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Research on the Secondary Recycling Strategy of Packaging Waste Based on a Tripartite Evolutionary Game Model

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ABSTRACT

Under the background of the "dual carbon" goals and the promotion of green development strategies, China has continuously strengthened the governance of packaging and the construction of packaging waste recycling systems. This paper focuses on the packaging issues in the online sales of gift-attribute commodities. Using evolutionary game theory as an analytical tool, it constructs an evolutionary game model. The results show that the initial recycling willingness of enterprises has the greatest impact on the synergy pace of the system, exhibiting a significant "herding effect"; enterprise recycling decisions are significantly influenced by reuse benefits, as well as R&D and operational costs; the depth of logistics enterprises' participation depends heavily on government special subsidies and social benefits; the sharing of environmental governance responsibility and governance investment both positively drive the behavior of the three parties; and an increase in the recycling benefit coefficient can enhance overall synergy from the market side.

KEYWORDS

Secondary Recycling; Evolutionary Game; Circular Economy; Tripartite Synergy; Replicator Dynamics

1. INTRODUCTION

In recent years, with the advancement of the global "dual carbon" goals and green development strategies, China has formally incorporated the transformation toward green packaging into its policy system. In recent years, China has issued a number of relevant policies to control packaging and encourage resource recycling: The*Law of the People's Republic of China on the Prevention and Control of Environmental Pollution by Solid Waste* explicitly proposes requirements to reduce the generation of packaging waste and promote recyclable and easily recoverable packaging models (Liu X, 2022) [1]; the*Notice on Further Strengthening the Governance of Commodity Packaging*specifies regulations for packaging in key areas such as food and cosmetics, while clearly calling for the improvement of packaging waste recycling systems (Wang L, 2022) [2]; the *14th Five-Year Plan for Circular Economy Development*(2023) [3] officially lists the resource utilization of packaging waste as a major task, explicitly stating that by 2025, the level of circular use of commodity packaging will achieve substantial improvement, with the recycling rate of packaging waste reaching around 60% (ational Development and Reform Commission, 2021"). It requires the improvement of packaging waste recycling systems, the enhancement of packaging circular utilization levels, and the promotion of a full-chain governance pattern of source reduction—recycling and reuse—end-of-life disposal, thereby providing solid policy support and directional guidance for the secondary recycling of packaging materials.

With the rapid development of the logistics industry, online recycling models have become an important pathway for the secondary recycling of packaging materials. Their efficient operation is highly dependent on the coordinated linkage and behavioral synergy among the three main parties: sales-recycling enterprises, logistics enterprises, and consumers. Due to prominent issues such as divergent interest demands, behavioral decision-making games, and the lack of synergy mechanisms among the three parties, the online recycling system struggles to operate stably, and the ideal state of coordination is difficult to achieve. Consequently, many scholars have focused on research related to secondary recycling issues, with existing research results mainly concentrated in the following three areas.

First, research has been conducted from the perspectives of packaging evaluation standards and institutional governance. Ma Aijin et al. (2013) [4] evaluated the implementation of the national standard "Requirements for Restricting Excessive Packaging — Food and Cosmetics," comprehensively examining the implementation status of the standard and identifying existing problems and suggestions for improvement. Sun Ling (2024) [5] analyzed cases of food packaging designs that achieve moderate packaging while demonstrating good market performance, and pointed out the principles of sustainable packaging design as well as effective pathways for achieving green transformation and upgrading. Li Li et al. (2005) [6] employed life cycle analysis to confirm that packaging imposes significant environmental burdens throughout its entire life cycle—from raw material extraction, production, and use to disposal. Their study indicates that optimizing packaging materials, simplifying structures, and enhancing recyclability design are feasible ways to reduce environmental impacts.

Second, research on the construction of models for packaging waste recycling and treatment. Luo Mingjun et al. (2025) [9] took 16 specific evaluation indicators from four dimensions—environmental, economic, social, and technological—as influencing factors, and selected traditional community recycling stations, packaging enterprise self-recycling, and third-party professional company recycling as evaluation schemes. They established a network relationship between indicators and constructed a packaging waste recycling evaluation model. Zhang Qiqi et al. (2024) [10] summarized the packaging waste recycling path planning problem as a reverse logistics vehicle routing problem with loops and time windows, modeling with the joint optimization objectives of minimizing recycling costs, dispatch costs, and time window penalties. Jia Yajuan et al. (2025) [11], based on synergy theory and the bounded rationality of different entities in packaging waste recycling activities, constructed a four-party evolutionary game model consisting of the government, third-party recycling enterprises, catering merchants, and consumers, analyzing the sensitivity of various influencing variables. Deng Xueping et al. (2018) [12] established a mathematical model minimizing costs such as transportation costs, processing costs, recycling costs, and time penalty costs, using an improved genetic algorithm to solve the model. They proposed using a two-point crossover method to improve the crossover operator and a two-point mutation operator to increase population diversity, and conducted sensitivity analysis on population size, mutation probability, and transportation costs.

Third, research focusing on game models of recycling participants in recycling. Cheng Zaoping et al. [13, 14], from the perspective of government regulation and based on evolutionary game theory, constructed a game model between government regulation and recycler recycling, studying the strategic interaction mechanisms under static and dynamic subsidy and penalty strategies. Xu Xiaoxuan et al. (2023) [15] constructed a tripartite game model of government, logistics platform, and consumer game model for green express packaging recycling, analyzing the factors leading to a stable strategy combination in the green express packaging recycling system.

Although existing research provides multiple perspectives for understanding packaging waste recycling, there are still shortcomings. First, existing research mostly focuses on single-factor analysis of recycling willingness, lacking systematic exploration of multi-factor interactions and their pathways from intention to behavior. Second, research on the specific link of "secondary recycling" remains relatively weak, especially lacking in-depth analysis of the cognition and behavior mechanisms of the three main parties—sales-recycling enterprises, logistics companies, and consumers—regarding packaging secondary use in the packaging context. Finally, there are few quantitative studies, making it difficult to support policy formulation and practical guidance.Based on this, this paper uses evolutionary game theory as the core tool to construct a tripartite evolutionary game model of sales-recycling enterprises, logistics enterprises, and consumers in the online model systematically analyzes the evolutionary paths, stable equilibrium conditions, and key driving factors of the strategy choices of the three parties, revealing the internal mechanism of interest conflicts and win-win cooperation among the parties, identifying policy tools and incentive mechanisms that promote the system to converge toward the ideal stable state of enterprise recycling-logistics cooperation-consumer participation, and ultimately proposes a collaborative optimization path for secondary recycling of packaging materials that balances the interests of all parties and adapts to online scenarios.

2. ESTABLISHMENT OF THE TRIPARTITE GAME MODEL

2.1. Basic Assumptions of the Model

In the online recycling model, a particularly typical and important mode involves collaboration between production/sales enterprises and professional logistics companies. The closed-loop governance of packaging for gift-attribute commodities sold online requires the coordinated efforts of sales-recycling enterprises and logistics enterprises to build a recycling system, along with the active participation of consumers. This process necessitates the formation of a linkage mechanism among the three parties to jointly complete the entire disposal process of gift packaging—from generation and circulation to reverse recycling. To deeply explore the interest games and intrinsic relationships among sales-recycling enterprises, logistics enterprises, and consumers, this study, based on evolutionary game theory, focuses on analyzing the dynamic game process among the three parties. To simplify the analysis, the following basic assumptions are made:

(1) The strategy of the sales-recycling enterprise is either "recycle packaging" or "not recycle packaging";

(2) The strategy of the logistics company is either "cooperate with the sales-recycling enterprise" or "not cooperate with the sales-recycling enterprise";

(3) The strategy of the consumer is either "participate in packaging recycling" or "not participate in packaging recycling".

The relationship among the game players is shown in Figure 1, and the relevant symbols and their meanings of the model are presented in Table 1.

