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Achieving a win-win situation by promoting internet recycling of waste electronics and preventing information leakage in a multi-party game

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ABSTRACT

With scientific and technological advancements and the diversification of residents' demands, the pace of electronic product replacement is accelerating, generating a rapidly increasing number of waste electronics. The rapid development of information technologies, such as the Internet, has brought significant opportunities for recycling waste electronics. However, this is hindered by information safety concerns from residents. To achieve a win-win situation of promoting Internet recycling of waste electronics and preventing information leakage, this study performed a game analysis using key stakeholders in the Internet recycling of waste electronics. The game analysis of recycling waste electronics revealed that the lower the personal information leakage, the more residents would participate in recycling. Strict government regulation would increase the credibility of Internet recycling companies in protecting information security. Further, if the government imposed high fines on companies that breach information security, Internet recycling companies would endeavor to protect information security. In conclusion, this study offers policy recommendations and a theoretical basis to achieve a win-win situation of promoting Internet recycling of waste electronics and preventing information leakage from the perspective of stakeholders.

1. Introduction

The continuous technological advances and increasingly diverse resident demands have accelerated the replacement rate of electrical and electronic products. Waste electrical and electronic equipment (WEEE) is now one of the fastest-growing waste streams in the world, with an annual growth rate of 4–5% [1]. As the world's second-largest economy, China has also become the second-largest WEEE producer globally [2].

WEEE is an "environmental bomb" but also an "urban mine", containing harmful substances and pollutants that are hazardous to public health and the environment as well as various metal and non-metal compounds that are high-value, limited resources [3]. The collection and recycling of WEEE have significant advantages, such as saving resources, reducing energy consumption, and reducing pollution, and the notion of a circular economy is highly valued and supported by the Chinese government [4]. To conserve resources and establish a sustainable economic system, the *Catalogue for the Recycling and Treatment of Waste Electrical and Electronic Equipment* (2014 Edition) was published in 2015. The energy used to recover metals from WEEE is a fraction of the energy used in metal mining

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and refining [5]. Recycling WEEE reduces natural resource extraction expenses and energy consumption, thereby reducing greenhouse gas emissions [6]. Therefore, the recycling of WEEE will contribute to the achievement of the United Nations Sustainable Development Goal 13 (Climate Action) and assist China in reaching its carbon neutrality target.

WEEE includes used appliances and waste electronics. Waste electronics mainly comprise obsolete computers, mobile phones, and other electronic communications products [7,8]. Waste mobile phones and computers contain higher-value components than used appliances [9]. Recycling waste electronics is difficult as residents are highly concerned about information security. In a survey of Hangzhou residents, 51.2% stated that they chose to retain waste electronics [10]. Personal information is being excessively incorporated into mobile phones as they become increasingly intelligent, causing many residents to keep unused ones at home. A questionnaire conducted in Hong Kong and Shenzhen also revealed that over 75% of the respondents preferred to store their used mobile phones at home rather than recycling them [11]. In general, 300–400 million mobile phones become redundant in China annually, but the recycling rate is still negligible [12,13]. Therefore, the waste electronics recycling industry needs strengthened policy guidance and supervision to open the "last mile" of information security.

The development of information technology has ushered in emerging technologies such as the Internet of Things and big data, driving the transformation of traditional industries towards a data-centric approach. The use of the Internet to "connect everything" should aid the current situation to achieve a stronger connection between residents and formal recycling channels [14]. In 2015, the Chinese government issued the *Guidance on Actively Promoting the "Internet Plus" action plan*. The plan suggests the use of electronic tags, two-dimensional codes, and other Internet of Things technologies to track WEEE flows. The plan also encourages companies to build Internet recycling platforms to promote the recycling of renewable resources. In 2021, China's State Council issued the *Guidance on Accelerating the Establishment of a Sound Economic System for Green, Low-Carbon, and Circular Development*, which proposes the efficient use of resources, strict protection of the ecological environment, effective control of greenhouse gas emissions, establishment of a sound economic system (for green, low-carbon, and circular development), and the promotion of a comprehensive, green transformation of economic and social development to reach the carbon peak and achieve carbon neutrality. As the scale of the recycling industry expands and the construction of recycling networks continues to improve, many companies in the WEEE recycling field have rapidly developed, improving the recycling system's efficiency and quality [15]. With the development of Internet information technology, third-party-established Internet recycling systems have experienced rapid growth and continuous innovation, providing support for innovative recycling models. Currently, several typical Internet recycling models have emerged, which can be categorized as follows: The first type is represented by Shanghai Xinqiao Environmental Protection Co., Ltd., featuring a data-driven recycling system. The second type is exemplified by Ai Bo Lv, demonstrating a collaborative recycling system involving multiple stakeholders. The third type is represented by Beijing Environmental Sanitation Group and Yingchuang Recycling, showcasing a recycling system integrated with garbage classification.

The Internet recycling model has opened a new door for the recycling of waste electronics. In the era of big data, the emergence of "Internet Plus" has brought new opportunities to the waste electronics recycling industry. The Internet recycling model has emerged as a crucial strategy to solve various problems associated with traditional recycling. It offers numerous advantages over conventional recycling methods, including improved resource recovery efficiency and cost reduction. However, there are still concerns among consumers regarding information security issues and low participation in electronic product recycling. Therefore, based on previous research [16], this study attempts to answer the following key questions through the construction of a game model incorporating the government, Internet recycling companies, and residents:

1. How will the behaviors of stakeholders in the Internet recycling network of waste electronics influence one another?
2. What kind of strategy will lead to efficient Internet recycling of waste electronics while preventing the leakage of information?
3. How should recommendations be proposed to key stakeholders?

In this study, a multi-party evolutionary game model was developed based on key stakeholders, to investigate how a win-win situation that promotes Internet recycling of waste electronics and prevents information leakage, can be achieved. The evolutionary game model was introduced to the field of Internet recycling, and parametric simulations were conducted to propose relevant suggestions for each key stakeholder.

2. Literature review

Our goal was to evaluate the impact of resident behavior and government policies on the Internet-based recycling of electronic waste through an evolutionary game model with the aim to promote efficient recycling of electronic waste while preventing information leakage. Therefore, in this section, we provide a review of three aspects: the factors affecting residents' willingness to participate in recycling and their behavior, the application of evolutionary game models in the study of recycling stakeholders' behaviors, and the role of the government in WEEE recycling.

2.1. Factors influencing residents' willingness and behavior toward recycling

The starting point for WEEE recycling is the residents, who determine the flow of waste [17]. Therefore, residents' willingness and recycling behavior is a major concern of many academics [8,18–21]. Most studies investigating the influences of environmental attitudes, psychological factors, and other variables on recycling intentions and behavior were based on the Theory of Planned Behavior (TPB), which was used to assess residents' willingness to recycle WEEE [22–24]. Using TPB as a theoretical framework, Lu and Zhao

[25] investigated the factors influencing the recycling behavior of Shanghai residents, which revealed that the residual effects (past recycling habits), behavioral control awareness factors (awareness of recycling facilities and routes), and attitudes toward the economics of recycling significantly influence residents' recycling behavior. However, previous studies all focused on traditional recycling, and the rise of the "Internet Plus" model has led to significant changes in the recycling sector; thus, further research focusing on the importance of motivating residents to participate in Internet recycling is necessary.

