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Towards a green mining future: A dynamic evolutionary game model for collaborative waste recycling

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A B S T R A C T

In the realm of environmental concerns, the management of mining waste has consistently emerged as a prominent issue. The accumulation of such waste not only results in substantial pollution but also signifies an inefficient use of resources. Rich in heavy metals and an array of toxic substances, mining waste poses a considerable challenge. In China, the situation is exacerbated by mining companies' inadequate and untimely efforts to address the extensive buildup of waste material. The long-term policy of recycling and regulating mining waste can be seen as the result of a long-term game between the government's regulatory decisions and the enterprises' fulfillment of their responsibilities, and the public's ability to participate in monitoring the decisions also changes the pattern of the game. In this study, we develop a tripartite evolutionary game model involving mining enterprises, the public, and local government. System dynamics are used to simulate the dynamic evolution of each stakeholder's strategy, examining the influence of various parameters on the evolution trajectory. Our findings show that: (1) reducing public subsidies, along with increasing enterprise supervision and penalties, effectively encourages public involvement in oversight and promotes proactive waste recycling by enterprises; (2) as enterprises actively engage in recycling efforts, the resulting environmental benefits boost public enthusiasm for participation in monitoring; (3) over time, heightened environmental awareness among the public and advances in recycling technology allow enterprises to improve the profitability of recycling, fostering a sustainable mine waste recycling industry; (4) once a virtuous mine waste recycling industry is established, enterprises autonomously engage in waste recycling, and the public actively participates in supervision, making strict government oversight unnecessary.

1. Introduction

In accordance with the principles of ecological development and to ensure sustainable and healthy economic growth, the 19th National Congress of China report explicitly introduced the novel development concept of "innovation, coordination, green, openness, and sharing." This concept imposes higher requirements on environmental management [1]. Mining waste management is a critical environmental issue, as mining activities generate substantial waste that is frequently not disposed of promptly by mining companies, leading to waste accumulation [2]. Mining waste contains significant quantities of heavy metals and other toxic substances that, if not

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treated properly, can severely pollute the surrounding environment, damage ecosystems, kill vegetation, degrade soil quality, and even contaminate local water resources [3,4]. Moreover, harmful substances in mining waste can cause severe health risks such as cancer and poisoning if consumed by humans [5,6]. For instance, in Linzhou City's lead-zinc mining area, Henan Province, long-term discharge and waste pile-up have resulted in severe environmental pollution and affected local residents, with a considerable number of people suffering from lead poisoning [7]. Although mine waste constitutes an important resource with high recovery value, the lack of effective management and oversight mechanisms has led to resource wastage and environmental pollution in the waste recycling industry [8,9].

To address this issue, the Chinese government has recently proposed measures to enhance public supervision and involve the public in the governance system of the waste recycling industry, thereby fostering the industry's healthy and sustainable development. Numerous scholars have also suggested approaches such as increasing public participation, refining regulatory mechanisms, and advancing technology [10,11]. In contrast to command-and-control and market-incentive environmental policy tools, public monitoring is a bottom-up, informal environmental regulation. Public participation in monitoring can help resolve the issue of insufficient corporate incentives for environmental protection [12]. However, public monitoring also presents certain challenges, such as low public participation and regulatory difficulties [13,14]. Supervision under public participation may lead to unnecessary disputes and conflicts, potentially adversely impacting the normal operation of businesses [15]. In summary, strengthening public supervision is a vital means of promoting the healthy and sustainable development of the waste recycling industry, but it requires ongoing exploration and refinement in practice. In quantitative research on public participation supervision, most literature uses static qualitative analysis and social surveys, focusing on the positive role of public participation, the influencing factors of public participation, and public participation methods [16–19]. There needs to be more research on the interaction between the public, enterprises, and the government. As for the interaction mechanism among the government, the public, and enterprises, evolutionary Game theory has become the best tool to study the behavior strategies of the three parties in developing the mining waste recycling industry.

The long-term policy of recycling and regulating mining waste can be seen as the result of a long-term game between the government's regulatory decisions and the enterprises' fulfillment of their responsibilities, and the public's ability to participate in monitoring the decisions also changes the pattern of the game. Due to factors such as information asymmetry and the complexity of the environment, the government, the public and mining enterprises all have limited rationality. Based on this, this paper combines evolutionary game theory and system dynamics simulation methods to study the dynamic evolution process of each player's strategy and its feedback mechanism in the tripartite game of "mining enterprises - public - government" for recycling mining waste.

This study makes marginal contributions in the following ways: (1) In contrast to existing research that primarily focuses on the regulatory game between governments and enterprises, this paper incorporates public participation behavior into an evolutionary game model. It explores the regulatory mechanism for waste material recycling in mining areas from multiple perspectives, including enterprises' recycling technology level, government reward and punishment policies, and public willingness to participate. (2) Using evolutionary game theory, the paper analyzes the stable equilibrium solutions for the strategies of different players during various stages of development in the waste material recycling industry in mining areas. (3) By employing System Dynamics (SD) simulation, the study examines the influence of factors such as enterprises' recycling technology level, public environmental awareness, and the intensity of subsidies and penalties on the evolution of waste material recycling. This paper also discusses the challenges and improvements in environmental regulation in mining areas.

2. Literature review

2.1. Problems with recycling of mine waste

In the realm of mining waste recycling, striking an equilibrium between environmental conservation and resource exploitation is of paramount importance for government entities. Concurrently, corporations must delicately balance economic gains with their commitment to environmental stewardship. Consequently, fostering synergistic collaboration between the government and the mining enterprises is crucial for propelling the mining waste recycling industry forward [20].

In China, the development of mining waste recycling faces three significant challenges. Firstly, the absence of an effective recycling mechanism impedes progress in this sector. Despite the issuance of regulatory documents such as the 2018 Law on the Prevention and Control of Environmental Pollution by Solid Waste, which governs the mining waste recycling industry and mandates the development of waste reduction and resource utilization plans [21], the recycling process remains inadequately regulated and standardized. Consequently, a large portion of mining waste is not efficiently recycled, leading to substantial environmental pollution.

Secondly, technological limitations in waste recycling enterprises and insufficient resource sharing and technology exchange among companies hinder the optimization of recycling processes and resource utilization [22,23]. For instance, the e-waste recycling sector, a crucial component of mining waste recycling in China, struggles with ineffective waste recycling and disposal due to a lack of technical support and collaboration between enterprises [24].

Lastly, policy support is critical for promoting mining waste recycling. However, China currently lacks sufficient policy support in this area, which contributes to the slow progress of mining waste recycling initiatives [25]. To overcome these challenges, it is essential for China to establish a comprehensive and effective regulatory framework, invest in advanced technologies, and provide robust policy support to advance the mining waste recycling industry.