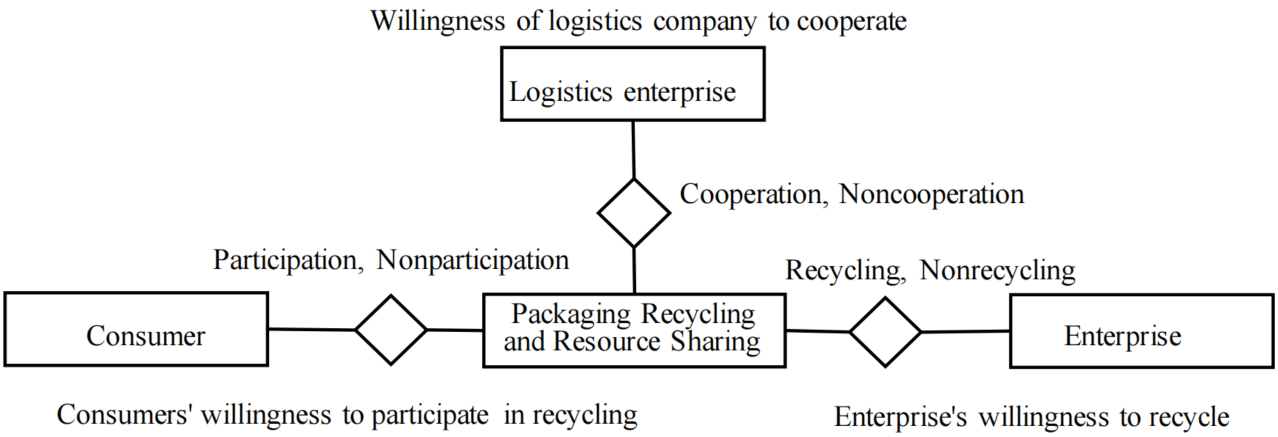

Figure 1. Relationships among game players

Table 1. Model notations

Symbol	Meaning
Enterprise	
C_1	Cost incurred by the enterprise for online sales of gift-type products
C_2	R&D cost incurred by the enterprise for packaging recycling
C_3	Recycling cost incurred when the enterprise implements recycling
R_1	Revenue generated by the enterprise from online sales of gift-type products
R_2	Reuse benefit generated from recycling of packaged products
S_1	Government subsidy obtained by the enterprise when it chooses to recycle
S_2	Social benefit obtained by the enterprise when it chooses to recycle
I_1	Reward given by the online platform to the enterprise when it chooses to recycle
I_2	Reward given to consumers when the enterprise chooses to recycle and consumers choose to participate
H	Total cost incurred by the government for packaging pollution control
α	Proportion of environmental governance borne by the enterprise
Logistics	
C_4	Cost incurred by the logistics company when choosing the "cooperate with the enterprise" strategy
C_5	Cost incurred by the logistics company when choosing the "do not cooperate with the enterprise but only provide basic logistics support" strategy
R_3	Benefit obtained by the logistics company when choosing the "cooperate with the enterprise" strategy
R_4	Benefit obtained by the logistics company when choosing the "do not cooperate with the enterprise but only provide basic logistics support" strategy
S_3	Government subsidy obtained by the logistics company for providing logistics support for product packaging recycling
S_4	Social benefit obtained by the logistics company for providing logistics support for product packaging recycling
β	Proportion of environmental governance borne by the logistics enterprise
Consumer	
C_6	Cost incurred by consumers when choosing the "participate in product packaging recycling" strategy
C_7	Cost incurred by consumers when choosing the "do not participate in product packaging recycling" strategy
R_5	Benefit obtained by consumers when choosing the "participate in product packaging recycling" strategy
R_6	Benefit obtained by consumers when choosing the "do not participate in product packaging recycling" strategy
γ	Proportion of environmental governance borne by consumers
Two-sided effect	
Q	Average recycling level of packaging when both the enterprise and consumers choose to recycle
P	Average environmental cost of non-recycling when either the enterprise or consumers choose not to recycle
φ	Proportion of product packaging that can be standardized for recycling
μ	Influence factor of product price

Note: where $\alpha+\beta+\gamma=1$.

Some large enterprises, thanks to their strong technical and financial capabilities, can build their own recycling platforms. However, for numerous small and medium-sized enterprises (SMEs), it is neither economical nor necessary to independently establish a recycling system. Therefore, the research in this section mainly focuses on SMEs that lack their own recycling logistics supply.

Assumption 1: Sales-recycling enterprises, logistics enterprises, and consumers are all bounded rational decision-makers. In the realistic context of incomplete and asymmetric information, the three parties make strategic choices independently, without perfect information or perfect foresight. Over a long-term repeated game process, they continuously learn, imitate, and adjust their strategies based on their own perceived payoffs, the behaviors of other parties, and the external policy environment, gradually approaching an evolutionarily stable equilibrium. It is assumed that sales-recycling enterprises, logistics enterprises, and consumers independently and randomly choose their respective strategies. At the initial stage of the game between sales-recycling enterprises and consumers, the model sets that the proportion of sales-recycling enterprises choosing the "recycle product packaging" strategy is $x(0 \leq x \leq 1)$, and the proportion choosing the "do not recycle product packaging" strategy is $1-x$. The proportion of logistics companies choosing the "cooperate with sales-recycling enterprises" strategy is $y(0 \leq y \leq 1)$, and the proportion choosing the "do not cooperate with sales-recycling enterprises but only provide basic logistics support" strategy is $1-y$. The proportion of consumers choosing the "participate in product packaging recycling" strategy is $z(0 \leq z \leq 1)$, and the proportion choosing the "do not participate in product packaging recycling" strategy is $1-z$.

Assumption 2: The strategy space of the sales-recycling enterprise is {recycle packaging, do not recycle packaging}; the strategy space of the logistics enterprise is {cooperate with the sales-recycling enterprise, do not cooperate with the sales-recycling enterprise}; the strategy space of consumers is {participate in packaging recycling, do not participate in packaging recycling}. At the initial moment, the three parties randomly choose their strategies with certain probabilities, and their strategy choices are independent and non-interfering.

Assumption 3: The total cost incurred by the government for packaging pollution control is a fixed value H. This control cost is shared by the three parties—the sales-recycling enterprise, the logistics enterprise, and consumers—according to their respective responsibility ratios, satisfying $\alpha+\beta+\gamma=1$. When a party adopts a passive strategy (i.e., not recycling, not cooperating, or not participating), it must pay a corresponding environmental cost in proportion to its environmental responsibility. The higher the degree of collaborative participation, the lower the environmental cost borne by each party.

Assumption 4: Only when the sales-recycling enterprise chooses to recycle, the logistics enterprise chooses to cooperate, and consumers choose to participate can the online packaging reverse recycling form a complete synergistic closed loop. The three parties can then jointly obtain positive returns such as recycling and reuse benefits, government subsidies, platform rewards, brand reputation, and social benefits, with the highest overall recycling efficiency and resource utilization value. If any party adopts a passive strategy, the recycling chain will be interrupted, the overall recycling level will decline, and the potential benefits of all parties will be compromised.

Assumption 5: All key parameters in the model—including costs (e.g., R&D costs, logistics costs, time costs), benefits (e.g., sales revenue, reuse benefits), subsidy and penalty mechanisms, as well as environmental costs—are exogenously given constants. During the evolutionary game process, these parameters remain fixed and do not adjust over time or with changes in the strategy proportions of the parties.

2.2. Construction of the Payoff Matrix

Based on the above assumptions, this section constructs a tripartite evolutionary game model among the sales-recycling enterprise, the logistics enterprise, and consumers. The mixed-strategy game matrix is shown in Table 2.

Table 2. Tripartite game strategy matrix

Logistics company	Consumer	Sales-recycling enterprise (x)	
		Recycle (x)	Not recycle (1-x)
Cooperates (y)	Participate (z)	(x, y, z)	(1-x, y, z)
	Not participate (1-z)	(x, y, 1-z)	(1-x, y, 1-z)
Does not cooperate (1-y)	Participate (z)	(x, 1-y, z)	(1-x, 1-y, z)
	Not participate (1-z)	(x, 1-y, 1-z)	(1-x, 1-y, 1-z)

Based on different combinations of game strategies, the payoffs for each party under various behavioral decisions of the sales-recycling enterprise, logistics company, and consumers can be calculated. The payoff matrix of the game model is shown in Table 3.