The new waste recycling model of "Internet + recycling" provides a convenient recycling option for residents and greatly increases the recycling rate of municipal solid waste [26]. As a new recycling model, "Internet + recycling" has significant advantages for recycling WEEE as it establishes a direct connection between the source and formal recycling companies through reverse logistics, which is highly transparent and easy to regulate [14]. However, the current Internet recycling model suffers from a poor connection between online and offline, is difficult for elderly participants, and has limitations in terms of recycling types and services [27]. Together, these issues result in a low degree of resident participation. To address these issues, scholars have analyzed the factors influencing residents' willingness to recycle WEEE on the Internet. Wang et al. [28] constructed a structural equation model from the resident perspective, identifying that perceived usefulness, perceived benefits, and subjective norms have a positive influence on attitudes toward "Internet + recycling".

Most studies that investigated the factors influencing residents' willingness and behavior considered only one dimension; however, aside from the individual residents, the behavior of other stakeholders can also have an important impact on residents' participation in recycling. Therefore, here, we used previously conducted research [16] as a basis to construct an evolutionary game model assessing the interrelationship of key stakeholders in the Internet recycling of waste electronics, aiming to provide theoretical support for improving residents' participation in Internet waste electronics recycling.

2.2. *Use of evolutionary game models for investigating stakeholder behavior in WEEE recycling*

Stakeholders depend on systems to achieve their personal goals, and systems depend on them to survive. Evolutionary game models are tools for capturing the impact of stakeholder interactions on social issues [29]. The literature focusing on applying evolutionary game models to WEEE recycling is growing. On one hand, relevant studies have focused on macro systems, such as constructing evolutionary game models to understand the current situation of the WEEE recycling industry in China [10,29]. These studies found that the stabilization strategy at each stage is mainly dependent on the trade-off between the costs and benefits for stakeholders, suggesting that governments should focus on improving the reward and punishment mechanisms and establish appropriate standards with subsidies to promote the WEEE recycling industry [2]. Other research has focused on the participation strategy options for WEEE recycling under an extended producer-responsibility system. With reasonable value transfer and responsibility sharing, this system can reach a stable, ideal equilibrium to achieve a win-win situation for all parties [30]. Conversely, some scholars have constructed evolutionary game models to investigate the government's role, and the results revealed that diverse factors, such as the return on government regulations, the cost of supervision, and government subsidies for companies to actively build reverse logistics, can significantly impact both sides [3].

The application of evolutionary game models to WEEE recycling mostly focuses on traditional recycling models with an optimal state of development achieved through overall system regulation or government intervention. Literature on the application of evolutionary game models to Internet recycling models is limited. Therefore, in our study, we constructed an evolutionary game model based on the Internet recycling of WEEE to fill this literature gap.

2.3. *Government's role in WEEE recycling*

The government plays a pivotal role in WEEE recycling [31]. Government interventions can motivate stakeholders to participate and effectively promote WEEE recycling [4]. As the WEEE recycling system evolves, the government should adopt different strategies and roles. The development of the WEEE recycling industry should be divided into three stages, with the government implementing greater regulation and subsidies at the initial stage and then gradually deregulating the market [29]. Notably, governments worldwide may adopt different involvement levels in regulating WEEE recycling [32].

Recently, in China, significant results have been achieved by regulating WEEE recycling, with the government guiding companies to participate through policies such as financial subsidies, qualification of recycling companies, and fund levies [33]. In the US state of Minnesota, authorities enacted the Minnesota Electronics Recycling Act in 2007 to manage the increasing amount of WEEE. The Act imposes strict collection and recycling targets on manufacturers, which has enabled manufacturers to achieve greater cost efficiency; it has also increased local government burdens [34]. In Europe, research revealed that an extended producer-responsibility system for regulating WEEE recycling did not have the desired effect and that there is a need for greater coordination between policies and a clearer definition of the responsibilities of each entity [35].

To date, the policy options for WEEE recycling in most countries are in the exploratory stages, and the specific implementation details need to be country specific. Here, we developed an evolutionary game model for China, providing recommendations for promoting Internet recycling of waste electronics and prevention of information leakage.

3. Evolutionary game model with three players

The evolutionary game model alters the strategic interactions over time based on one or more groups of players, strategic state spaces, and game stages in normal or extended forms [36]. The dynamic adjustment process explains the phenomena of mutual learning, competition, and adaptation during biological evolution. In this study, we constructed an evolutionary game model for the recycling of waste electronics to analyze the behaviors of key stakeholders, aiming to identify a win-win situation promoting efficient Internet recycling of waste electronics and information leakage prevention.

3.1. *Model description and assumptions*

The key stakeholders in waste electronics Internet recycling are Internet recycling companies, the government, and residents [16]. Fig. 1 shows the relationships between the three.

Based on the evolutionary game theory and the current situation of the Chinese waste electronics recycling industry, the model included the following assumptions:

Hypothesis 1. The strategy choices of the players are as follows: the probability of the government selecting “strict regulation” is x; the probability of the government selecting “no strict regulation” is 1 - x; the probability of Internet recycling companies selecting “protecting information security” is y; the probability of Internet recycling companies selecting “not protecting information security” is 1 - y; the probability of residents selecting “participating in recycling” is z; and the probability of residents selecting “not participating in recycling” is 1 - z, where $0 \leq x, y, z \leq 1$.

Hypothesis 2. The cost of strict government regulation is C_1 and the cost of no strict government regulation is αC_1, where $0 < \alpha < 1$; the credibility of the government is enhanced when the government strictly regulates Internet recycling companies and is recorded as I_1. If the government does not strictly regulate Internet recycling companies, the credibility of the government decreases when companies fail to protect residents’ information, which is recorded as D_1. Strict government regulation imposes a fine R_1 on Internet recycling companies that breach information security, and the government’s benefit of resource recycling with active resident participation is R_2.

Hypothesis 3. Residents receive R_4 when participating in recycling. The loss of resident information when Internet recycling companies do not protect information security is C_2. The increase in resident satisfaction when Internet recycling companies protect information security under strict government regulation is I_3. The decrease in resident satisfaction when Internet recycling companies do not protect information security when under strict government regulation is D_3.

The parameter symbols used in the model and in the above assumptions (along with their definitions) are provided in Appendix A

3.2. *Replicate dynamic equation analysis of the three stakeholders*

Using the assumptions discussed in Section 3.1 along with the parameter settings, the payment matrix for each factor under different decision combinations was calculated (Tables 1 and 2).

In the payoff matrix, each game subject continuously adjusts to maximize the expected payoff. Therefore, using the payoffs of each game subject under different strategy combinations, replicator dynamic equations for the strategies selected by the government, Internet recycling companies, and residents were constructed.