2.2. Game theory in the regulation of the mining waste recycling industry

The primary factor hindering the progress of the mining waste recycling industry is the negative externalities produced by mining enterprises, with the environmental management of these sites relying heavily on the enforcement of local regulations [26,27]. The majority of current scholarly studies concentrate on the interactions between governments and corporations. As an example, Xia et al. [28] created a non-cooperative game model to examine the effects of strict environmental regulations on companies' emissions reduction technologies. In addition, Zhenling and Wenju [29] formulated a game model that included local governments and enterprises to study a workable environmental taxation system during a transition from a fee-based to a tax-based approach. However, obstacles like collusion between governments and businesses or insufficient enforcement can occur while implementing these regulations. Achieving the intended environmental management outcomes solely through government regulation is difficult; hence, public involvement can help overcome the shortcomings of government actions and market mechanisms [30]. Consequently, You and Yang [31] integrated public reporting into the government-enterprise game model to examine the strategic decisions between governmental regulatory actions and innovative business practices under various circumstances.

The integration of system dynamics (SD) simulation methodology and equilibrium strategy analysis of stable evolutionary game strategies has gained increasing recognition among scholars in recent years. The analysis of feedback structures within system dynamics can effectively uncover the intricate patterns of dynamic feedback that emerge from interactions among game participants [32]. Researchers have attempted to employ the fusion of evolutionary game analysis and SD simulation methods in various applications. For instance, Hu and Qi [33] conducted a simulation study on the dynamic evolution of digital currency proliferation, considering the interplay between public participation and government regulation using an SD-based evolutionary game model. Ma et al. [34] combined evolutionary game theory with SD to investigate the issue of state inspections concerning coal mine safety. Liu et al. [35] carried out an SD simulation analysis addressing the recycling problem faced by household medical equipment enterprises.

In summary, while numerous research findings on environmental pollution regulation have been achieved by both domestic and international scholars, providing a vital theoretical foundation for this study, there are still certain limitations that need to be addressed. First, while mining waste pollution constitutes a form of environmental pollution, the regulation of mining waste recycling should not be treated as merely a traditional environmental regulation; rather, it should account for the advantages gained through environmental regulation and resource recycling. Second, the majority of existing research primarily focuses on environmental regulation, corporate innovation, and government-corporate collusion, without taking into account the behavioral requirements of diverse stakeholders involved in implementing environmental regulations.

Thirdly, when examining the impact of public influence on environmental pollution management, some researchers have primarily focused on constructing two-sided game models involving either the government and the public or the public and enterprises to investigate the equilibrium strategies of the participating agents. To address this limitation, we propose a tripartite evolutionary game model, grounded in the principles of finite rationality from evolutionary game theory, which encompasses local governments, mining enterprises, and the public. Our study aims to elucidate the dynamic evolutionary processes of each stakeholder's strategic choices and their feedback mechanisms by employing System Dynamics (SD) simulation analysis. The findings of this research offer valuable insights for policymakers in devising scientifically sound and well-informed environmental regulations that foster the sustainable growth of the mining waste recycling industry.

3. Basic assumptions and model building

3.1. Basic assumptions

The process of implementing environmental regulations in mining regions involves the collaboration of various stakeholders such as mining enterprises, local communities, and government authorities [36]. The accumulation of mining waste not only represents a loss of valuable resources, but also poses significant threats to the ecological environment. To facilitate the development of the mining waste recycling industry, it is essential to identify a game equilibrium under the conditions of incomplete information [37]. This paper presents the following basic assumptions:

3.1.1. Game players

The mining enterprises, the public and the local government are selected as game players and all three are assumed to be finite rational.

3.1.2. The parties in the game and their strategy choices

Mining enterprises: As the primary actors responsible for waste recycling, mining companies must strike a balance between maintaining their corporate image and managing the costs associated with recycling. While some companies are actively engaged in waste recycling, others may be deterred by factors such as high input costs, outdated technology and profitability challenges [38]. Let us denote the strategy set of mining companies as (actively recycling, negatively recycling), where the probability of actively waste recycling is x and the probability of negatively waste recycling is $1-x$.

Public: Public participation in monitoring will be rewarded by the government, and active recycling by companies will result in environmental preference gains for the public. Even if they choose not to participate in monitoring, the public may still receive compensation from the government in the event of environmental damage. We can represent the public's strategy set as (scrutiny, non-scrutiny), where the probability of choosing scrutiny is y and the probability of choosing non-scrutiny is $1-y$.

Government: As the primary regulator of environmental management, local governments must weigh the social and environmental benefits of recycling regulations against the administrative costs of implementing such policies [39]. We can model the government's strategy set as (strict regulation, lenient regulation), where the probability of strict regulation is z and the probability of lenient regulation is 1-z.

3.1.3. Setting of profit and loss variables

In the context of mining enterprises, several variables determine the profit and loss dynamics. These variables involve the costs and benefits experienced by the enterprises themselves, the public, and the government.

For mining enterprises, the cost of active waste recycling is denoted as C_T, while the potential gains in corporate reputation from such recycling activities are represented by R_T. The relationship between these variables is given as $C_T > R_T$. Furthermore, the gains from resource recycling and laddering achieved by mining enterprises are represented as βR_M, where R_M signifies the maximum possible gain from comprehensive waste recycling, and β indicates the technological efficiency of recycling, with $\beta \in (0, 1)$. Higher β values, approaching 1, suggest a more advanced level of technology.

Regarding public profit and loss variables, the cost of public engagement in regulatory oversight is C_P, while the government-provided reward for such participation is R_P. Active recycling by mining enterprises, which reduces environmental damage due to waste accumulation, generates an environmental preference benefit, μL, for the public. Here, L represents the maximum environmental benefit attainable from waste recycling, and μ denotes public environmental awareness, with $\mu \in (0, 1)$. Higher μ values, nearing 1, indicate heightened public environmental consciousness. In the absence of public monitoring, the government compensates the public with R_C for the losses incurred from environmental pollution. The condition $-C_P + R_P + \mu L > R_C$ must hold.

As for governmental profit and loss variables, when implementing strict regulatory strategies, the government offers financial and tax subsidies, T, to encourage enterprises to actively recycle waste. Concurrently, it imposes penalties, P, on enterprises that neglect recycling and cause environmental pollution. To stimulate public participation in environmental monitoring, the government reduces public compensation for non-participation to $(1 - \alpha)R_C$, where α signifies the extent of compensation reduction. The cost of stringent governmental regulation is C_G, whereas rewards from higher authorities and gains in government credibility are represented by R_G, with the condition $R_G > C_G$. When enterprises actively recycle, the government accrues environmental benefits, R_E, due to the externalities of mining waste recycling. In contrast, under lax regulatory strategies, non-participation by the public in supervision results in environmental pollution and resource waste, imposing an environmental management cost, C_I, on the government.

3.2. Construction of the payoff matrix

Considering the assumptions mentioned earlier, the meanings of various parameters are summarized in Table 1. The mixed strategy game matrix for mining enterprises, the public, and local governments is presented in Table 2.

