic subsidy scheme to compensate WCDEs for extra expenditures on classified collection, transportation, and resource recovery. The government could also raise its share of publicity and supporting facility costs to relieve enterprises' operational burden. Meanwhile, a penalty framework should be introduced to fine enterprises for non-compliant behaviors. Nevertheless, subsidy incentives should be prioritized over pure penalty deterrence, complemented by tax preferences and technical support to promote standardized enterprise operation. The government can also help WCDEs expand profit sources and upgrade recycling technologies to realize the value addition of recyclable waste and strengthen their endogenous motivation for participation.

Second, policymakers should reduce rural households' participation costs and build targeted incentive guidance systems. To lower the cost barrier for rural household engagement, the government may simplify classification requirements and cut the time cost of household sorting and waste delivery. Moderate economic incentives for rural households can be designed, where rewards are tied to classification performance to boost participation enthusiasm. Policy design should avoid imposing unaffordable waste charges and set fees matching local rural economic conditions.

Third, differentiated subsidy–penalty portfolios should be formulated to accommodate grassroots fiscal constraints and governance demands. In routine governance, a low-subsidy and low-penalty combination can sustain stable supervision and avoid heavy fiscal pressure. For priority villages and regions with poor governance performance, temporary high-subsidy and high-penalty packages can accelerate the system's evolution toward the target strategy profile. As governance matures, the government can gradually tune incentive intensity and build a long-run balancing mechanism to achieve sustainable RSW governance without persistent high fiscal input.

Fourth, the government should assume primary responsibility for publicity campaigns and infrastructure investment. It is necessary to increase funding for user-friendly classification facilities adapted to rural living contexts and carry out targeted publicity activities matching rural residents' habits, laying hardware and cognitive foundations for household participation. Formal contracts between governments and WCDEs can clarify service standards, obligations, and reward–penalty rules to prevent responsibility diffusion.

In addition, to clarify the multi-agent responsibility chain and consolidate the government's leading role, normalized township- and village-level management mechanisms

should be established. Dedicated institutions and full-time staff can be deployed to conduct regular inspections of WCDEs' classified transportation and disposal and investigate mixed transportation and indiscriminate dumping. A simplified two-category waste classification standard (decomposable versus non-decomposable waste) can be adopted to facilitate on-site implementation. In addition, social supervision and violation reporting channels should be opened, encouraging rural households to report illegal enterprise behaviors and non-compliant sorting by residents, which can strengthen public engagement and gradually transform passive participation into voluntary action.

Several limitations of this work should be acknowledged. First, simulation outputs rely on baseline parameters calibrated from semi-structured field interviews in rural Hohhot. Many decomposed micro-cost and benefit indicators are not available in official statistical reports, and interview-derived information inevitably contains stakeholder-subjective judgment, introducing potential simulation uncertainty. Second, the model adopts a complete-information assumption for all three stakeholders and holds payoff parameters static over simulation time. In practice, information asymmetry exists among government, WCDE operators, and rural households, and stochastic shocks including fiscal adjustments, market-price fluctuations, and policy revisions may dynamically alter cost–benefit conditions, which our static-parameter framework cannot capture. Third, rural-household agents are treated as homogeneous groups. In reality, households differ in income level, environmental awareness and policy acceptance, and future work could introduce heterogeneous-agent settings and social-network spill-over effects to improve behavioral realism. Fourth, the baseline scenario is calibrated for rural Hohhot of northern China; the quantitative simulation outcomes are scenario-specific and cannot be directly generalized to other regions, even though the evolutionary-game analytical framework can be transferred to other rural-waste-governance research contexts.

Future research directions include collecting large-scale questionnaire-survey datasets to support more robust parameter calibration, constructing asymmetric-information evolutionary-game models, incorporating time-varying payoff parameters and stochastic policy shocks, implementing multi-regional comparative case studies, and exploring heterogeneous-household and social-network effects within RSWM systems.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Research Ethics Committee of Inner Mongolia Agricultural University (Science and Technology Department) (Approval Code: NNDKY2021001;

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Abbreviations

The following abbreviations are used in this manuscript:

RSW	Rural solid waste
WCDE	Waste collection and disposal enterprises

Appendix A

Table A1. Eigenvalues and stability of game equilibrium solution.