Table 3. Payoff matrix

Strategy Combination	Salesrecycling Enterprise	Logistics Company	Consumer
(x, y, z)	$R_1+R_2+I_1+S_1+S_2+\varphi Q*ln\mu-C_1-C_2-C_3-I_2$	$R_3+S_3+S_4-C_4$	$R_5+I_2+\varphi Q*ln\mu-C_6$
(x, y, 1-z)	$R_1+R_2+S_1-C_1-C_2$	R_3-C_4	$R_6-C_7-H-P*ln\mu$
(x, 1-y, z)	$R_1+I_1+S_1+S_2-C_1-C_2$	$R_4-C_5-S_4-H$	R_5-C_6
(x, 1-y, 1-z)	$R_1+I_1-C_1-C_2$	$R_4-C_5-(\beta+\frac{1}{2}\alpha)H$	$R_6-C_7-(\gamma+\frac{1}{2}\alpha)H$
(1-x, y, z)	$R_1-C_1-S_1-S_2-H-P*ln\mu$	$R_3+S_3+S_4-C_4$	R_5-C_6
(1-x, y, 1-z)	$R_1-C_1-(\alpha+\frac{1}{2}\beta)H$	R_3-C_4	$R_6-C_7-(\gamma+\frac{1}{2}\beta)H$
(1-x, 1-y, z)	$R_1-C_1-S_2-(\alpha+\frac{1}{2}\gamma)H$	$R_4-C_5-S_4-(\beta+\frac{1}{2}\gamma)H$	R_5-C_6
(1-x, 1-y, 1-z)	$R_1-C_1-\alpha H$	$R_4-C_5-\beta H$	$R_6-C_7-\gamma H$

3. SOLUTION OF EVOLUTIONARY STABLE STRATEGIES

3.1. Construction of Expected Payoff Functions

Based on Table 2 and Table 3, the expected payoff of the sales-recycling enterprise when choosing the "participate" strategy in the game is denoted as U_{x_1}, the expected payoff when choosing the "not participate" strategy is denoted as U_{x_2}, and the average expected payoff is denoted as $\overline{U}_x$. These are given as follows:

$$U_{x_1}=yz(R_1+R_2+I_1+S_1+S_2+\varphi Q*ln\mu-C_1-C_2-C_3-I_2)+y(1-z)(R_1+R_2+S_1-C_1-C_2)+(1-y)z(R_1+I_1+S_1+S_2-C_1-C_2)+(1-y)(1-z)(R_1+I_1-C_1-C_2)$$

$$U_{x_2}=yz(R_1-C_1-S_1-S_2-H-P*ln\mu)+y(1-z)(R_1-C_1-(\alpha+\tfrac{1}{2}\beta)H)+(1-y)z(R_1-C_1-S_2-(\alpha+\tfrac{1}{2}\gamma)H)+(1-y)(1-z)(R_1-C_1-\alpha H)$$

$$\overline{U}_x=xU_{x_1}+(1-x)U_{x_2}$$

The expected payoff of the logistics company when choosing the "cooperate with the sales-recycling enterprise" strategy in the game is denoted as U_{y_1}, the expected payoff when choosing the "do not cooperate with the sales-recycling enterprise" strategy is denoted as U_{y_2}, and the average expected payoff is denoted as $\overline{U}_y$. These are given as follows:

$$U_{y_1} = xz(R_3 + S_3 + S_4 - C_4) + x(1-z)(R_3 - C_4) + (1-x)z(R_3 + S_3 + S_4 - C_4) + (1-x)(1-z)(R_3 - C_4)$$

$$U_{y_2} = xz(R_4 - C_5 - S_4 - H) + x(1-z)(R_4 - C_5 - (\beta + \tfrac{1}{2}\alpha)H) + (1-x)z(R_4 - C_5 - S_4 - (\beta + \tfrac{1}{2}\gamma)H) + (1-x)(1-z)(R_4 - C_5 - \beta H)$$

$$\overline{U}_y = yU_{y_1} + (1-y)U_{y_2}$$

The expected payoff of consumers when choosing the "participate in packaging recycling" strategy in the game is denoted as U_{z_1}, the expected payoff when choosing the "do not participate in packaging recycling" strategy is denoted as U_{z_2}, and the average expected payoff is denoted as $\overline{U}_z$. These are given as follows:

$$U_{z_1} = xy(R_5 + I_2 + \varphi Q * ln\mu - C_6) + x(1-y)(R_5 - C_6) + (1-x)y(R_5 - C_6) + (1-x)(1-y)(R_5 - C_6)$$

$$U_{z_2} = xy(R_6 - C_7 - H - P * ln\mu) + x(1-y)(R_6 - C_7 - (\gamma + \tfrac{1}{2}\alpha)H) + (1-x)y(R_6 - C_7 - (\gamma + \tfrac{1}{2}\beta)H) + (1-x)(1-y)(R_6 - C_7 - \gamma H)$$

$$\bar{U}_z = zU_{z_1} + (1-z)U_{z_2}$$

3.2. Solution of Evolutionary Stable Strategies Using the Replicator Dynamic Equation

The growth rate of enterprises choosing the "recycle packaging" strategy should equal the difference between the expected payoff and the average expected payoff. From the above analysis, the replicator dynamic equation is given as follows:

$$F(x) = \frac{dx}{dt} = x(U_{X_1} - \overline{U}_x) = x(1-x)(U_{x_1} - U_{x_2}) = x(1-x)[yz(R_2 + I_1 + 2S_1 + 2S_2 + H + (\varphi Q + P)\ln\mu - C_2 - C_3 - I_2) + y(1-z)(R_2 + S_1 + (\alpha + \tfrac{1}{2}\beta)H - C_2) + (1-y)z(I_1 + S_1 + 2S_2 + (\alpha + \tfrac{1}{2}\gamma)H - C_2) + (1-y)(1-z)(I_1 + \alpha H - C_2)] \quad (1)$$

The replicator dynamic equation for the logistics company is:

$$F(y) = \frac{dy}{dt} = y\left(U_{y_1} - \bar{U}_y\right) = y(1-y)\left(U_{y_1} - U_{y_2}\right) = y(1-y)[xz(R_3 - R_4 + S_3 + 2S_4 + H - C_4 + C_5) + x(1-z)(R_3 - R_4 - C_4 + C_5 + (\beta + \tfrac{1}{2}\alpha)H) + (1-x)z(R_3 - R_4 + S_3 + 2S_4 + (\beta + \tfrac{1}{2}\gamma)H - C_4 + C_5) + (1-x)(1-z)(R_3 - R_4 - C_4 + C_5 + \beta H)] \quad (2)$$

The replicator dynamic equation for consumers is:

$$F(z) = \frac{dz}{dt} = z(U_{z_1} - \bar{U}_z) = z(1-z)(U_{z_1} - U_{z_2}) = z(1-z)[xy(R_5 - R_6 - C_6 + C_7 + H + I_2 + (\varphi Q + P)l\eta\mu) + x(1-y)(R_5 - R_6 - C_6 + C_7 + (\gamma + \tfrac{1}{2}\alpha)H) + (1-x)y(R_5 - R_6 - C_6 + C_7 + (\gamma + \tfrac{1}{2}\beta)H) + (1-x)(1-y)(R_5 - R_6 - C_6 + C_7 + \gamma H)] \tag{3}$$

By combining equations (1), (2), and (3), we obtain the replicator dynamic system for the sales-recycling enterprise, the recycling logistics company, and consumers:

$$\begin{cases} F(x) \\ F(y) \\ F(z) \end{cases} \tag{4}$$

According to the method proposed by Friedman (1991) [14], the evolutionarily stable strategy (ESS) of a differential equation system can be obtained through the local stability analysis of the Jacobian matrix of the system. From equation (4), the Jacobian matrix of the system is given as follows:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{5}$$

By setting F(x)=0, F(y)=0, F(z)=0, we can obtain eight pure-strategy Nash equilibrium points in the game among the sales-recycling enterprise, logistics company, and consumers. These are E1(0, 0, 0), E2(0, 0, 1), E3(0, 1, 0), E4(0, 1, 1), E5(1, 0, 0), E6(1, 0, 1), E7(1, 1, 0), E8(1, 1, 1). According to evolutionary game theory, an equilibrium point is an evolutionarily stable point (ESS) of the system when all eigenvalues of the Jacobian matrix are non-positive.

3.3. Stability Analysis of Equilibrium Points

In the previous section, eight pure-strategy Nash equilibrium points were obtained. Substituting these eight points into the Jacobian matrix J yields the eigenvalues of the Jacobian matrix J corresponding to these eight points, as shown in Table 4.