3.2.1. *Replicator dynamic equations for government strategy options*

The expected government benefits under the “strict regulation” strategy are:

$$E_{11} = yz(I_1 + R_2 - C_1) + y(1-z)(I_1 - C_1) + (1-y)z(I_1 + R_1 + R_2 - C_1) + (1-y)(1-z)(I_1 + R_1 - C_1) = I_1 + R_1 - C_1 - yR_1 + zR_2 \tag{1}$$

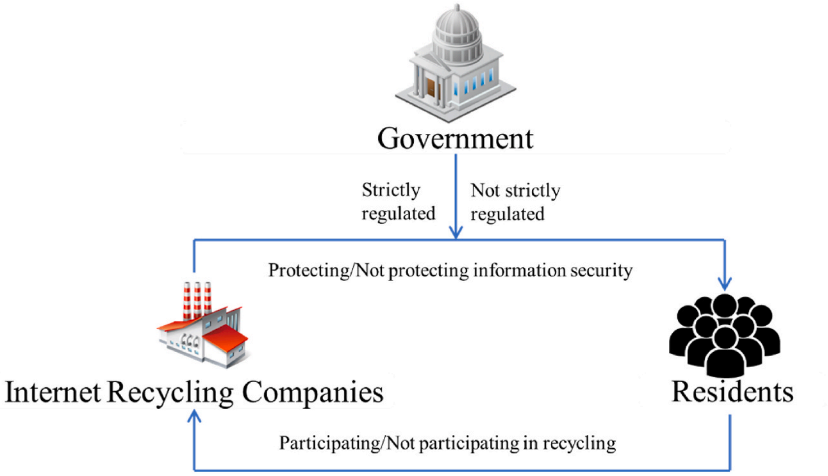


Fig. 1. Relationships between stakeholders in the recycling of waste electronics.

Table 1
Tripartite evolutionary game payoff matrix when the government chooses strict regulation (x).

Internet recycling companies	Residents	
	Participation in recycling (z)	No participation in recycling ($1-z$)
Protecting information security (y)	$I_1 + R_2 - C_1$; $I_2 + \beta R_3$; $R_4 + I_3$;	$I_1 - C_1$; I_2; I_3;
Not protecting information security ($1-y$)	$I_1 + R_1 + R_2 - C_1$; $R_3 - R_1 - D_2$; $R_4 - D_3 - C_2$;	$I_1 + R_1 - C_1$; $-R_1 - D_2$; $-D_3$;

Table 2
Tripartite evolutionary game payoff matrix when the government chooses no strict regulation ($1-x$).

Internet recycling companies	Residents	
	Participation in recycling (z)	No participation in recycling ($1-z$)
Protecting information security (y)	$R_2 - \alpha C_1$; βR_3; R_4;	$-\alpha C_1$; 0; 0;
Not protecting information security ($1-y$)	$R_2 - \alpha C_1 - D_1$; R_3; $R_4 - C_2$;	$-D_1 - \alpha C_1$; 0; 0;

The expected government benefits under the “no strict regulation” strategy are:

$$E_{12} = yz(R_2 - \alpha C_1) + y(1-z)(-\alpha C_1) + (1-y)z(R_2 - \alpha C_1 - D_1) + (1-y)(1-z)(-D_1 - \alpha C_1) = -D_1 - \alpha C_1 + yD_1 + zR_2 \tag{2}$$

where the probabilities of the government selecting “strict regulation” or “no strict regulation” are x and $1-x$, respectively. Therefore, the average government benefits can be calculated from Equations (1) and (2) as follows:

$$\overline{E}_1 = xE_{11} + (1-x)E_{12} \tag{3}$$

The replicator dynamic Equation (4) for the government strategy options can be calculated using Equations (1) and (3) as follows:

$$\begin{cases} f(x) = \dfrac{dx}{dt} = x(E_{11} - \overline{E}_1) = x(1-x)A(y,z) \\ A(y,z) = I_1 + R_1 + D_1 - (1-\alpha)C_1 - y(R_1 + D_1) \end{cases} \tag{4}$$

3.2.2. Replicator dynamic equations for internet recycling strategy options

The expected benefits for Internet recycling companies when selecting the “information security” strategy are as follows:

$$E_{21} = xz(I_2 + \beta R_3) + x(1-z)(I_2) + (1-x)z(\beta R_3) + (1-x)(1-z)(0) = xI_2 + zR_3 \tag{5}$$

The expected benefits of the " no information security” strategy can be represented as Equation (6):

$$E_{22} = xz(R_3 - R_1 - D_2) + x(1-z)(-R_1 - D_2) + (1-x)z(R_3) + (1-x)(1-z)(0) = x(-R_1 - D_2) + zR_3 \tag{6}$$

where the probabilities of an Internet recycling company selecting “protect information security” and “not protect information security” are y and $1-y$, respectively. Therefore, the average revenue of an Internet recycling company can be expressed as follows:

$$\overline{E}_2 = yE_{21} + (1-y)E_{22} \tag{7}$$

Using Equations (5) and (7), the replicator dynamic equation for the strategy options of Internet recycling companies can be calculated as Equation (8):

$$\begin{cases} f(y) = \dfrac{dy}{dt} = y(E_{21} - \overline{E}_2) = y(1-y)B(x,z) \\ B(x,z) = x(I_2 + R_1 + D_2) + z(\beta - 1)R_3 \end{cases} \tag{8}$$

3.2.3. Replicator dynamic equation for resident strategy options

The expected benefits when residents select “participation in recycling” are:

$$E_{31} = xy(R_4 + I_3) + x(1-y)(R_4 - D_3 - C_2) + (1-x)y(R_4) + (1-x)(1-y)(R_4 - C_2) = R_4 - C_2 + xy(I_3 + D_3) - xD_3 + yC_2 \tag{9}$$

The expected benefits when residents select “no participation in recycling” are presented in Equation (10).

$$E_{32} = xy(I_3) + x(1-y)(-D_3) + (1-x)y(0) + (1-x)(1-y)(0) = xy(I_3+D_3) - xD_3 \tag{10}$$

where the probabilities of residents selecting “participate in recycling” and “not participate in recycling” are z and $1\text{-}z$, respectively. Therefore, the average benefits to residents can be expressed as follows:

$$\overline{E}_3 = zE_{31} + (1-z)E_{32} \tag{11}$$

According to Equations (9) and (11), the replicator dynamic equation of the resident strategy can be calculated as Equation (12):

$$\begin{cases} f(z) = \dfrac{dz}{dt} = z(E_{31} - \overline{E}_3) = z(1-z)C(x,y) \\ \qquad C(x,y) = R_4 - C_2 + yC_2 \end{cases} \tag{12}$$

3.3. Solving evolutionary stability strategies

3.3.1. Stability analysis of government strategies

According to Equation (4), the main factors affecting the government’s propensity to regulate include two aspects: the probability of strategy options being chosen by the other game subjects, namely the probability y of Internet recycling companies selecting to “protect information security,” and other factors that determine the government benefits when selecting a strategy. The stability of the government’s strategic options was analyzed as follows:

The government’s strategic direction achieves stability when the government selects the “strict regulation” strategy and satisfies $f(x) = 0$ and $\frac{df(x)}{dx} < 0$, which is calculated as follows:

$$\frac{df(x)}{dx} = (1-2x)A(y,z) \tag{13}$$

Using Equations (4) and (13), the stability of the government’s strategic options, which consist of three scenarios, can be calculated as follows:

① If $A(y,z) = 0$, set $f(x) = 0$ to obtain the following result, followed by:

$$y = y_1 = \frac{I_1 + R_1 + D_1 - (1-\alpha)C_1}{R_1 + D_1} \tag{14}$$

When Equation (14) is met, then $f(x) \equiv 0$ is correct, and any $x \in [0,1]$ is a stable point, suggesting the probability of the strategy selected by Internet recycling companies meeting the above conditions and the government involvement reaching a stable state, regardless of the selected strategy; the calculation is as follows:

② If $A(y,z) < 0$, then $0 < y_1 < y < 1$, $f(x)|_{x=0} = 0$, and $\left.\frac{df(x)}{dx}\right|_{x=0} < 0$; therefore, $x = 0$ is the evolutionary stability of the selected government strategy in this case, which suggests that the government supports the “no strict regulation” strategy and is calculated as follows:

③ If $A(y,z) > 0$, then $0 < y < y_1 < 1$, $f(x)|_{x=1} = 0$, and $\left.\frac{df(x)}{dx}\right|_{x=1} < 0\_(x = 1) < 0$; therefore, $x = 1$ is the evolutionary stability point of the selected government strategy in this case, suggesting that the government supports the “strict regulation” strategy.

3.3.2. Stability analysis of internet recycling company strategies

From Equation (8), it is evident that the main factors affecting the behavior of Internet recycling companies involve two aspects: the probability of strategy options selected by other game subjects and other factors that determine Internet recycling company benefits when selecting their strategic direction.

When the probability y of an Internet recycling company selecting the “protect information security” strategy satisfies $f(y) = 0$ and $\frac{df(y)}{dy} < 0$, the selected strategy of the Internet recycling company reaches a stable point of:

$$\frac{df(y)}{dy} = (1-2y)B(x,z) \tag{15}$$

Further, using Equations (8) and (15), the stability of the strategy was selected by Internet recycling companies. which has three scenarios, can be calculated as follows:

① If $B(x,z) = 0$, let $f(y) = 0$, and the following result is:

$$\begin{cases} x = x_1 = -\dfrac{z(\beta-1)R_3}{I_2 + R_1 + D_2} \text{或} \\ z = z_1 = -\dfrac{x(I_2 + R_1 + D_2)}{(\beta-1)R_3} \end{cases} \tag{16}$$

When Equation (16) is met, then $f(y) \equiv 0$, and any $y \in [0,1]$ is a stable point and represents:

② If $B(x,z) < 0$, then $0 < x_1 < x < 1$, $0 < z_1 < z < 1$ $f(y)|_{y=0} = 0$, and $\left.\frac{df(y)}{dy}\right|_{y=0} < 0$; therefore, $y = 0$ is the evolutionarily stable point of the strategy option for Internet recycling companies, which means that Internet recycling companies will select “no information security protection."

③ If $B(x,z) > 0$, then $0 < x < x_1 < 1$, $0 < z < z_1 < 1$, $f(y)|_{y=1} = 0$, and $\frac{df(y)}{dy}\Big|_{y=1} < 0$; therefore, $y = 1$ is the evolutionarily stable point of the strategy selected by Internet recycling companies, suggesting that Internet recycling companies will select “protecting information security."

3.3.3. Stability analysis of resident strategies

Equation (12) reveals that the main factors influencing resident behavior are the strategy selected by other game factors and other factors that determine resident benefits when selecting an option.

When the probability z of a resident selecting “participate in recycling” satisfies $f(z) = 0$ and $\frac{df(z)}{dz} < 0$, the resident strategy selection reaches a stable point.

$$\frac{df(z)}{dz} = (1-2z)C(x,y) \tag{17}$$

From Equations (1) and (17), it is evident that the stability of resident strategy choices includes three scenarios:

① If $C(x,y) = 0$, let $f(z) = 0$, resulting in:

$$y = y_2 = \frac{R_4 - C_2}{C_2} \tag{18}$$

When Equation (18) is met, then $f(z) \equiv 0$, at which point any $z \in [0,1]$ is a stable point.

② If $C(x,y) < 0$, then $0 < y_2 < y < 1$, $f(z)|_{z=0} = 0$, and $\frac{df(z)}{dz}\Big|_{z=0} < 0$. Therefore, $z = 0$ is the stable point of the selected resident strategy if residents select “no participation in recycling."

③ If $C(x,y) > 0$, then $0 \ll y < y_2$, $f(z)|_{z=1} = 0$, and $\frac{df(z)}{dz}\Big|_{z=1} < 0$.

Therefore, $z = 1$ is the stable point of the selected resident strategy “participate in recycling."

3.4. Stability analysis of strategy combinations using tripartite game factors

Replicating the dynamic equations of each factor (using Equations (4), (8) and (12)) shows that the set of replicator dynamic equations for the tripartite game system is:

$$\begin{cases} f(x) = x(1-x)[I_1 + R_1 + D_1 - (1-\alpha)C_1 - y(R_1 + D_1)] \\ f(y) = y(1-y)[x(I_2 + R_1 + D_2) + z(\beta - 1)R_3] \\ f(z) = z(1-z)(R_4 - C_2 + yC_2) \end{cases} \tag{19}$$

If $f(x) = f(y) = f(z) = 0$ in Equation (19), then we can obtain eight pure strategy solutions in the tripartite evolutionary game system and the strategy choice probability of each game factor is 0 or 1. Therefore, the pure strategy combinations of the government, Internet recycling companies, and residents are $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, and $E_8(1,1,1)$.

To investigate the stability of the combinations of government, Internet recycling companies, and resident strategies, the following Jacobi matrix replicating the dynamic system was constructed:

$$J = \begin{pmatrix} \frac{\partial f(x)}{\partial x} & \frac{\partial f(x)}{\partial y} & \frac{\partial f(x)}{\partial z} \\ \frac{\partial f(y)}{\partial x} & \frac{\partial f(y)}{\partial y} & \frac{\partial f(y)}{\partial z} \\ \frac{\partial f(z)}{\partial x} & \frac{\partial f(z)}{\partial y} & \frac{\partial f(z)}{\partial z} \end{pmatrix} \tag{20}$$

Of these:

$$\begin{cases} \dfrac{\partial f(x)}{\partial x} = (1-2x)[I_1 + R_1 + D_1 - (1-\alpha)C_1 - y(R_1 + D_1)] \\ \dfrac{\partial f(x)}{\partial y} = -x(1-x)(R_1 + D_1) \\ \dfrac{\partial f(x)}{\partial z} = 0 \\ \dfrac{\partial f(y)}{\partial x} = y(1-y)(I_2 + R_1 + D_2) \\ \dfrac{\partial f(y)}{\partial y} = (1-2y)[x(I_2 + R_1 + D_2) + z(\beta - 1)R_3] \\ \dfrac{\partial f(y)}{\partial z} = y(1-y)(\beta - 1)R_3 \\ \dfrac{\partial f(z)}{\partial x} = 0 \\ \dfrac{\partial f(z)}{\partial y} = z(1-z)C_2 \\ \dfrac{\partial f(z)}{\partial z} = (1-2z)(R_4 - C_2 + yC_2) \end{cases} \tag{21}$$