3.3. Replication of dynamic equations and equilibrium points

Based on the payment matrix of the three parties of the mining waste recycling game in Table 2, the expected returns and the average expected returns of the mining enterprises opting for active and negative recovery are shown in equations (1)–(3):

$$U_{m1} = yz(R_T - C_T + \beta R_M + T) + y(1-z)(R_T - C_T + \beta R_M) + (1-y)z(R_T - C_T) + (1-y)(1-z)(R_T - C_T) \quad (1)$$

$$U_{m2} = yz(-P) + z(1-y)(-P) \quad (2)$$

$$U_m = xU_{m1} + (1-x)U_{m2} = Txyz + \beta R_M xy + Pxz + (R_T - C_T)x - Pz \quad (3)$$

Table 1
Parameters symbol descriptions.

Parameters	Descriptions
C_T	The costs of recycling.
R_T	Potential benefits for mining companies associated with active recycling efforts.
R_M	The peak of the benefits from full recycling of mining waste.
β	Recycling technology level，$\beta \in (0, 1)$.
C_P	The costs of public scrutiny.
R_P	Rewards for public scrutiny.
L	Peak environmental benefit achievable through mining waste recycling.
μ	Public awareness of environmental protection, with awareness coefficient $\mu \in (0, 1)$.
R_C	Public compensation provided by the government.
T	The subsidies given by the local government.
P	Penalties imposed by the government on enterprises.
α	Proportion of subsidy reduction.
C_G	The cost of strict regulation.
R_G	The benefits of improving government credibility.
R_E	The benefits of environmental protection.
C_I	The costs of government-managed environmental remediation efforts.

Table 2
Payoff matrix among each game player.

Game players		Enterprises			
		Actively recycle x		Negatively recycle 1-x	
		Public		Public	
		Scrutiny y	Non-scrutiny 1 - y	Scrutiny y	Non-scrutiny 1 - y
Local government	Strict regulation z	$RT-CT+\beta RM+T$, $-CP+RP+\mu L$, $RE+RG-CG-T$	$RT-CT$, $(1\text{-}\alpha)RC$, $RG-CG-CI$	$-P$, $-CP+RP$, $RG-CG+P$	$-P$, $(1\text{-}\alpha)RC$, $RG-CG+P-CI$
	Lenient regulation 1-z	$RT-CT+\beta RM$, $-CP+RP+\mu L$, RE	$RT-CT$, RC, $-CI$	0, $-CP+RP$, 0	0, RC, $-CI$

The computation of the replicator dynamics equation for mining companies follows equation (4):

$$F(x)=x(U_{m1}-U_m)=x(1-x)(C_T-R_T-\beta R_My-Tyz-Pz) \tag{4}$$

The expected returns and the average expected returns of the public opting for scrutiny and non-scrutiny are shown in equations (5)–(7):

$$U_{c1}=xz(-C_P+R_P+\mu L)+x(1-z)(-C_P+R_P+\mu L)+(1-x)z(-C_P+R_P)+(1-x)(1-z)(-C_P+R_P) \tag{5}$$

$$U_{c2}=xz(1-\alpha)R_C+x(1-z)R_C+z(1-x)(1-\alpha)R_C+(1-x)(1-z)R_C \tag{6}$$

$$U_{c2}=yU_{c1}+(1-y)E_{c2}=\mu Lxy-(C_P-R_P)y+(1-y)(1-\alpha z)R_C \tag{7}$$

The computation of the replicator dynamics equation for the public follows equation (8):

$$F(y)=y(U_{c1}-U_c)=y(1-y)(\mu Lx+\alpha R_Cz-C_P+R_P-R_C) \tag{8}$$

The expected returns and the average expected returns of the local governments opting for strict and lenient regulation are shown in equations (9)–(11):

$$U_{g1}=xy(R_E+R_G-C_G-T)+x(1-y)(R_G-C_G-C_I)+(1-x)y(R_G-C_G+P)+(1-x)(1-y)(R_G-C_G+P-C_I) \tag{9}$$

$$U_{g2}=xyR_E-x(1-y)C_I-(1-x)(1-y)C_I \tag{10}$$

$$U_g=zU_{g1}+(1-z)U_{g2}=(R_G-C_G)z-Txyz+R_Exy+P(1-x)Z+(y-1)C_I \tag{11}$$

The computation of the replicator dynamics equation for the local governments follows equation (12):

$$F(z)=z\left(U_{g1}-U_g\right)=z(z-1)(Txy+Px+C_G-P-R_G) \tag{12}$$

The dynamics of mining companies, the public, and government strategies evolve as the game progresses. According to the principle of stability in differential equations, when the replicated dynamic equations for the three parties in the game converge to zero, the system approaches a stable state.

From F(x) = 0,F(y) = 0,F(z) = 0, we can get 8 system local equilibrium points: E1 (0,0,0),E2 (1,0,0),E3 (0,1,0),E4 (0,0,1),E5 (0,1,1), E6 (1,0,1),E7 (1,1,0),E8 (1,1,1). The partial derivatives of F(x), F(y), and F(z) with respect to x, y, and z are solved separately to obtain the Jacobi matrix, as shown in equation (13):

$$J=\begin{bmatrix}J_1 & J_2 & J_3\\ J_4 & J_5 & J_6\\ J_7 & J_8 & J_9\end{bmatrix}=\begin{bmatrix}\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z}\\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z}\\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z}\end{bmatrix}=$$

$$\begin{bmatrix}2(x-1)(C_T-R_T-\beta R_My-Tyz-Pz) & x(x-1)(-\beta R_M-Tz) & x(x-1)(P+Tx)\\ y(1-y)\mu L & (1-2y)(\mu Lx+\alpha R_Cz-C_P+R_P-R_C) & y(1-y)\alpha R_C\\ z(z-1)(P+Ty) & z(1-z)xT & (2z-1)(Txy+Px+C_G-P-R_G)\end{bmatrix} \tag{13}$$

According to the Lyapunov stability theorem for ordinary differential equations, an equilibrium point that meets the condition of having all negative eigenvalues in the Jacobian matrix is considered an evolutionarily stable strategy (ESS) for the replicator dynamic system. By inserting each of the eight equilibrium points into the Jacobian matrix, the associated eigenvalues for each point can be determined, as displayed in Table 3. The analysis of the evolutionary stability strategy of the equilibrium points is shown in Table 4.

3.4. Analysis of evolutionary stabilization strategies

In summary, the equilibrium states E1(0,0,0), E2(1,0,0), E3(0,1,0), E5(0,1,1), and E6(1,0,1) possess non-negative eigenvalues, thereby contradicting established stability theory principles. In light of these findings, our analysis will focus on evaluating the stability of the local equilibrium points E4(0,0,1), E7(1,1,0), and E8(1,1,1). By doing so, we aim to delineate the mine waste recycling industry's progression into three primary stages: initial, intermediate, and advanced.

In the initial stage, the system reaches a stable equilibrium at E4(0,0,1) when the following conditions are met: $C_T > R_T + P$, $-C_P + R_P < (1-\alpha) R_C$, and $R_G + P > C_G$. This indicates that companies choose a passive recycling strategy when the cost of active recycling exceeds the potential benefits and penalties combined. The public opts not to participate in scrutiny when the benefits of participation are smaller than those of non-scrutiny. The government selects strict regulation when the benefits of stringent oversight surpass the costs. Under these conditions, the system stabilizes at a strategy combination characterized by negative recycling, non-scrutiny, and strict regulation. This outcome reveals that insufficient penalties for companies' passive recycling behavior ($P < C_T - R_T$) and a relatively high level of compensation for the public ($1-\alpha > (-C_P + R_P)/R_C$) result in both companies and the public adopting passive strategies. During the early development of the recycling industry, mining enterprises may struggle to generate profits from short-term waste material recovery due to high recycling costs. Consequently, even strict governmental regulation may not yield significant improvements in this phase.