Table 4. Eigenvalues of the Jacobian matrix at each equilibrium point

(x, y, z)	$\frac{\partial F(x)}{\partial x}$	$\frac{\partial F(y)}{\partial y}$	$\frac{\partial F(z)}{\partial z}$
(0, 0, 0)	$I_1 + \alpha H - C_2$	$R_3 - R_4 - C_4 + C_5 + \beta H$	$R_5 - R_6 - C_6 + C_7 + \gamma H$
(0, 0, 1)	$I_1 + S_1 + 2S_2 + (\alpha + \frac{1}{2}\gamma)H - C_2$	$R_3 - R_4 + S_3 + 2S_4 + (\beta + \frac{1}{2}\alpha)H - C_4 + C_5$	$-(R_5 - R_6 - C_6 + C_7 + \gamma H)$
(0, 1, 0)	$R_2 + S_1 + (\alpha + \frac{1}{2}\beta)H - C_2$	$-(R_3 - R_4 - C_4 + C_5 + \beta H)$	$R_5 - R_6 - C_6 + C_7 + (\gamma + \frac{1}{2}\beta)H$
(0, 1, 1)	$R_2 + I_1 + 2S_1 + 2S_2 + H + (\varphi Q + P)\ln\mu - C_2 - C_3 - I_2$	$-(R_3 - R_4 + S_3 + 2S_4 + (\beta + \frac{1}{2}\alpha)H - C_4 + C_5)$	$-(R_5 - R_6 - C_6 + C_7 + (\gamma + \frac{1}{2}\beta)H)$
(1, 0, 0)	$-I_1 - \alpha H + C_2$	$R_3 - R_4 - C_4 + C_5 + (\beta + \frac{1}{2}\alpha)H$	$R_5 - R_6 - C_6 + C_7 + (\gamma + \frac{1}{2}\alpha)H$
(1, 0, 1)	$-I_1 - S_1 - 2S_2 - (\alpha + \frac{1}{2}\gamma)H + C_2$	$R_3 - R_4 + S_3 + 2S_4 + H - C_4 + C_5$	$-(R_5 - R_6 - C_6 + C_7 + (\gamma + \frac{1}{2}\alpha)H)$
(1, 1, 0)	$-R_2 - S_1 - (\alpha + \frac{1}{2}\beta)H + C_2$	$-(R_3 - R_4 - C_4 + C_5 + \beta H)$	$R_5 - R_6 - C_6 + C_7 + H + I_2 + (\varphi Q + P)\ln\mu$
(1, 1, 1)	$-R_2 - I_1 - 2S_1 - 2S_2 - H - (\varphi Q + P)\ln\mu + C_2 + C_3 + I_2$	$-(R_3 - R_4 + S_3 + 2S_4 + H - C_4 + C_5)$	$-(R_5 - R_6 - C_6 + C_7 + H + I_2 + (\varphi Q + P)\ln\mu)$

To facilitate the analysis of the signs of the eigenvalues corresponding to different equilibrium points, and without loss of generality, it is assumed that when the sales-recycling enterprise, the logistics company, and consumers collaboratively carry out secondary packaging recycling, the net benefits of all parties are significantly higher than those in the non-cooperative scenario. Due to the large number of model parameters and their complex relationships, the evolutionarily stable strategies of the game are discussed below under three typical scenarios.

Scenario 1: When $I_1 + \alpha H - C_2 < 0, R_3 - R_4 - C_4 + C_5 + \beta H < 0, R_5 - R_6 - C_6 + C_7 + \gamma H < 0$. That is, when the basic benefits obtained by the sales-recycling enterprise from secondary recycling cannot cover the recycling costs, the additional benefits for the logistics company from participating in reverse logistics cooperation are less than the input costs, and the time and effort costs for consumers to participate in recycling are higher than the utility brought by environmental improvement. In this case, all three parties lack positive incentives to participate in recycling: the sales-recycling enterprise chooses not to recycle, the logistics company chooses not to cooperate, and consumers choose not to participate. At this point, the eigenvalues of the Jacobian matrix corresponding to equilibrium point $E_1(0,0,0)$ in the table are all negative. Therefore, the system has a unique stable point (0,0,0), and the corresponding evolutionary strategy is (no recycling, no cooperation, no participation).

Scenario 2: When $I_1 + \alpha H - C_2 > 0, R_3 - R_4 - C_4 + C_5 + \beta H < 0, R_5 - R_6 - C_6 + C_7 + \gamma H < 0$. That is, when the sales-recycling enterprise, supported by policy subsidies, brand reputation, etc., obtains a positive net benefit from secondary recycling, but the logistics company's cost of participating in reverse logistics exceeds the cooperation benefits, and consumers' benefits from participating in recycling (without collaborative incentives) cannot cover their participation costs. In this case, the sales-recycling enterprise has the incentive to recycle, but logistics collaboration and consumer participation are difficult to form spontaneously; the enterprise pushes forward recycling efforts unilaterally. At this point, the eigenvalues of the Jacobian matrix corresponding to equilibrium point $E_5(1,0,0)$in the table are all negative. Therefore, the system has a unique stable point (1,0,0), and the corresponding evolutionary strategy is (recycle, no cooperation, no participation).

Scenario 3: When $I_1 + S_1 + 2S_2 + \left(\alpha + \frac{1}{2}\gamma\right)H - C_2 > 0, R_3 - R_4 + S_3 + 2S_4 + \left(\beta + \frac{1}{2}\alpha\right)H - C_4 + C_5 > 0, R_5 - R_6 - C_6 + C_7 + \left(\gamma + \frac{1}{2}\beta\right)H > 0$. That is, when the recycling benefits and subsidies for the sales-recycling enterprise are sufficient to cover its costs, the cooperation benefits for the logistics company from participating in reverse logistics are significantly higher than its additional inputs, and the comprehensive benefits for consumers from participating in recycling (including environmental improvement and incentive returns) are positive. In this case, the three parties form a community of shared interests; the net benefits of collaborative recycling are all positive. The sales-recycling enterprise actively recycles, the logistics company cooperates actively, and consumers participate widely. At this point, the eigenvalues of the Jacobian matrix corresponding to equilibrium point $E_8(1,1,1)$ in the table are all negative. Therefore, the system has a unique stable point (1, 1, 1), and the corresponding evolutionary strategy is (recycle, cooperate, participate). Table 5 summarizes the local stability of each equilibrium point under different benefit-cost scenarios.

Table 5. Local stability of equilibrium points (Scenarios 1, 2, 3)

	Scenario1				Scenario2				Scenario3			
	$\frac{\partial F(x)}{\partial x}$	$\frac{\partial F(y)}{\partial y}$	$\frac{\partial F(z)}{\partial z}$	Stability	$\frac{\partial F(x)}{\partial x}$	$\frac{\partial F(y)}{\partial y}$	$\frac{\partial F(z)}{\partial z}$	Stability	$\frac{\partial F(x)}{\partial x}$	$\frac{\partial F(y)}{\partial y}$	$\frac{\partial F(z)}{\partial z}$	Stability
E_1(0, 0, 0)	-	-	-	ESS	+	-	-	Unstable	+	-	-	Unstable
E_2(0, 0, 1)	-	-	+	Unstable	+	-	+	Unstable	+	-	+	Unstable
E_3(0, 1, 0)	-	+	-	Unstable	+	+	-	Unstable	+	+	-	Unstable
E_4(0, 1, 1)	-	+	+	Unstable	+	+	+	Saddle	+	+	+	Saddle
E_5(1, 0, 0)	+	-	-	Unstable	-	-	-	ESS	-	-	-	Unstable
E_6(1, 0, 1)	+	-	+	Unstable	-	-	+	Unstable	-	-	+	Unstable
E_7(1, 1, 0)	+	+	-	Unstable	-	+	-	Unstable	-	+	-	Unstable
E_8(1, 1, 1)	+	+	+	Saddle	-	+	+	Unstable	-	-	-	ESS

Note: In the table, "Unstable point" is abbreviated as "Unstable", and "Saddle point" is abbreviated as "Saddle".

4. SIMULATION ANALYSIS OF THE TRIPARTITE EVOLUTIONARY GAME

Based on multiple factors involved in the preliminary model parameter settings, such as seasonality and price levels, this section screens products with gift attributes and ultimately selects tea packaging as the specific object of analysis. This product not only lacks obvious seasonal characteristics but also covers both high and medium price ranges, fully reflecting the typical traits of gift-oriented products. Drawing on industry real data, national standards, and relevant policy guidelines, this paper scientifically sets the initial parameters of the tripartite game model consisting of online sales-recycling enterprises, logistics enterprises, and consumers.