Using Equations (20) and (21) with the equilibrium point $E_1(0,0,0)$, the Jacobi matrix is:

$$J = \begin{pmatrix} I_1 + R_1 + D_1 - (1-\alpha)C_1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & R_4 - C_2 \end{pmatrix} \tag{22}$$

Using Equation (22), the eigenvalues of the Jacobi matrix corresponding to the equilibrium point $E_1(0,0,0)$ are: $\lambda_1 = I_1 + R_1 + D_1 - (1-\alpha)C_1$, $\lambda_2 = 0$, and $\lambda_3 = R_4 - C_2$. Similarly, the associated characteristic values of all pure strategy combinations of the government, Internet recycling companies, and residents can be calculated, and the positive and negative characteristics can be combined to determine the stability of each equilibrium point; Table 3 provides the results.

As demonstrated by the stability analysis in Table 3, of the eight pure strategy combinations in the tripartite game system, five strategy combinations $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_5(1,1,0)$, and $E_7(0,1,1)$ are unstable. In turn, three strategy combinations of $E_4(0,0,1)$, $E_6(1,0,1)$, and $E_8(1,1,1)$ may become stable solutions when certain conditions are satisfied.

Scenario 1: The replicated dynamic system converges at $E_4(0,0,1)$ when the condition $I_1 + R_1 + D_1 - (1-\alpha)C_1 < 0$ is satisfied. In this case, the government selects no strict regulation because the cost of strict regulation is excessive and greater than other incomes, while Internet recycling companies select to not protect information security as it is not regulated, and residents select to participate in recycling because of the higher benefits. This game strategy may be stable at {no strict regulation, no information security protection, participation in recycling}, but this strategy combination is not an ideal outcome.

Scenario 2: The replicated dynamic system converges at $E_6(1,0,1)$ when the conditions $I_1 + R_1 + D_1 - (1-\alpha)C_1 > 0$, $I_2 + R_1 + D_2 + (\beta - 1)R_3 < 0$, and $R_4 - C_2 > 0$ are satisfied. This scenario reveals that the fines for companies that do not protect information security under strict government regulation increase WEEE recycling credibility due to strict government regulations. The benefits of strict regulations are much greater than the benefits of no strict regulations. Internet recycling companies seek higher benefits by not protecting information security, preferring to invest in fines and the residents' benefits from participating in recycling outweighing information security losses. The game strategy eventually stabilizes at {strict regulation, no information security, participation in recycling}. However, the strategy combination in this scenario is also not the most desirable outcome, as residents' participation without any information security assurance is highly unlikely.

Scenario 3: The replicated dynamic system converges to $E_8(1,1,1)$ when the conditions $I_1 - (1-\alpha)C_1 > 0$ and $I_2 + R_1 + D_2 +$

Table 3
Stability analysis of the equilibrium point in a tripartite game system.

Point of equilibrium	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3	Symbolic judgment	Stability
$E_1(0,0,0)$	$I_1 + R_1 + D_1 - (1-\alpha)C_1$;	0;	$R_4 - C_2$;	$(U,0,U)$	Unstable
$E_2(1,0,0)$	$-[I_1 + R_1 + D_1 - (1-\alpha)C_1]$;	$I_2 + R_1 + D_2$;	$R_4 - C_2$;	$(U,+,U)$	Unstable
$E_3(0,1,0)$	$I_1 - (1-\alpha)C_1$;	0;	R_4;	$(U,0,+)$	Unstable
$E_4(0,0,1)$	$I_1 + R_1 + D_1 - (1-\alpha)C_1$;	$(\beta - 1)R_3$;	$-R_4$;	$(U,-,-)$	Condition 1
$E_5(1,1,0)$	$-[I_1 - (1-\alpha)C_1]$;	$-(I_2 + R_1 + D_2)$;	R_4;	$(U,-,+)$	Unstable
$E_6(1,0,1)$	$-[I_1 + R_1 + D_1 - (1-\alpha)C_1]$;	$I_2 + R_1 + D_2 + (\beta - 1)R_3$;	$-(R_4 - C_2)$;	(U,U,U)	Condition 2
$E_7(0,1,1)$	$I_1 - (1-\alpha)C_1$;	$-(\beta - 1)R_3$;	$-R_4$;	$(U,+,-)$	Unstable
$E_8(1,1,1)$	$-[I_1 - (1-\alpha)C_1]$;	$-[I_2 + R_1 + D_2 + (\beta - 1)R_3]$;	$-R_4$;	$(U,U,-)$	Condition 3

Note: U indicates that the positive or negative value of this characteristic cannot be assessed; Conditions 1, 2, and 3 indicate that the equilibrium point is stable when the condition is satisfied.

$(\beta - 1)R_3 > 0$ are satisfied. In this scenario, the government's credibility improves due to strict regulation outweighing the extra cost of regulations; thus, the government imposes strict regulations. Internet recycling companies protect information security to avoid fines for not protecting information security and the high losses caused by the loss of reputation if fined. The residents willingly participate in recycling because of the high gains and assured information security. The game strategy stabilizes at {strict regulation, protection of information security, participation in recycling}. This is the most desirable outcome and conducive to the sustainable development of the Internet recycling industry for waste electronics.

4. Numerical simulation

The stability of the tripartite game strategy (1,1,1) is the most ideal combination. The strategies adopted by the government, Internet recycling companies, and residents are strict regulation, protection of information security, and participation in recycling, respectively. Initially, each game parameter assigned for achieving stability was as follows: $I_1 = 15$, $C_1 = 20$, $D_1 = 10$, $R_1 = 10$, $I_2 = 10$, $D_2 = 15$, $R_3 = 80$, $R_4 = 30$, $C_2 = 10$, $\alpha = 0.5$, and $\beta = 0.7$. The evolutionary game processes of the government, Internet recycling companies, and residents for this strategy are provided in Fig. 2, Simulation and modeling were conducted in three-dimensional space using Fig. 2(a), while Fig. 2(b) demonstrates how, over time, the system eventually stabilizes at the strategy combination (1,1,1).

To verify the reliability of the model and the accuracy of the analysis, the impact of each changed parameter using the selected strategy was analyzed separately.