In the intermediate phase, the system stabilizes at equilibrium point E8(1,1,1) under the condition that $C_T < R_T + \beta R_M + P + T$, $(1-\alpha)R_C < -C_P + R_P + \mu L$, and $R_G - C_G > T$. This implies that when the government's regulatory benefits outweigh the costs by a margin greater than the subsidy, stringent regulatory strategies will be employed. In such a scenario, if the cost of active recycling for enterprises is lower than the benefits, and the public's participation yields higher returns than non-participation, the system stabilizes at a strategy combination of (active recycling, scrutiny, strict regulation). Under the stability condition at E8(1,1,1), the recycling technology level of enterprises is relatively low, i.e., $(C_T - R_T - P - T)/R_M < \beta < (C_T - R_T)/R_M$, and the public's environmental awareness is also low, with $((1 - \alpha)R_C + C_P – R_P)/L < \mu < (R_C + C_P – R_P)/L$. This indicates that during the developmental phase of waste recycling and utilization, the low level of recycling technology contributes to a weak willingness for enterprises to actively engage in recycling efforts. Simultaneously, the majority of the public lacks sufficient environmental awareness, which further diminishes the enterprises' motivation to recycle waste materials.

In the mature phase of the mine waste recycling industry, the system stabilizes at point E7(1,1,0) under the following conditions: $C_T < R_T + \beta R_M$, $R_P – C_P + \mu L > R_C$, and $R_G - C_G < T$. This indicates that when the benefits of proactive recycling by enterprises outweigh the costs, firms will adopt aggressive recycling strategies. Public participation in supervision is chosen when the combined environmental preference gains and government rewards under public supervision are greater than the benefits of non-participation. Although the costs of stringent government regulation exceed the benefits, enterprises and the public spontaneously choose proactive strategies, leading the government to adopt a relaxed regulatory approach. At this point, the system stabilizes with a strategy combination of active recycling, public scrutiny, and lenient government regulation. Under the stable conditions at E7(1,1,0), the recycling utilization level of enterprises is relatively high ($\beta > (C_T - R_T)/R_M$), and the environmental awareness of consumers is also high ($\mu > (C_P - R_P + R_C)/L$). This suggests that, with the continuous advancement of waste recycling in mining areas and the sustained promotion of national dual-carbon goals, recycling technology has reached a higher level, and public awareness of environmental protection has been steadily strengthened. As a result, the recycling industry has entered a mature stage, where enterprises can profit from the recycling process, and the public actively practices low-carbon green actions. At this stage, ideal environmental regulation results can be achieved through public supervision alone. Accompanying the improvement of government environmental regulation systems and the healthy development of the industry, the government only needs to adopt a more relaxed regulatory strategy.

4. Simulation analysis of system dynamics for evolutionary stable dynamic processes

Based on the evolutionary game analysis in the previous section, the three main stakeholders in mining waste recycling – enterprises, the public, and the government – may evolve into two ideal stable states: (active recycling, scrutiny, lenient regulation) or

Table 3
Eigenvalues of the Jacobi matrix corresponding to each equilibrium point.

Balancing Point	λ1	λ2	λ3
$E_1(0,0,0)$	$R_T – C_T$	$–C_P + R_P − R_C$	$RG−CG + P$
$E_2(1,0,0)$	$C_T – R_T$	$–C_P + R_P − R_C + \mu L$	$RG−CG$
$E_3(0,1,0)$	$R_T – C_T + \beta R_M$	$R_C + C_P - R_P$	$RG−CG + P$
$E_4(0,0,1)$	$R_T – C_T + P$	$–C_P + R_P - (1-\alpha) R_C$	$CG−RG−P$
$E_5(0,1,1)$	$R_T – C_T + \beta R_M + P + T$	$(1–\alpha) R_C + C_P − R_P$	$CG−RG−P$
$E_6(1,0,1)$	$C_T – R_T – P$	$–C_P + R_P – (1–\alpha) R_P + \mu L$	$CG−RG$
$E_7(1,1,0)$	$C_T – R_T – \beta R_M$	$C_P − R_P + R_C - \mu L$	$RG−CG−T$
$E_8(1,1,1)$	$C_T – R_T – \beta R_M – P – T$	$(1–\alpha) R_C + C_P – R_P – \mu L$	$CG – RG + T$

Table 4
Equilibrium point evolutionary stabilization strategy (ESS) analysis.

Balancing Point	Eigenvalue Real Part Sign	Stability	Judgment Conditions
$E_1(0,0,0)$	(-,-,+)	Unstable	/
$E_2(1,0,0)$	(+,+,+)	Unstable	/
$E_3(0,1,0)$	(±,+,+)	Unstable	/
$E_4(0,0,1)$	(±,-,-)	ESS	$C_T > R_T + P$, $-C_P + R_P <(1-\alpha) R_C$, $R_{G+P} > C_G$
$E_5(0,1,1)$	(±,+,-)	Unstable	/
$E_6(1,0,1)$	(±,+,-)	Unstable	/
$E_7(1,1,0)$	(±,-,±)	ESS	$C_T < R_T+\beta R_M$, $-C_P + R_P +\mu L > R_C$, $R_G - C_G < T$
$E_8(1,1,1)$	(±,-,±)	ESS	$C_T < R_T+\beta R_M + P + T$, $(1-\alpha) R_C < -C_P + R_P + \mu L$, $R_G - C_G > T$

(active recycling, scrutiny, strict regulation). However, the tripartite game may also result in an evolutionary outcome of (negative recycling, non-scrutiny, strict regulation). In the following, we employ a system dynamics approach to simulate the dynamic evolution of stakeholder strategy selection, analyze the impact of key system parameters on the mining waste recycling evolutionary state, and thereby explore the pathways to transition from the current state to the desired state in mining waste recycling.

4.1. Construction of a system dynamics simulation model

In accordance with the tripartite strategy replication dynamics equation, we employed Vensim software to construct a system dynamics (SD) flow diagram model for the evolutionary game of waste recycling in mining areas, as illustrated in Fig. 1. The model encompasses three stock variables: the probability of proactive recycling by enterprises (x), public participation probability (y), and the probability of stringent government regulation (z); three flow variables: the rate of change in proactive recycling probability F(x), the rate of change in participation probability F(y), and the rate of change in strict regulation probability F(z); as well as several exogenous variables. The causal relationships among these variables are determined by Table 2 and the tripartite replication dynamics equation.