Based on real data feedback from the tea industry (Li J L, 2024) [17], the parameters for the online sales-recycling enterprise are set as follows: online tea sales revenue $R_1 = 300$, sales cost $C_1 = 176$; packaging recycling R&D cost $C_2 = 63$, recycling implementation cost $C_3 = 20$, recycling and reuse benefit $R_2 = 45$; platform recycling reward $I_1 = 20$, environmental governance responsibility sharing coefficient $\alpha = 0.5$.

For the logistics enterprise: cooperative reverse logistics cost $C_4 = 40$, non-cooperative opportunity cost $C_5 = 27$, cooperation benefit $R_3 = 50$, non-cooperative potential benefit $R_4 = 16$, environmental governance responsibility sharing coefficient $\beta = 0.3$.

For consumers: time cost of participating in recycling $C_6 = 8$, opportunity cost of not participating $C_7 = 5$, enterprise recycling reward $I_2 = 8$, basic benefit of participating in recycling $R_5 = 20$, benefit of not participating in recycling $R_6 = 0$, environmental governance responsibility sharing coefficient $\gamma = 0.2$.

Regarding common parameters: total government environmental governance cost $H = 40$, average recycling level $Q = 35$, environmental cost of non-recycling $P = 25$, standardized recycling ratio $\varphi = 0.65$, tea price impact factor $\mu = 3$. Meanwhile, the initial willingness to participate of the three parties is set as $x = y = z = 0.5$.

Based on the above analysis and the initial parameter settings, this paper uses MATLAB to conduct numerical simulation of the tripartite evolutionary game model involving the sales-recycling enterprise, the logistics company, and consumers. By setting different initial strategy probabilities, the evolution trajectories of the three parties' strategies are simulated. Subsequently, sensitivity simulations of key parameters are carried out to verify the evolution patterns of the parties' strategies under different scenarios, intuitively presenting the dynamic convergence process of the system and its influencing mechanisms.

4.1. Simulation Analysis Under Varying Initial Probabilities of the Three Parties

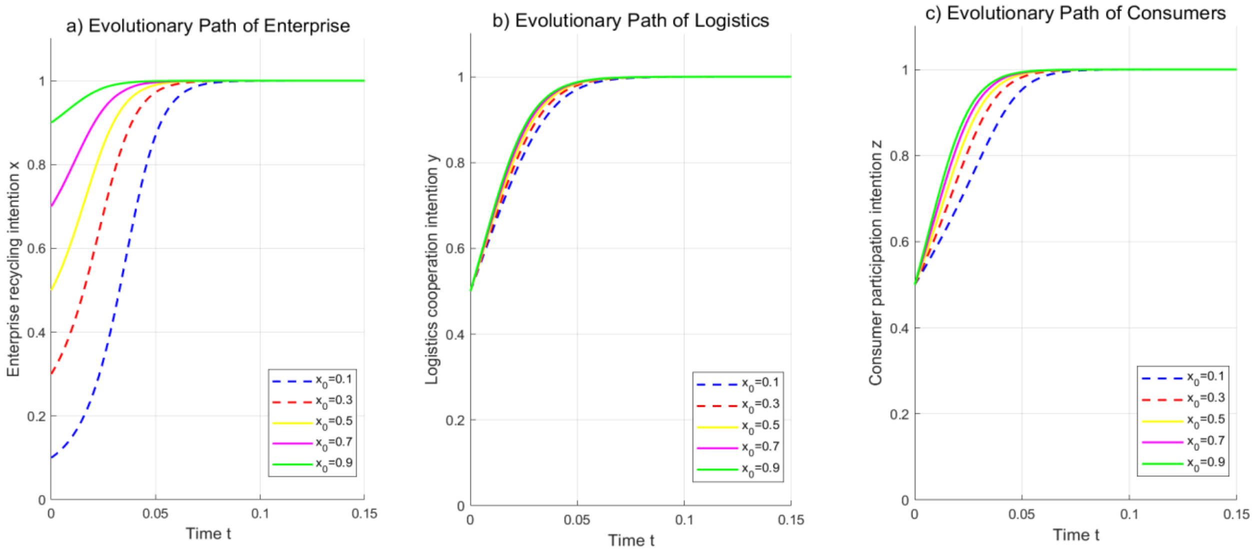

Figure 2. Tripartite evolutionary choices when the initial probability of the sales-recycling enterprise changes

Figure 2 shows the evolutionary paths of the three parties when the initial probability of the sales-recycling enterprise changes. As can be seen from the figure, the enterprise's initial willingness to recycle has the most significant impact on the overall process of tripartite collaborative evolution. When the enterprise's initial participation probability increases from 0.1 to 0.9, all three parties eventually converge to a stable state of active participation, but there are obvious differences in the evolution rates. The convergence speed of the enterprise itself accelerates significantly as its initial participation probability increases; after the initial probability rises from 0.1 to 0.9, the time it takes to reach the stable state is nearly halved. At the same time, the evolution curves of the logistics enterprise and consumers also shift forward synchronously, indicating that the enterprise's willingness to recycle has a strong driving effect. As the initiator of the recycling chain, once the enterprise demonstrates a positive recycling attitude, it can directly reduce the wait-and-see mentality of logistics enterprises and consumers, promoting the entire recycling system to reach a collaborative stable state more quickly. This "leading goose effect" further confirms that, under the current cost and benefit structure, the enterprise is the core driving force of the entire recycling system. Enhancing the enterprise's initial willingness to recycle is a key entry point for promoting tripartite collaborative recycling efforts.

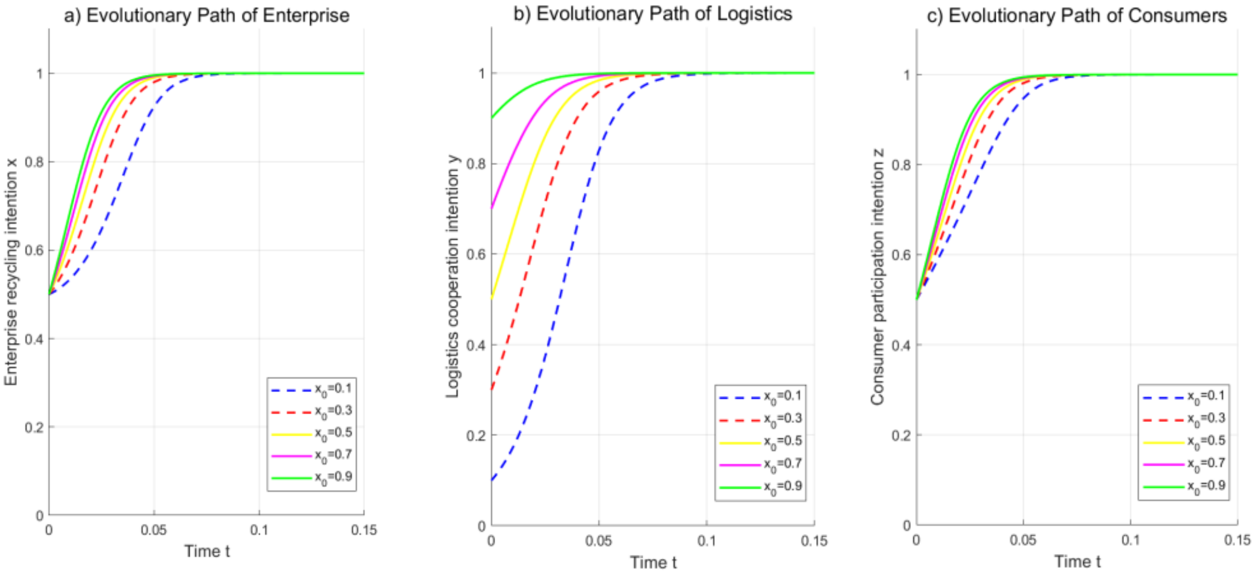

Figure 3. Tripartite evolutionary choices when the initial probability of the logistics enterprise changes

Figure 3 shows the evolutionary paths of the three parties when the initial probability of the logistics enterprise changes. The results indicate that the logistics enterprise's initial willingness to cooperate plays a critical supporting role in the operational efficiency of the entire recycling chain. It can be observed that when the logistics enterprise's initial probability increases from 0.1 to 0.9, all three parties still converge to a state of active participation. However, the evolution curve of the logistics enterprise itself changes most notably: the lower the initial probability, the longer it takes to converge to 1, and the slower the "climbing" phase of the curve. At the same time, the evolution curves of the enterprise and consumers are also affected by the logistics enterprise's initial willingness. When the logistics initial probability is high, the convergence speeds of the enterprise and consumers increase slightly; conversely, a low initial probability slows down the overall pace. This aligns with the actual logic of the recycling chain: logistics serves as the intermediate hub connecting the enterprise and consumers. A low willingness to cooperate in logistics means the recycling channel is not smooth, constraining both the enterprise's recycling efforts and consumer participation. A high willingness in logistics, on the other hand, provides stable support for the entire recycling system, making the tripartite collaborative evolution smoother.