4.1. Government credibility enhancement I_1, government regulatory costs C_1, and the effect of α on strategy choice

Keeping other parameters unchanged, the temporal evolution processes of the strategies selected by the government, Internet recycling companies, and residents using I_1 values of 5, 10, 15, and 20 were obtained, as demonstrated in Fig. 3(a). Additionally, while the other parameters remained unchanged, C_1 was assigned values of 10, 20, 30, and 40, and the temporal evolution processes of the strategies selected by the government, Internet recycling companies, and residents with different values of C_1 were obtained, as demonstrated in Fig. 3(b). Finally, keeping all other parameters constant, the temporal evolutionary processes of the government, Internet recycling companies, and resident strategy selections with different α values of 0.1, 0.3, 0.5, and 0.7 were calculated, as shown in Fig. 3(c).

As demonstrated in Fig. 3, an increase in credibility I_1 gained through strict government regulation influenced the cost of regulation C_1, and the cost of regulation coefficient α slightly impacted the residents' selected strategy when the government did not apply strict regulations without altering the trend in resident strategy decisions. Conversely, this scenario had a larger impact on the strategies selected by the government and Internet recycling companies.

As demonstrated in Fig. 3(a) and (c), increases in I_1 and α caused the probability of the government and Internet recycling companies strategy selection to be larger and gradually converge to 1. This suggests increased credibility when the government adopts strict regulations, and that the main regulation costs under no strict regulations increase the probability of strict government regulations and Internet recycling companies protecting information security. Conversely, as demonstrated in Fig. 3(b), an increase in C_1 decreased the probability of the government and Internet recycling companies to make strategic choices. Therefore, an increase in the cost of strict government regulation would cause the government to select "no strict regulation" and Internet recycling companies to select "no information security."

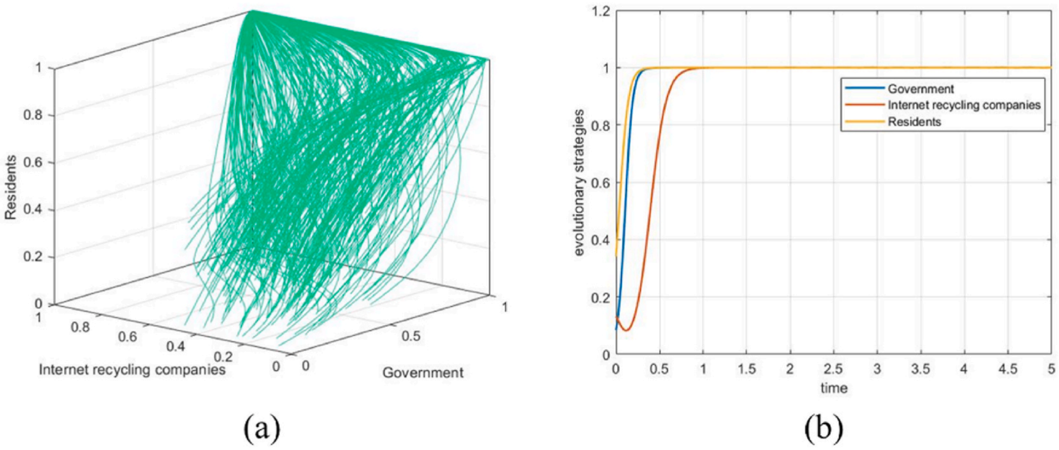
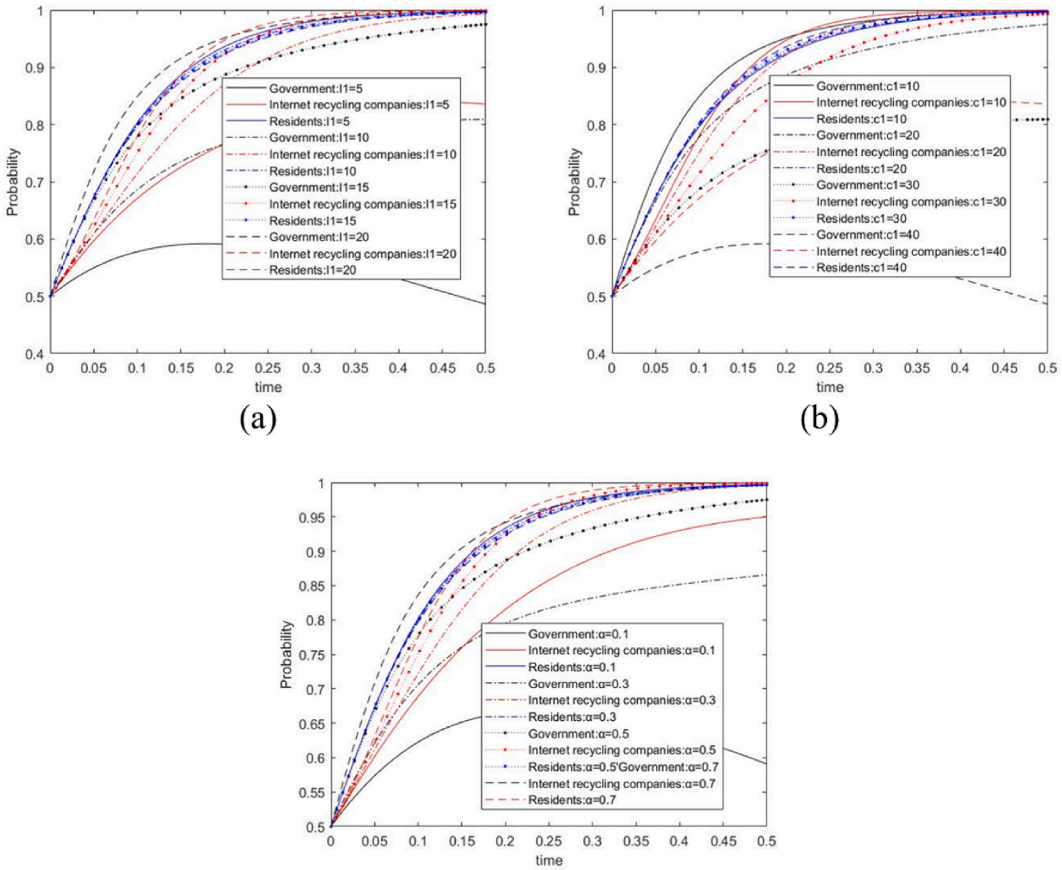


Fig. 2. Process of strategy evolution using a tripartite game system.



(a)

(b)

(c)

Fig. 3. Effects of I_1, C_1, and α variations on strategy selection.