Considering the stated assumptions and relationships between variables, the model is configured as follows: the initial time is set to 0, the final time is 15, with a time step of 0.125, and the unit of measurement is months. The nascent mining waste recycling sector in China is currently in the initial phase of its developmental trajectory [40,41]. In order to reach the equilibrium point E4(0,0,1), the industry must achieve evolutionary stability at this stage. Consequently, we can derive the following arrays that fulfill the requisite conditions: $C_T = 8$, $R_T = 2$, $R_M = 10$, $C_P = 2$, $R_P = 5$, $L = 3$, $R_C = 5$, $C_G = 5$, $R_G = 8$, $R_E = 4$, and $C_I = 4$. During the initial stage of industrial development, the level of recycling technology and public environmental awareness were relatively low. At this point, the government began to recognize the necessity of regulating the waste recycling industry. Consequently, we set $P = 2$, $T = 2$, $\alpha = 0.3$, $\beta = 0.3$, and $\mu = 0.2$. The simulation results are depicted in Fig. 2.

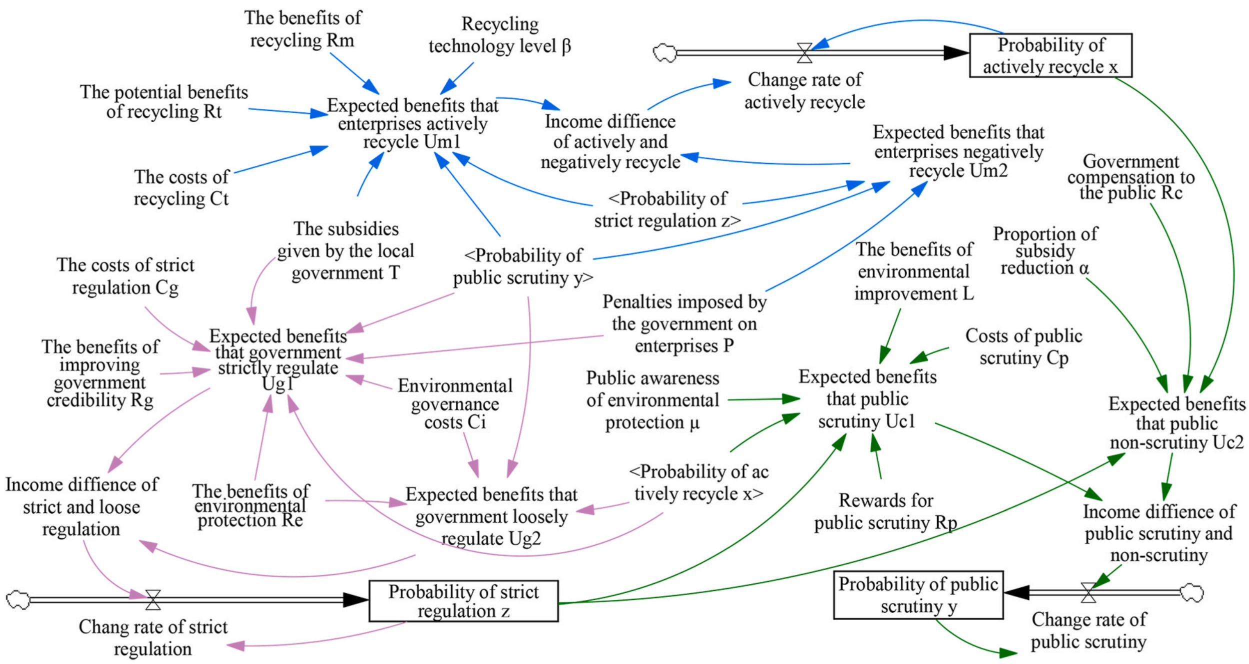

Fig. 1. SD stock and flow diagram of mining waste recycling evolutionary game.

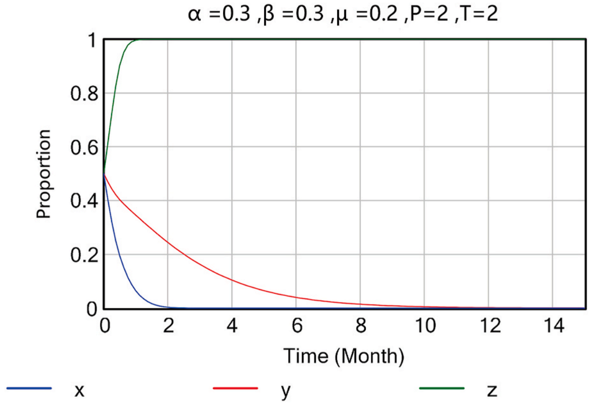

Fig. 2. Base simulation results of system evolution dynamics.

4.2. The impact of the subsidy cuts to the public on evolutionary results

Excessive compensation may reduce public sensitivity to environmental damage [42]. If the public feels that regardless of how companies damage the environment, they will receive a large amount of compensation, they may reduce their attention to environmental protection because compensation has become an economic reward [43]. In this situation, the government needs to reduce subsidies. Fig. 3(a) and (b) illustrate the effects of government subsidy reductions on the evolutionary trajectory of the system, with α set to 0.5 and 0.7, respectively. When $\alpha = 0.5$, the system transitions from the initial state (0,0,1) to (1,1,1).

As the reduction in government subsidies intensifies, public behavioral strategies shift from non-scrutiny to scrutiny, resulting in an

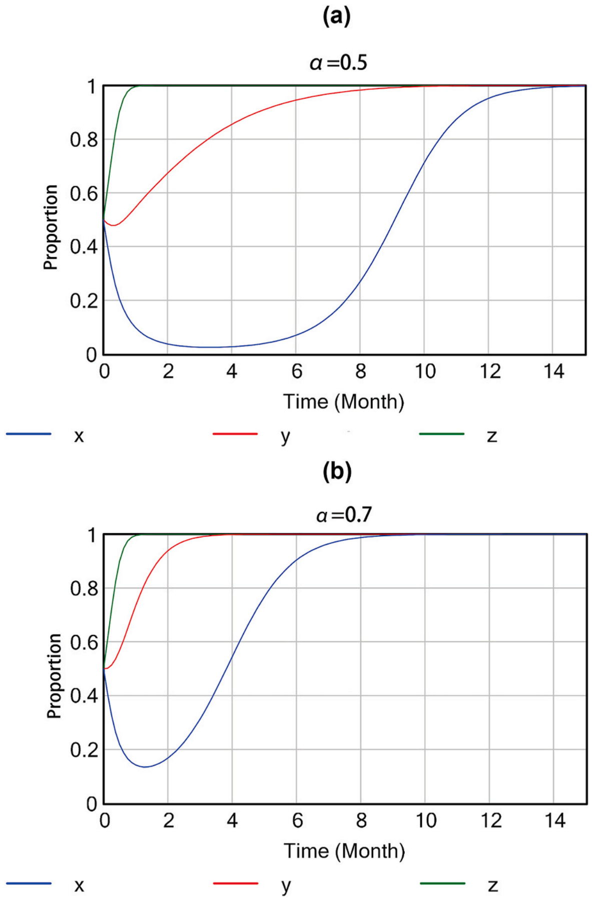

Fig. 3. Impact of α on the evolutionary process: (**a**) $\alpha = 0.5$; (**b**) $\alpha = 0.7$.

accelerated evolution toward involvement. In the case of enterprises, the evolutionary pathway of positive recall probability exhibits a U-shaped curve, characterized by an initial decline followed by an increase, ultimately culminating in active recycling. This suggests that government subsidy cuts directly diminish the benefits of public abstention from monitoring, thereby elevating the likelihood of people engagement in oversight activities.