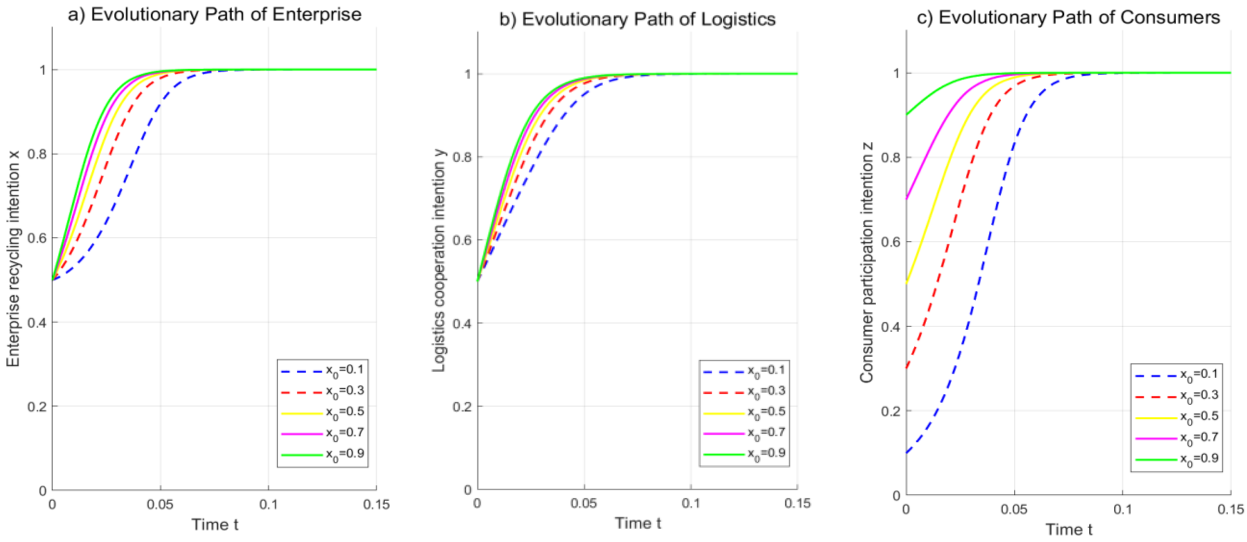

Figure 4. Tripartite evolutionary choices when the initial probability of consumers changes

Figure 4 shows the evolutionary paths of the three parties when the initial probability of consumers changes. The results indicate that consumers' initial willingness to participate mainly affects the "closed-loop efficiency" of the recycling system. It can be observed that when the initial probability of consumers increases from 0.1 to 0.9, all three parties eventually converge to a state of active participation. The evolution curve of consumers themselves accelerates as the initial probability increases, while the curves of the enterprise and logistics also shift slightly forward, but the magnitude of change is less obvious than in the previous two cases. This suggests that consumers' willingness to participate is the foundation of the recycling closed loop, but under the current parameter conditions, the initial willingness of the enterprise and logistics has a stronger impact on the overall evolution. Even if consumers' initial willingness is low, as long as the willingness of the enterprise and logistics is sufficiently positive, consumers can eventually be driven to participate. Conversely, an increase in consumers' initial willingness can significantly shorten the overall time for tripartite collaboration, indicating that higher consumer participation leads to a smoother closed loop of the recycling chain and higher evolutionary efficiency of the entire system.

Through the simulation analysis of the changes in the initial participation probabilities of the sales-recycling enterprise, logistics, and consumers, it can be seen that in the collaborative system of secondary tea packaging recycling, the initial willingness of the three parties has a significant impact on the system's evolutionary path and convergence speed, with clear hierarchical differences in the roles of each party. In summary, the initial willingness of the three parties does not function independently but influences the system's evolution through mutual interaction. To promote the implementation of a secondary tea packaging recycling system, it is necessary to enhance enterprises' recycling incentives while strengthening logistics cooperation support, supplemented by guidance for consumer participation, forming a collaborative pattern of "enterprise-led, logistics-supported, consumer-participated". Only then can the system quickly converge to a stable and active recycling state, truly realizing the circular utilization of tea packaging.

4.2. Tripartite Evolution Results Under Different Parameter Conditions

(1) Scenario 1 — The influence of R2, C2, C3 on the evolutionary path of the sales-recycling enterprise's behavioral decisions

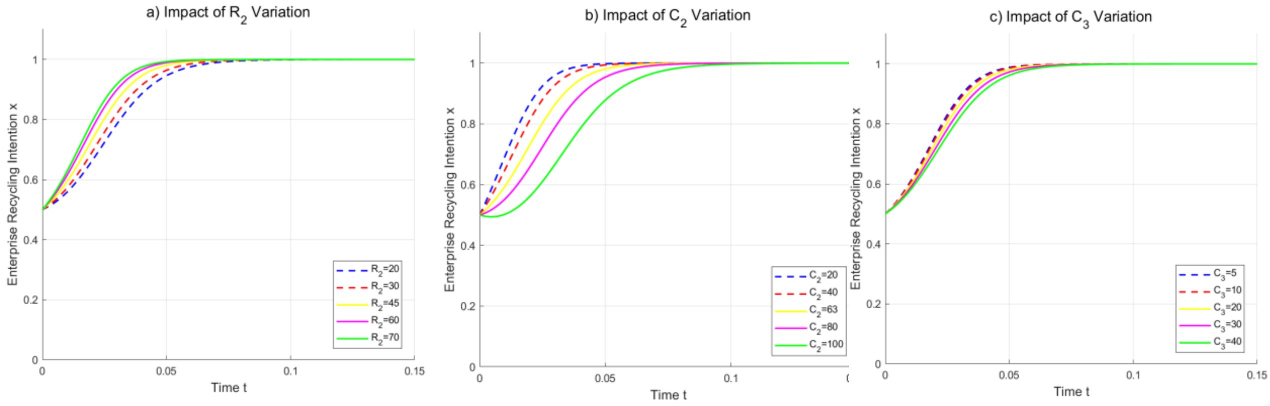

Figure 5. The influence of R2, C2, C3 on the evolutionary path of the sales-recycling enterprise's behavioral decisions

In the context of secondary tea packaging recycling, the cost and benefit factors of enterprises play a significant role in the evolutionary path of their recycling decisions. As shown in the simulation results in Figure 5, the enterprise's recycling and reuse benefit R_2, recycling R&D cost C_2, and operational cost C_3, all significantly affect the convergence rate of the enterprise's strategy. Overall, the pattern is that the higher the benefit and the lower the cost, the stronger the enterprise's willingness to participate in recycling. Specifically, the recycling and reuse benefit R_2 has a clear positive incentive effect on the enterprise's decision. When R_2 increases from 20 to 70, the evolution curve of the enterprise's recycling willingness shifts forward as a whole; the higher the benefit, the faster the enterprise converges to an active recycling strategy. This indicates that the economic benefits brought by tea packaging recycling, such as material regeneration and secondary resale, are the core drivers of the enterprise's participation. An increase in the benefit space can effectively stimulate the enterprise's intrinsic motivation to carry out recycling activities. In contrast, recycling R&D costs and operational costs impose significant negative constraints on the enterprise's decision. When the recycling R&D cost increases from 20 to 100 and the operational cost increases from 5 to 40, the convergence speed of the enterprise's recycling willingness slows down markedly. Particularly when costs are at a high level, even if the enterprise ultimately still chooses the recycling strategy, the evolutionary cycle of its decision is prolonged. This reflects that upfront equipment investment and sorting costs in tea packaging recycling remain important factors restricting enterprise enthusiasm.