4.2. *Impact of reputation enhancement and declines in $\boldsymbol{I_2}$, $\boldsymbol{D_2}$, $\boldsymbol{R_3}$ earnings, and $\boldsymbol{\beta}$ on strategies selected by internet recycling companies*

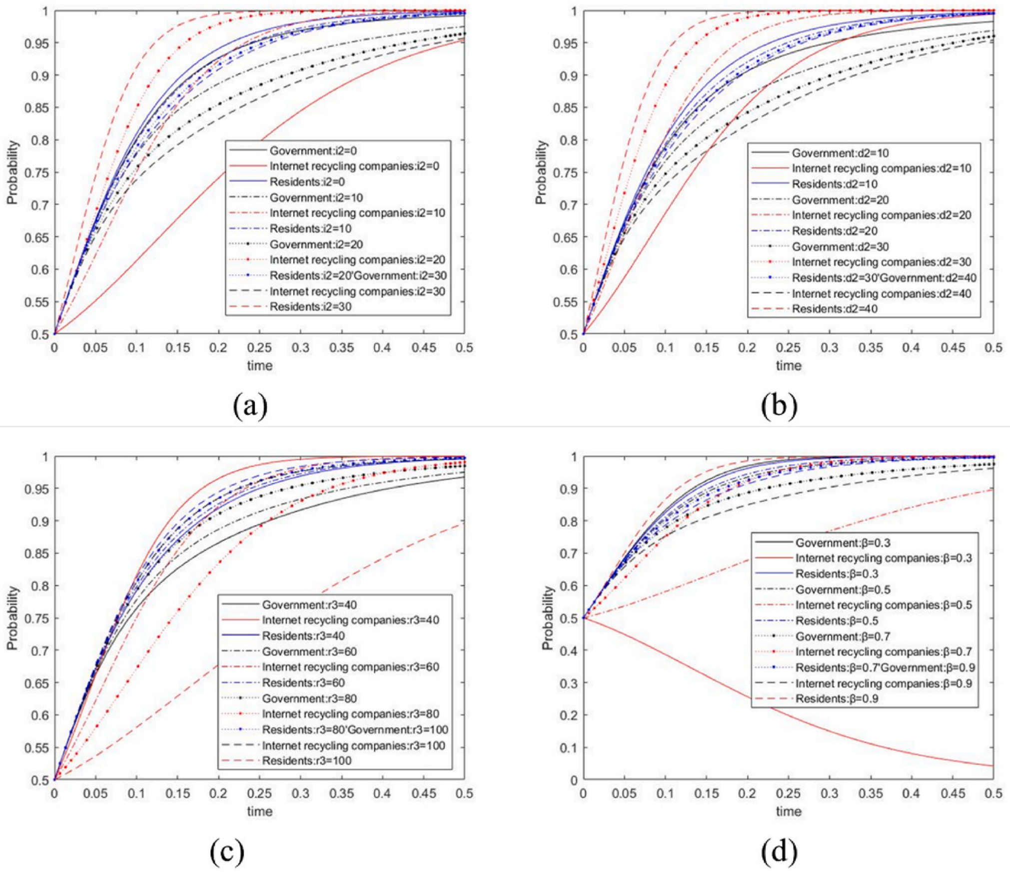
Keeping the other parameters unchanged, the evolutionary processes of government, Internet recycling companies, and residents' strategy selection for I_2 values of 0, 10, 20, and 30 were obtained, as shown in Fig. 4(a). Further, all other parameters remained unchanged while D_2 was assigned values of 10, 20, 30, and 40, which allowed assessment of the temporal evolution of the strategy selection of the government, Internet recycling companies, and residents at varying D_2 values, as shown in Fig. 4(b). The temporal evolution of the government, Internet recycling companies, and resident strategy selection at R_3 values of 40, 60, 80, and 100 are visualized in Fig. 4(c). Finally, the temporal evolution of the government, Internet recycling companies, and resident strategy selections with different β values was obtained by assigning β values of 0.3, 0.5, 0.7, and 0.9, while all other parameters were held constant, as demonstrated in Fig. 4(d).

Fig. 4 demonstrates that altering the reputation of Internet recycling companies to increase or decrease I_2 and D_2, influencing the increase in R_3 when Internet recycling companies do not protect information security, and changing the gain coefficient β when information security is protected had a small impact on residents' strategy selection. While it did not significantly alter the trend in the resident strategy selection, it did have a larger impact on the strategy selection of the government and Internet recycling companies.

As demonstrated in Fig. 4(a) and (b), increases in I_2 and D_2 slowed the convergence of the probability of the government strategy selection to 1 and sped up the convergence of the probability of the Internet recycling company strategy selection to 1. As shown in Fig. 4(c) and (d), an increase in R_3 caused the government strategy selection probability to quickly converge to 1. Conversely, an increase in β caused the government strategy selection probability to slowly converge to 1. An increase in R_3 decreased the probability that an Internet recycling company would select to preserve information security. Conversely, an increase in β increased the probability that an Internet recycling company would strive to keep information secure, eventually converging to 1.

4.3. *Impact of resident participation benefiting recycling $\boldsymbol{R_4}$ and information loss $\boldsymbol{C_2}$ on strategy selection*

Keeping all other parameters unchanged and varying the R_4 values between 20, 30, 40, and 50, the temporal evolutionary processes



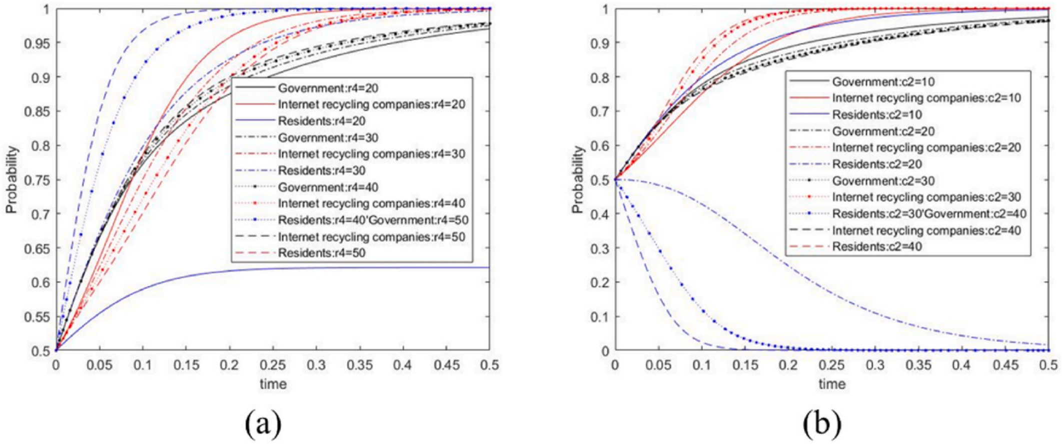
(a) (b)

(c) (d)

Fig. 4. Effects of I_2, D_2, R_3, and β variations on strategy selection.

of the strategy selection by the government, Internet recycling companies, and residents were obtained, as shown in Fig. 5(a). Similarly, keeping all other parameters constant and assigning C_2 values of 10, 20, 30, and 40, the temporal evolutionary processes of the government, Internet recycling companies, and resident strategy selection were investigated, as shown in Fig. 5(b).

As demonstrated in Fig. 5, changes in R_4 and C_2 mainly affected the probability of resident strategy selection. An increase in R_4 increased the probability of resident strategy selection, while an increase in C_2 decreased it. Therefore, the greater the benefits of participation to residents, the more likely residents are to participate in recycling; the greater the losses suffered by residents owing to information leakage, the more likely residents are to avoid participating in recycling.



(a) (b)

Fig. 5. Effect of R_4 and C_2 on strategy selection.