The U-shaped curve representing the probability of positive recall for enterprises arises from the fact that public stakeholders are primarily impacted when government subsidies are curtailed. Consequently, as public entities become more involved in monitoring, companies are compelled to adopt proactive recycling strategies in response to the combined regulatory pressures exerted by both the government and the public. In conclusion, the reduction of government subsidies serves as an effective catalyst for fostering public participation in monitoring and encouraging active recycling initiatives among businesses.

4.3. The impact of recycling technology level and environmental awareness on evolutionary results

The technological level can improve the efficiency and cost of waste recycling, making the recycling process more efficient and economically feasible [44]. The improvement of public environmental awareness means that people attach more importance to environmental issues, and more people will take proactive environmental measures [45]. Overall, the level of waste recycling technology and public environmental awareness complement each other. Improving the technological level provides more possibilities and opportunities for the recycling industry. In contrast, enhancing public environmental awareness provides a solid foundation for the industry's sustainable development. As recycling technology advances concurrently with the growth of environmental consciousness, the evolutionary trajectory of the three involved parties will be influenced, as demonstrated in Fig. 4(a) and (b). This progression will lead the game to evolve from its initial state of (0,0,1) to a final evolutionary state characterized by (1,1,1), which corresponds to active recycling, public scrutiny, and strict regulatory.

Fig. 4 demonstrates that in conditions of low technological capability, corporations are inclined to adopt a negative recycling approach. However, when technology surpasses a critical threshold, a transition from negative to positive recycling strategies is observed. Simultaneously, public behavior manifests a shift from non-participation to active involvement in monitoring as environmental awareness exceeds a certain level.

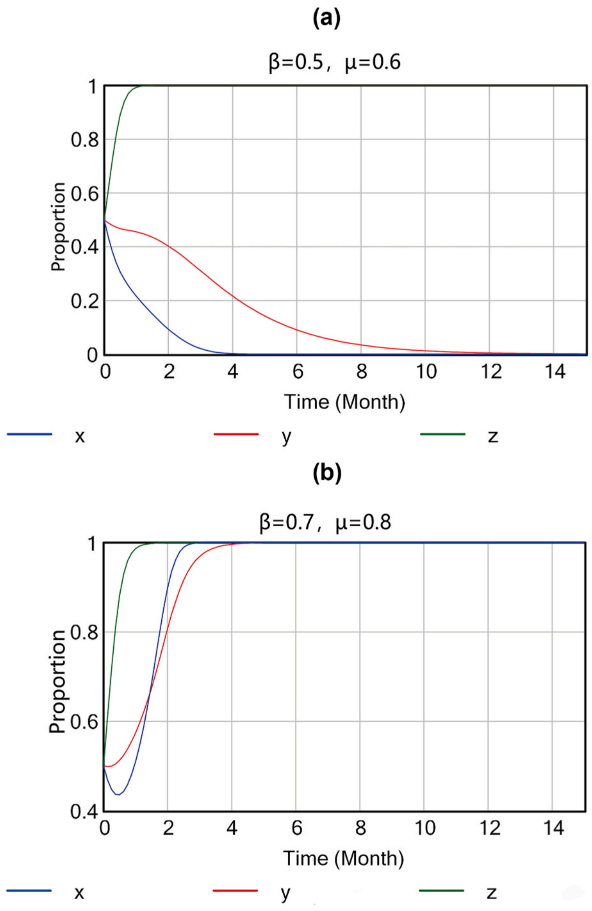

Fig. 4. Impact of β and μ on the evolutionary process: (**a**) $\beta = 0.5$, $\mu = 0.6$; (**b**) $\beta = 0.7$, $\mu = 0.8$.

The government consistently enforces stringent monitoring measures, signifying that under rigorous regulatory oversight, businesses strive to augment their economic benefits derived from waste recycling by fostering technological innovation and enhancing waste reprocessing techniques. This, in turn, elevates the likelihood of companies embracing proactive recycling practices.

Concurrently, as public environmental consciousness progressively intensifies, the propensity for public engagement in monitoring escalates, further amplifying corporate inclination towards active recycling. Ultimately, through increased public supervision and advancements in recycling technology employed by enterprises, the profitability of recycling experiences a gradual upsurge, culminating in the establishment of a virtuous cycle within the mining waste recycling sector.

4.4. The impact of governmental punishment on evolutionary results

The government's punitive measures can reduce the incidence of violations, reduce environmental pollution and resource waste during the waste recycling process [46]. By strengthening supervision and implementing strict penalties, enterprises will attach greater importance to environmental protection and take necessary measures to avoid or reduce negative environmental impacts [47]. The impact of an increasing negative recycling penalty, as given by the government to an enterprise, on the evolutionary path of three game subjects (represented by the initial state (0,0,1)) is demonstrated in Fig. 5(a) and (b). Specifically, using values of 2, 4, and 8 for the penalty, the system evolves towards the state (1,1,1) when the penalty reaches 8. These findings offer insights into the dynamics of the system and the effects of government policy on the behavior of game subjects in the context of mine waste recycling.

As government penalties for negative recycling practices remain low, companies tend to opt for negative recycling strategies. However, once penalties exceed a certain threshold and increase, firms tend to shift towards active recycling strategies. Interestingly, consumers also tend to shift their strategy from non-participation to participation. While the government maintains strict regulatory strategies as penalties increase, the rate of convergence slows down. However, this suggests that stronger penalties imposed by the government can effectively restrain negative recycling behavior by companies. As companies engage more actively in recycling initiatives, the public's motivation to participate in monitoring will increase, as the environmental benefits of waste recycling become more apparent.

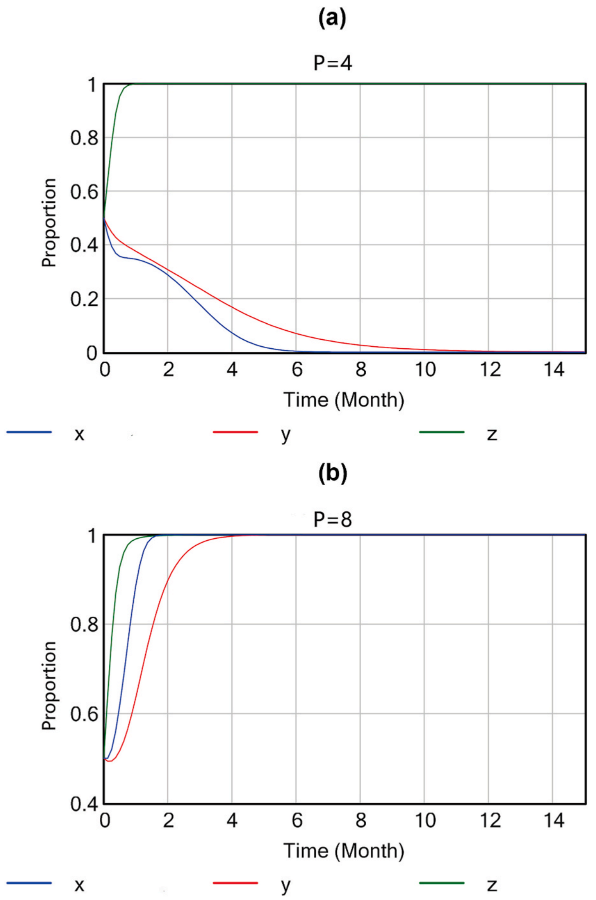

Fig. 5. Impact of P on the evolutionary process: (**a**) $P = 4$; (**b**) $P = 8$.