(2) Scenario 2 — The influence of S3, S4 on the evolutionary path of the logistics enterprise's behavioral decisions

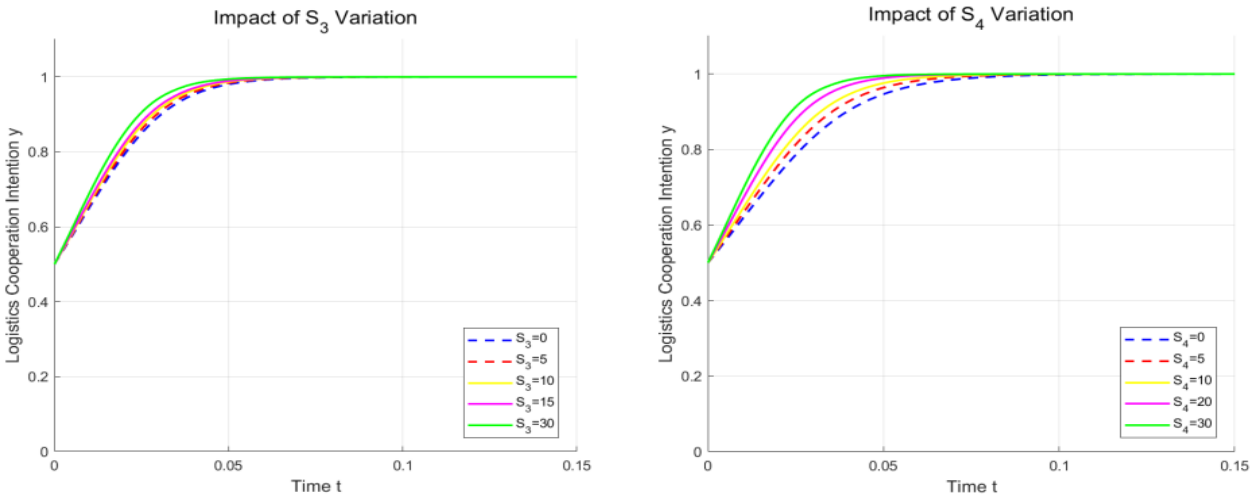

Figure 6. The influence of S3, S4 on the evolutionary path of the logistics enterprise's behavioral decisions

In the secondary tea packaging recycling chain, the logistics enterprise's willingness to participate directly determines the smoothness of the recycling channel. From the simulation results, both the government special subsidy S_3 and the social benefit S_4, from participating in recycling have a significant positive impact on the logistics enterprise's cooperation decision, but their pathways and incentive effects differ. The government special subsidy has a very direct incentive effect on the logistics enterprise. As S_3 increases from 0 to 30, the speed at which the logistics enterprise converges to an active cooperation strategy accelerates significantly, and the entire curve shifts forward. This indicates that special subsidies for the recycling logistics segment can effectively offset the additional costs incurred by enterprises during the sorting and transportation of tea packaging, dispel their wait-and-see attitude, and prompt them to quickly enter a cooperative state. Even at lower subsidy levels, enterprises will ultimately choose to cooperate, but the higher the subsidy, the lower the uncertainty in the decision-making process, and the smoother the evolutionary pace of cooperation willingness.

(3) Scenario 3 — The influence of α, β, γ on the evolutionary paths of the behavioral decisions of the sales-recycling enterprise, logistics enterprise, and consumers respectively

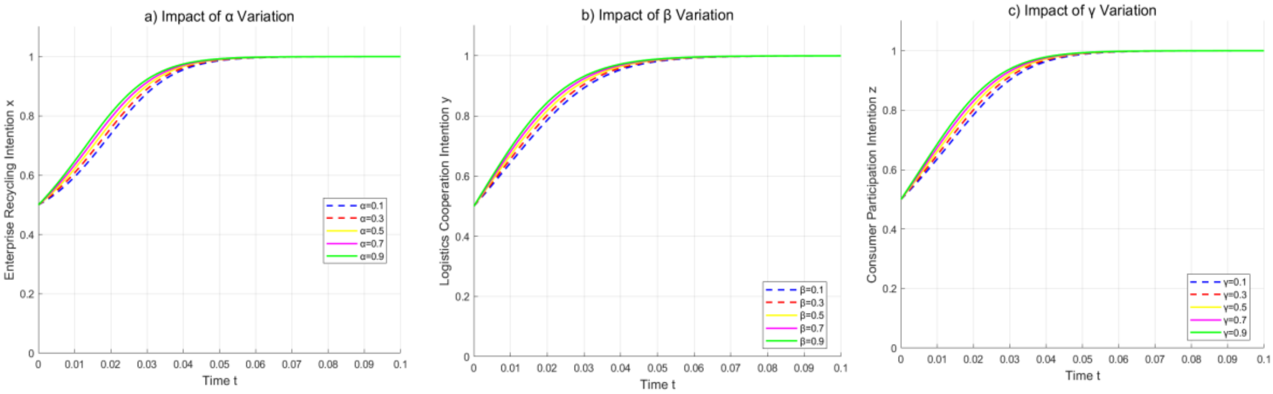

Figure 7. The influence of α, β, γ on the evolutionary paths of the behavioral decisions of the sales-recycling enterprise, logistics enterprise, and consumers respectively

In the tripartite collaborative chain of secondary tea packaging recycling, the sharing ratios of environmental governance costs directly affect the recycling enthusiasm and decision-making pace of each party. Simulation results show that the governance responsibility shares (α, β, γ) of the sales-recycling enterprise, logistics company, and consumers all have a significant positive impact on their respective behavioral evolution paths, and the underlying logic is highly correlated with the characteristics of each party.

For the sales-recycling enterprise, as its governance share α increases from 0.1 to 0.9, the speed of convergence to an active recycling strategy accelerates significantly. This is not a negative constraint of increasing costs, but rather stems from the "responsibility-incentive" linkage mechanism in the model: the higher the enterprise's governance responsibility, the stronger the corresponding government subsidies and policy support. The comprehensive benefits increase markedly, wait-and-see attitudes weaken, and the enterprise stabilizes on the recycling strategy more quickly. The logistics enterprise's willingness to cooperate is similarly positively driven by its governance share β. When β increases from 0.1 to 0.9, the evolution curve of its cooperation strategy shifts forward as a whole, with a clear gradient effect. At low levels of logistics environmental governance responsibility, the willingness to participate rises slowly. As the governance share increases, both special subsidies and social benefit incentives are enhanced, effectively offsetting the additional costs of transportation and sorting, and both cooperation motivation and decision-making pace are significantly improved.

(4) Scenario 4 — The influence of H on the evolutionary paths of the behavioral decisions of the sales-recycling enterprise, logistics enterprise, and consumers

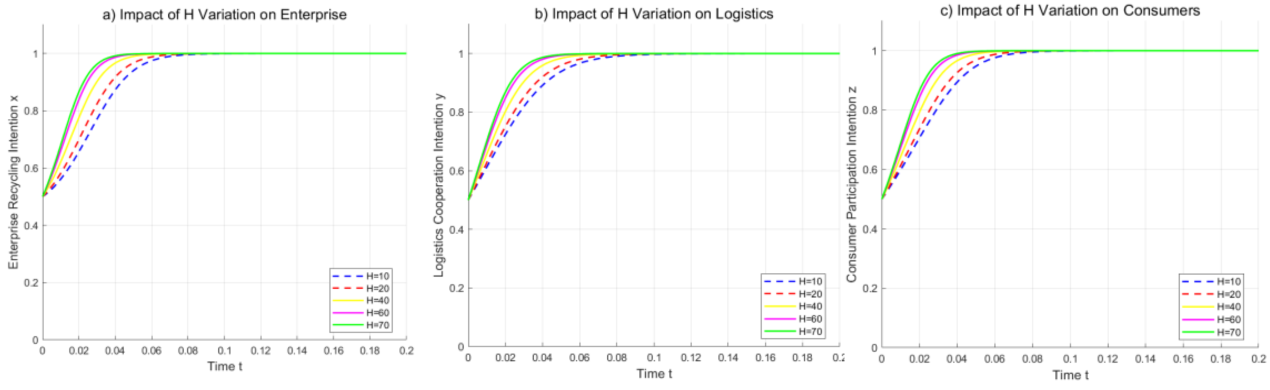

Figure 8. The influence of H on the evolutionary paths of the behavioral decisions of the sales-recycling enterprise, logistics enterprise, and consumers

In the tripartite collaborative system for secondary tea packaging recycling, the government's environmental governance investment H serves as a key lever for activating the participation motivation of enterprises, logistics providers, and consumers. The simulation results show that the level of governance investment significantly affects the evolutionary pace and stability of the three parties' behavioral decisions, with the pathways of influence differing according to the characteristics of each party.