5. Conclusions and policy recommendations

5.1. Conclusion and discussion

The recycling of waste electronics is an important part of a circular economy. An Australian study reported the stocks of light and heavy rare earth metals in household electronic devices, such as smartphones and computers, to be 105,199 kg and approximately 35,412 kg, respectively [5]. In China, these figures are suggested to be even higher. However, the Internet recycling model is in its infancy, and public willingness to participate is low [37]. To better promote the efficient recycling of waste electronics on the Internet and prevent the leakage of the information of the resident, we constructed a game model to conduct a simulation analysis of the factors affecting the behavioral decisions of each key stakeholder.

Through simulations, we found that: (1) The higher the price Internet recycling companies pay for waste electronics, the more likely residents are to participate in Internet recycling. (2) The less loss caused by information leakage in Internet recycling, the higher the potential of Internet recycling. However, the development of information security technology by recyclers will increase operating costs, thereby reducing revenue and thus evolving into a "negative recycling" strategy. Therefore, the government should provide special funding to support Internet recycling companies [38]. (3) The regulatory role of the government is crucial in driving the development of Internet recycling. Given the substantial amount of personal information contained in waste electronics, the government should rigorously oversee Internet recycling companies to ensure they fulfill their responsibility of safeguarding information security. Additionally, the government can employ policy incentives to encourage businesses to increase their investment in information security, thereby enhancing residents' confidence in participating in Internet recycling.

In conclusion, the Internet recycling model holds significant importance in addressing challenges faced by traditional recycling. Offering competitive prices for recycling, ensuring information security, and implementing effective government regulations are key factors in promoting the development of the Internet recycling model. Through the analysis of a game model, we have provided recommendations for the government, internet recycling companies, and residents to facilitate better cooperation and drive the efficient development of Internet recycling. This will contribute to the sustainable recycling and reuse of waste electronics, playing a vital role in achieving a circular economy. However, it is important to acknowledge the limitations, such as parameter rationality, in the model. Future research can further explore and optimize the model to cater to practical applications.

In the context of mobile phones, the issue of information leakage is the biggest obstacle to recycling [39], necessitating joint efforts by the government and Internet recycling companies to improve residents' willingness to recycle. First, the government should improve the laws and regulations pertaining to the protection of personal information, establish standards for the removal of this information from mobile phones, develop technical specifications and standardized processes, and require enterprises to meet certain criteria. Second, Internet recycling companies can be required to make the process of removing old mobile phone information public and provide residents with authoritative and officially certified information removal reports, enabling them to have a clear understanding of the specific handling of old mobile phones after processing. Finally, mobile phone companies can offer guidance to residents who wish to remove their accounts and information from cloud storage. This will strengthen residents' trust in Internet recycling and foster a win-win scenario of efficient recycling and information leakage prevention.

However, there are still many shortcomings, including the rationality of the model parameters, that require further investigation to confirm our findings' applicability in practical situations owing to the complexity of the influencing factors. Existing literature has applied intelligent algorithms and novel machine learning methods in the field of circular economy research [40,41], and this will also be the direction of our future efforts. Additionally, the government's regulatory efforts toward Internet recycling companies aiming to achieve optimal policy effects require further research.

5.2. Policy implications

Based on the findings of this study, to effectively promote Internet recycling and prevent information leakage through a multi-party game, each stakeholder should make corresponding efforts to ensure mutual benefit and success. Based on our results, we suggest the following:

The government's strict regulation of information security protection practices of Internet waste electronics recycling companies is an important factor influencing residents' willingness to participate in Internet waste electronics recycling. Whether Internet recycling companies are willing to invest in protecting information security remains unknown. Therefore, it is necessary for the government to strictly supervise Internet recycling of waste electronics, establish an open and transparent regulatory system to ensure information security, and reward companies that protect information security through funding support. This would enhance the credibility of Internet recycling companies in protecting information security. Government subsidies may enable the market to reallocate resources, providing a vital macro-regulatory tool [42]. Public criticism or increased penalties could be imposed on Internet recycling companies that do not protect information security, for their reputation to suffer with breaches. Moreover, the government could further introduce industry standards for eliminating information in waste electronics, which would also reduce the cost of regulation to some extent.

For resident participation, it is important to actively monitor and report information leakage by Internet recycling companies. This would enhance participation and increase residents' willingness to participate in recycling. An open and transparent information security regulatory system would aid in reducing information leakage by encouraging Internet recycling company monitoring, thereby reducing government regulatory costs.

Residents are reluctant to recycle their mobile phones because of privacy protection concerns [43]. Internet recycling companies can work with cell phone manufacturers to introduce personal storage cloud drives or transfers to new devices to help residents address the risk of losing or leaking personal information. They can also bridge the gap between recycling rare metals and reuse. Further, this would, to some extent, be a win-win situation for all parties. Moreover, implementing measures such as the exchange of recycling points for gifts could encourage residents to participate. Liu et al. suggested designing resident incentive mechanisms based on Maslow's Hierarchy of Needs theory for the users to realize their own value in the process of recycling when operating the platform [44]. Companies can also reduce operating costs and improve competitiveness by optimizing their logistics systems. In 2021, Ai Huishou launched a "Privacy Protection Plan" to safeguard user information security. During the campaign, they offered substantial privacy security subsidies and provided free privacy clearing services. They also proposed a 100-fold compensation in case of any privacy leakage, undoubtedly enhancing residents' confidence in participating in Internet recycling.

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Author contribution statement

Tingting Liu: Conceived and designed the experiments.
Peize Wang: Wrote the paper; Analyzed and interpreted the data.
Shangyun Wu: Performed the experiments.
Yufeng Wu: Conceived and designed the experiments.

Data availability statement

Data will be made available on request.

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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Appendix A. Stakeholder game model parameter settings and their implications

Notations	Descriptions	Remarks
R_1	Fines for companies that do not protect information security when strictly regulated by the government	–
R_2	Benefits of resource recycling for the government from residents' participation in recycling	$0 < \alpha < 1$
R_3	Internet recycling companies' net benefits when information security is not protected	–
βR_3	Net benefit to Internet recycling companies when protecting information security	$0 < \beta < 1$
R_4	Benefits for residents when they participate in recycling	–
C_1	Cost of regulation with strict government regulation	–
αC_1	Cost of regulation with no strict government regulation	$0 < \alpha < 1$
C_2	Losses caused to residents when Internet recycling businesses do not keep information secure	–
I_1	Credibility improvement when government conducts strict regulation	–
I_2	Company credibility enhanced by strict government regulation of Internet recycling companies to protect information security	–
I_3	Internet recycling companies protect information security under strict government regulation, leading to increased resident satisfaction	–
D_1	Decreased government credibility due to companies' failures to protect information security when not strictly regulated by the government	–
D_2	Internet recycling companies not protecting information security under strict government regulation leads to loss of corporate reputation	–
D_3	Internet recycling companies not protecting information security under strict government regulation reduces resident satisfaction	–
x	Probability of the government choosing "strict regulation"	$0 \leq x \leq 1$
y	Probability of Internet recycling companies choosing to "protect information security"	$0 \leq y \leq 1$
z	Probability of residents choosing to "participate in recycling"	$0 \leq z \leq 1$

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