4.5. The impact of government subsidies to enterprises on evolutionary results

Subsidy policies play a crucial role in developing renewable energy, and government subsidy strategies based on carbon emission reduction levels can effectively drive low-carbon enterprises to reduce carbon emissions further [48]. In this section, we examined the impact of government subsidies on the development of the mining waste recycling industry under low and high levels of technology and environmental awareness. In the early stages of the development of the mining waste recycling industry, both technological level and environmental awareness are low. And after reaching maturity, the technological level and environmental awareness will be high. Specifically, when technology and environmental awareness are low ($\beta = 0.3$, $\mu = 0.2$), the impact of government subsidies on enterprise evolution is limited. However, under high levels of technology and environmental awareness ($\beta = 0.7$, $\mu = 0.8$), the subsidies have a more pronounced effect on the evolutionary path of the game subjects. Government subsidies can play a crucial role in shaping the evolutionary trajectories of enterprises, particularly in settings where technology and environmental awareness are high. As such, policymakers may wish to consider providing greater levels of support to businesses operating in these contexts.

When $\beta = 0.3$ and $\mu = 0.2$, the evolutionary trajectory of increasing the subsidy T for the three players in the game is depicted in Fig. 6(a) and (b). Despite the gradual increase in subsidies, the ultimate evolutionary outcome for all three parties remains unchanged at (0,0,1), denoting negative recycling, non-scrutiny, and strict regulation. The graphical representations clearly indicate that raising subsidies has minimal impact on the strategic choices made by firms and the general public. These findings suggest that when the company's recycling technology is poor and the public's environmental consciousness is lacking, governmental incentive subsidies do not incentivize companies, given the unprofitability of recycling practices.

When the parameters $\beta = 0.7$ and $\mu = 0.8$ are set, Fig. 7(a) and (b) demonstrate the impact of an increase in incentive subsidies on the evolutionary path of the three parties in the game. Specifically, when the intensity of the incentive subsidy T is increased to 4, the game's three parties will evolve from a state of (1,1,1) to a state of (1,1,0), resulting in the final evolutionary strategy of active recycling, scrutiny, and lenient regulation.

Fig. 7 depicts an inverted U-shaped curve for the probability of strict government regulation. The graph shows that the probability of strict government regulation tends to approach 1 when the subsidy level is at 3. However, when the subsidy level is at 5, the probability of strict government regulation initially strengthens, then weakens, and eventually converges to 0. These results suggest

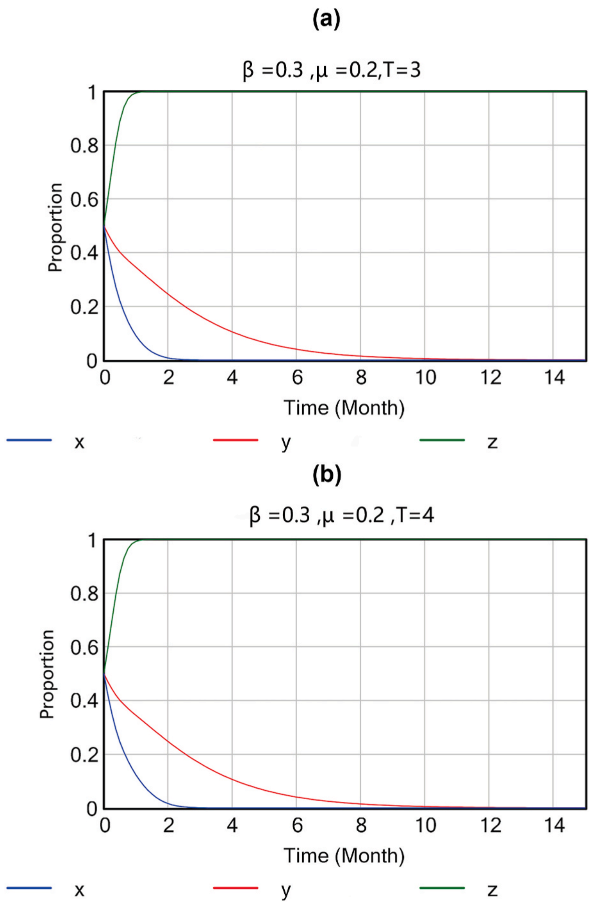

Fig. 6. Impact of T on the evolutionary process when $\beta = 0.3$ and $\mu = 0.2$: (**a**) $T = 3$; (**b**) $T = 4$.

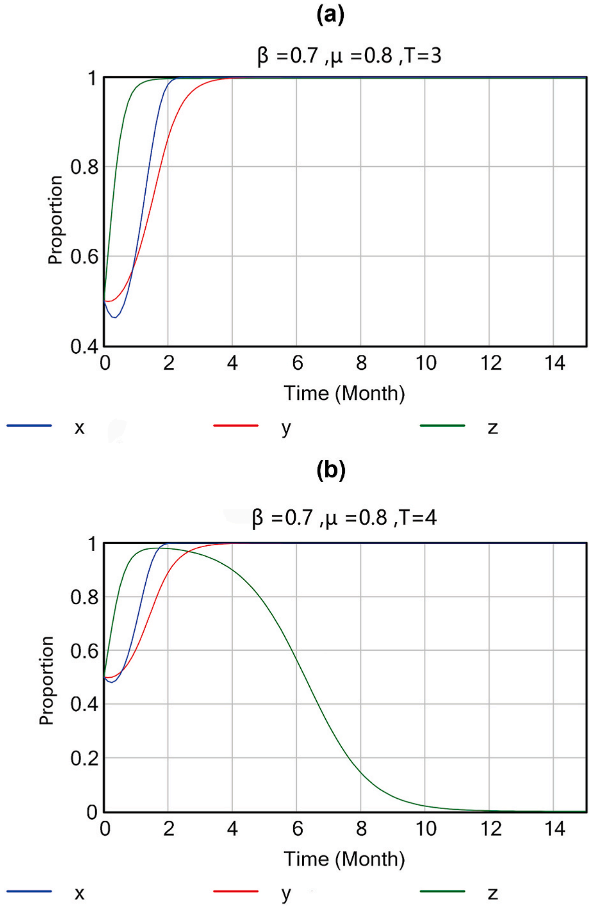

Fig. 7. Impact of T on the evolutionary process when $\beta = 0.7$ and $\mu = 0.8$: (**a**) $T = 3$; (**b**) $T = 4$.

that high levels of recycling technology enable enterprises to increase their profitability by recycling waste. In addition, the formation of good environmental awareness among the public and increased participation in monitoring further enhance the willingness of enterprises to engage in recycling initiatives. At this point, the incentive subsidies provided by the government act as a positive incentive for companies to undertake recycling activities. As a benign mining waste recycling industry emerges, enterprises will actively engage in recycling waste, and the public will actively participate in monitoring. Consequently, the probability of strict government regulation gradually decreases, thereby achieving the evolutionary path from exogenous government regulation to an endogenous drive for enterprise profitability under public monitoring.