For the salesrecycling enterprise, an increase in government governance investment directly strengthens the positive incentives for the enterprise to participate in recycling. As H increases from 10 to 70, the enterprise's convergence speed to an active recycling strategy accelerates markedly, with the entire curve shifting forward and a clear gradient effect. At a high level of H, the enterprise's wait-and-see attitude weakens, allowing it to stabilise on the recycling strategy more quickly, while low investment prolongs the decision-making cycle and reduces participation willingness.

The logistics enterprise's willingness to cooperate is also directly driven by government governance investment. When H rises from 10 to 70, the slope of its convergence curve towards a cooperative strategy continuously increases: the higher the governance investment, the stronger the motivation to participate in recycling logistics. At low H levels, the logistics enterprise's willingness to participate increases slowly and is accompanied by a waitandsee attitude. As H increases, special subsidies and policy support are simultaneously enhanced, effectively offsetting the cost pressures of transportation and sorting, thereby pushing the enterprise more quickly into a stable cooperative state.

Consumers' willingness to participate is the most sensitive to changes in government governance investment. As H increases, the convergence speed of consumers' willingness to participate in recycling accelerates accordingly, and the differentiation among curves at different investment levels is even more pronounced. When governance investment is low, consumers have a weak perception of the environmental value of tea packaging recycling and lack sufficient motivation to participate. As H increases, the effects of policy advocacy, environmental education, and incentive measures gradually emerge, enabling consumers to more clearly recognise the environmental significance of secondary tea packaging recycling and thus actively participate, forming a collaborative closed loop with the enterprise and logistics.

(5) Scenario 5 — The influence of the recycling benefit coefficient φ on the evolutionary paths of the tripartite behavioral decisions

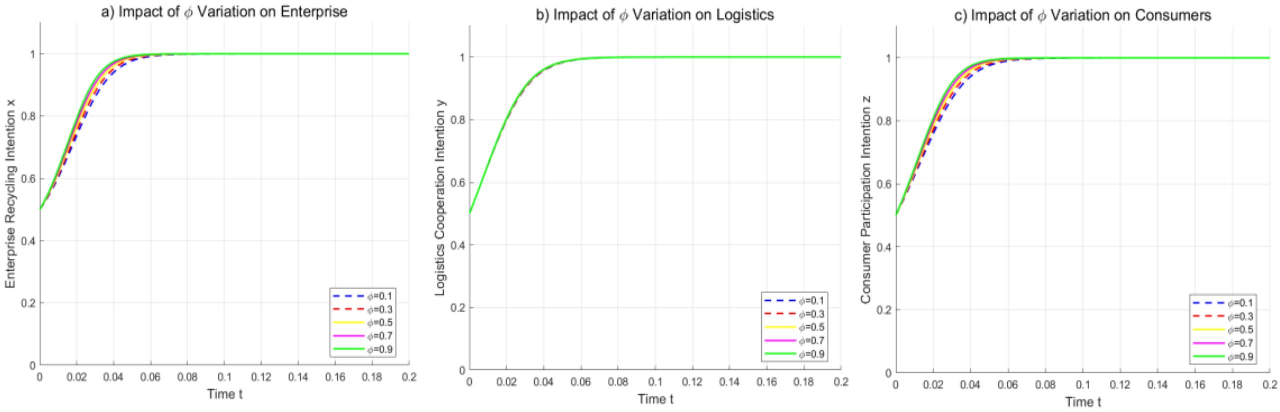

Figure 9. The influence of the recycling benefit coefficient φ on the evolutionary paths of the tripartite behavioral decisions

In the market-driven chain of secondary tea packaging recycling, the recycling benefit coefficient φ directly reflects the resource utilization efficiency of the recycling system and is a key market variable affecting the participation motivation of enterprises, logistics providers, and consumers. The simulation results show that as the recycling benefit coefficient increases, the convergence speed of all three parties toward active strategies exhibits a clear positive change, and the underlying logic is highly correlated with each party's position in the recycling chain.

For the salesrecycling enterprise, an increase in the recycling benefit coefficient directly strengthens the enterprise's intrinsic motivation to participate in tea packaging recycling. As φ increases from 0.1 to 0.9, the entire curve of the enterprise's convergence to an active recycling strategy shifts forward; the higher the benefit coefficient, the smoother the enterprise's decisionmaking pace. This is because a higher recycling benefit coefficient means a higher economic value from tea packaging recycling and reuse. The benefits obtained by the enterprise through recycling can better offset cost pressures, its waitandsee attitude is significantly weakened, and it can stabilise on the recycling strategy more quickly.

The evolution of the logistics enterprise's willingness to cooperate is also positively driven by the recycling benefit coefficient. As φ increases, the speed at which the logistics enterprise converges to a cooperative strategy accelerates correspondingly. Especially at high levels of the benefit coefficient, the rise in the enterprise's cooperation willingness becomes smoother. This is because an increase in the recycling benefit coefficient leads to an expansion of recycling business scale. The costs incurred by logistics enterprises in the transportation and sorting of tea packaging can be diluted through economies of scale. At the same time, the overall value of the recycling chain increases, making enterprises more willing to participate in the collaborative recycling system.

5. CONCLUSION

Under the premise of bounded rationality of the game parties, this paper constructs a tripartite evolutionary game model of collaborative recycling involving sales-recycling enterprises, logistics enterprises, and consumers. It systematically analyzes the decision-making evolution process of these three parties regarding collaborative recycling. Combined with numerical analysis, the strategic behaviors of each party and their influencing factors are examined, leading to the following conclusions:

(1) Sales-recycling enterprises are the most sensitive to changes in government subsidies and recycling returns, making them the key factor driving the system toward synergy. In the online recycling scenario for gift product packaging, enterprises' recycling behavior heavily depends on the balance between recycling costs and the benefits of reuse. When government subsidies and packaging resource recovery benefits can effectively cover the enterprises' operational and technological input costs, enterprises will proactively expand their recycling operations. Conversely, if the benefits are insufficient and cost pressures are too high, enterprises will choose a 'no-recycling' strategy, directly causing the reverse recycling chain to break. Therefore, the government can reduce enterprises' recycling costs through targeted subsidies and support for recycled resources, enabling enterprises to become stable initiators of the online recycling system, thereby driving the collaborative participation of logistics and consumers.

(2) The logistics enterprise's willingness to cooperate is primarily influenced by reverse logistics costs and collaborative benefits, and it serves as the key hub connecting the enterprise and consumers. As the intermediary that transfers packaging from consumers to enterprises, the logistics enterprise's cooperation decision is driven not only by collaborative benefits from the enterprise side but also by government policy incentives for green logistics. When reverse logistics transportation costs are too high and collaborative benefits are unclear, logistics enterprises tend not to cooperate, resulting in inefficient uptake of consumers' recycling demands. When both the enterprise and the government jointly share reverse logistics costs and clearly define the distribution of collaborative benefits, the logistics enterprise's cooperation enthusiasm significantly increases. Therefore, the government and enterprises should jointly introduce special green logistics subsidies to reduce reverse transportation

costs, while also clarifying benefit distribution through long-term cooperation agreements to enhance the stability of logistics enterprise participation.

(3) For consumers, their willingness to participate is influenced by both the convenience of recycling and economic incentives, and exhibits a following effect with respect to the strategy choices of the enterprise and logistics. As the source of recycling behavior, consumers' participation decisions are affected both by the convenience of the recycling process (e.g., online appointment, door-to-door pickup) and by economic incentives such as point exchange and small cashbacks. When enterprise recycling channels are not smooth and logistics cooperation is insufficient, consumers tend not to participate due to high participation costs. Conversely, when the enterprise and logistics provide convenient recycling services collaboratively, supplemented by moderate economic incentives, consumers' willingness to participate increases significantly. Meanwhile, higher consumer participation enhances the collaborative benefits for the enterprise and logistics, forming a virtuous cycle. Therefore, enterprises should cooperate with logistics companies to optimize online recycling processes, simplify consumer participation steps, and at the same time reduce consumer participation costs through methods such as points and rebates, thereby driving the healthy operation of the entire recycling system.

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