Equilibrium Solutions	Corresponding Eigenvalues	Symbols of the Eigenvalues	Stability of Game Equilibrium Solution
$E_1(0,0,0)$	$\lambda_1 = -R_c - P_e - S_f + F_e + F_f + C_f$ $\lambda_2 = -A_c + C_r - P_e - S_f - E_x$ $\lambda_3 = -T_c - E_i + E_c$	(*, *, *)	indeterminate
$E_2(0,0,1)$	$\lambda_1 = -E_f - R_c - P_e - S_f + F_e + C_f$ $\lambda_2 = -S_h - A_c + C_r - P_e - S_f$ $\lambda_3 = T_c + E_i - E_c$	(*, *, *)	indeterminate
$E_3(0,1,0)$	$\lambda_1 = aP_e - bS_f - S_e - R_c + F_f$ $\lambda_2 = A_c - C_r + P_e + S_f + E_x$ $\lambda_3 = S_h - T_c - E_i + E_c$	(*, *, *)	indeterminate
$E_4(0,1,1)$	$\lambda_1 = -aP_e - bS_f - S_e - E_f - R_c$ $\lambda_2 = S_h + A_c - C_r + P_e + S_f$ $\lambda_3 = -S_h + T_c + E_i - E_c)$	(*, *, *)	indeterminate
$E_5(1,0,0)$	$\lambda_1 = R_c + P_e + S_f - F_e - F_f - C_f$ $\lambda_2 =$ $aP_e + bS_f + S_e + F_e - A_c + C_r - P_e - S_f - E_x$ $\lambda_3 = E_f + F_f - T_c - E_i + E_c$	(*, *, *)	indeterminate
$E_6(1,0,1)$	$\lambda_1 = E_f + R_c + P_e + S_f - F_e - C_f$ $\lambda_2 = -(1-a)P_e - (1-b)S_f + S_e + F_e -$ $S_h - A_c + C_r$ $\lambda_3 = -\left(E_f + F_f - T_c - E_i + E_c\right)$	(*, *, *)	indeterminate
$E_7(1,1,0)$	$\lambda_1 = aP_e + bS_f + S_e + R_c - F_f$ $\lambda_2 = (1-a)P_e + (1-b)S_f - S_e - F_e +$ $A_c - C_r + E_x$ $\lambda_3 = E_f + F_f + S_h - T_c - E_i + E_c$	(*, *, *)	indeterminate
$E_8(1,1,1)$	$\lambda_1 = aP_e + bS_f + S_e + R_c + E_f$ $\lambda_2 =$ $(1-a)P_e + (1-b)S_f - S_e - F_e + A_c - C_r$ $\lambda_3 = -\left(E_f + F_f + S_h - T_c - E_i + E_c\right)$	(+, *, *)	indeterminate

Note : * is not sure of its positivity or negativity; any positive real eigenvalue indicates local instability or saddle-point behavior.

Table A2. The real-world values of some parameters.

Parameter	Real-World Value	Unit	Source	Dimensionless Baseline Value
R_c	600–1100	ten-thousand RMB/year	Assumption	4
C_f	350–650	ten thousand RMB/year	Assumption	2
P_e	2500	RMB/village/year	Investigation	8
S_f	1700	ten thousand RMB/year	Investigation	6
A_c	500–1000	ten-thousand RMB/year	Investigation	4
T_c	5–8	hours/household per month	Institutional report	3
E_i	20–30	RMB/household per year	Investigation	2
C_n	300–700	ten thousand RMB/year	Assumption	2
E_x	40–80	RMB/ton	Investigation	3
a	0.45	-	Investigation	0.45
b	0.65	-	Investigation	0.65
F_e	0.5–3	ten-thousand RMB/single penalty	Official announcement	3
F_f	30–50	RMB/household single fine	Investigation	3
S_e	40–170	ten thousand RMB/village/year	Investigation	14
E_f	10	ten-thousand RMB/village/year	Investigation	2
S_h	20	RMB/household per year	Investigation	2
R_n	500–700	ten-thousand RMB/year	Investigation	2
E_b	-	-	References [36,39]	1.82 * Sf
C_r	-	-		0.84 * Sf
E_c	-	-		0.64 * Pe

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