5. Discussion

Mining of ores in China has resulted in severe environmental pollution due to inadequate mining technology and insufficient laws and regulations [49]. China's policies and development strategies are being adjusted to address this issue, which places significant pressure on the ore industry to restructure and prioritize environmental protection [50]. However, China's "top-down" approach to environmental regulation tends to overlook the important role of the public in regulating mining activities in affected areas. In light of this, we present an analysis that includes the public and develops a three-pronged game model involving local government, businesses, and the public in order to create a more efficient environmental regulatory framework for mining regions.

5.1. The challenge of implementing environmental regulations in areas with mining activities

In local governments, China's hierarchical environmental regulatory framework positions them as pivotal agents for local environmental management. The fiscal decentralization mechanism grants local governments the flexibility to allocate resources for environmental management based on prevailing circumstances, as well as some discretion in determining subsidies and penalties. Research examining the correlation between fiscal decentralization and environmental governance, conducted by Hao et al. [51] and Guo et al. [52], reveals that fiscal decentralization detrimentally impacts the efficacy of local environmental governance.

Moreover, Liu et al. [53] discovered that institutional challenges and economic development constraints at mining sites hinder local governments from effectively regulating the mining environment over an extended period. The present study demonstrates that augmenting government subsidies for companies proves efficacious only if recycling technology and public environmental awareness are sufficiently elevated ($\beta = 0.7$ and $\mu = 0.8$) (T = 2,3,4). Conversely, at diminished levels of recycling technology and public awareness ($\beta = 0.3$ and $\mu = 0.2$), penalties for negative recyclers must increase substantially ($P = 8$) to alter strategic decisions from negative to positive recycling. Importantly, indiscriminately escalating penalties is not an optimal solution.

Therefore, the most effective strategy to address environmental issues stemming from mining waste entails enhancing recycling technology and elevating public environmental awareness.

5.2. Improving the current state of environmental regulation through public participation

Public engagement plays a crucial role in environmental regulation, either indirectly through online discourse or directly via letters and reports [54]. Factors such as heightened public awareness of environmental protection and governmental subsidies following environmental damage strongly influence public involvement. Increased understanding of the environmental benefits derived from recycling mining waste (environmental awareness μ) fosters spontaneous public participation in monitoring activities. Conversely, diminished government compensation stimulates public involvement to minimize personal loss of benefits. In both cases, the advantages of public participation outweigh those of non-participation, leading to a strategic inclination toward involvement.

When recycling technology and public awareness reach sufficient levels ($\beta = 0.7$ and $\mu = 0.8$), public participation in monitoring alleviates the burden on government regulation, prompting a shift from strict to lenient policies. Public engagement in monitoring can generate similar effects to governmental environmental enforcement, ultimately achieving the goal of effective environmental governance [55]. Consequently, the three parties in the game evolve from a (1,1,1) state to a (1,1,0) state, characterized by active recycling, participation, and lax regulation. In this scenario, enterprises proactively engage in waste recycling, while the public actively participates in monitoring, fostering the positive growth of the mining waste recycling industry.

In conclusion, the government and the public are interdependent parties in mining environmental regulation, and the successful development of the mining waste recycling industry necessitates their collaboration. Public participation in monitoring can efficiently alleviate the pressure on government regulation while maximizing environmental benefits. As the industry matures and recycling technology advances, companies will independently and profitably recycle waste. At this stage, public oversight alone will suffice in accomplishing the objectives of environmental management.

6. Conclusions

The development of the mining waste recycling industry is a multifaceted process involving various stakeholders. We propose a tripartite dynamic evolutionary game model incorporating local governments, mining enterprises, and the public. By combining the system dynamics method, we simulate the evolutionary process and analyze the impact of key system parameters on the development of mining waste recycling. Our conclusions are as follows:

(1) Reducing government subsidies to the public effectively encourages public participation in monitoring and stimulates active recycling by enterprises.
(2) By increasing public awareness of environmental protection and advancing recycling technologies, enterprises can enhance profitability and foster a sustainable mining waste recycling industry.
(3) Governmental supervision and enforcement measures can effectively curb negative recycling behaviors. As enterprises actively engage in recycling initiatives, the environmental benefits derived from waste recycling increase public enthusiasm for oversight.
(4) When a sustainable mining waste recycling industry is established, enterprises will proactively participate in waste recycling, and the public will actively engage in monitoring, thereby rendering strict government regulation unnecessary.

Based on these conclusions, we propose the following recommendations:

(1) Enhance the multi-stakeholder governance model for environmental regulation in mining areas, in line with the advocacy of Xi Jinping, General Secretary of the Central Committee of the Communist Party of China, for a government-led environmental governance system involving enterprises, social organizations and the public. Optimize strategic choices by promoting a multi-principal system and coordinating stakeholder interests. Simultaneously, encourage the development of the mining waste recycling industry by providing policy support such as tax concessions and financial subsidies to reduce enterprise operating costs.
(2) Bolster research, development, and innovation in technology. The technical level of the mining waste recycling industry directly influences resource recovery rates and environmental management efficacy. Incentivize enterprises to increase R&D investment, adopt advanced processing technologies and equipment, and enhance mining waste recycling rates. Concurrently, establish an innovation platform integrating industry, academia, and research to facilitate the development and dissemination of novel technologies, methodologies, and materials.
(3) Develop a comprehensive mining waste recycling industry chain. Foster collaboration and knowledge exchange among enterprises to create an integrated industrial chain for mining waste recycling. By synergistically developing each link - from raw material collection, sorting, treatment, and reprocessing to the production and sale of end products - the industry's overall

effectiveness can be improved. Furthermore, establishing a robust platform for recycling, trading, and mining waste information exchange can reduce transaction costs and increase resource utilization efficiency.

(4) Encourage public participation and social supervision. Through public education campaigns, raise awareness of mining environmental improvements and waste recycling industry development, and guide public involvement in mining area environmental management. Simultaneously, establish a transparent and open information disclosure mechanism to welcome supervision and evaluation from all sectors of society, ensuring the healthy and sustainable development of the mining waste recycling industry.

Data availability statement

Data included in article/supplementary material/referenced in article.

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CRediT authorship contribution statement

Chunxi Zhou: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Yu Xin:** Writing – original draft, Visualization, Software, Investigation, Formal analysis, Conceptualization. **Yang Han:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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