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Research article

Exploring the e-waste reverse logistics governance dynamics: A four-party evolutionary game model for green innovation cooperation

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Abstract: In the context of tightening energy constraints and increasing resource security risks, inadequate collaborative governance in reverse logistics networks has become a critical bottleneck constraining the efficiency of urban mining. However, the literature on reverse logistics governance remains largely confined to traditional supply-chain cooperation paradigms, offering limited insight into the synergistic governance mechanisms among the four parties under green innovation cooperation. This study constructs a four-party evolutionary game model involving the government, recycling enterprises, remanufacturing enterprises, and consumers from the perspective of green innovation cooperation. Green innovation spillover effects, subsidy intensity, and product pricing are integrated into a unified evolutionary framework, where system dynamics are examined through replicator dynamics, Jacobian stability analysis, and numerical simulations. The results reveal four distinct stable equilibrium states within the system. Notably, green innovation spillovers exhibit a significant threshold effect, whereby excessive spillovers undermine incentive compatibility constraints and induce opportunistic behavior. Furthermore, government subsidies exhibit stage-dependent incentive effects, with system stability requiring both internal transfer prices and terminal market prices within effective boundaries. The system converges toward an optimal collaborative equilibrium only when government incentives, enterprise cooperation, and consumer support are synergistically enhanced. These findings provide theoretical insights and practical implications for designing optimal reverse logistics policy frameworks and constructing sustainable urban mining development models.

Keywords: reverse logistics; sustainable resource recovery; evolutionary game; green innovation cooperation; collaborative governance; spillover effects
Mathematics Subject Classification: 91A22, 90B06

1. Introduction

As global resource constraints tighten and critical mineral supply chains become increasingly fragile, the supply of primary minerals under traditional economic frameworks falls short of sustaining the demands of strategically vital emerging industries [1]. As a secondary resource that complements conventional primary mineral reserves, e-waste has assumed growing resource value and strategic significance [2]. Consequently, from a resource security perspective, unlocking the regeneration potential of these strategic metals and facilitating their systematic transformation into high-quality secondary resources constitute a core contemporary research agenda for optimizing mineral supply chain resilience [3].

However, the rapid iteration of electronic products and surging global consumption have led to a dramatic increase in e-waste generation. China currently accounts for approximately 20% of global e-waste generation. However, the proportion recovered and treated through formal channels remains relatively low [4]. Such persistently low recovery rates not only result in the severe loss of strategic resources but also generate significant environmental externalities and public health risks through rudimentary disposal practices such as heavy metal release [5,6]. Projections indicate that China's total e-waste generation will exceed 25 million metric tons by 2030 [7]. Therefore, improving the efficiency of e-waste collection, recycling, and recovery is imperative [8].

The efficient operation of reverse logistics networks provides the foundation for a sustainable e-waste recovery system [9]. Nevertheless, China's e-waste reverse logistics networks still face several structural barriers, such as low formal collection rates [10], insufficient green design practices [11], weak consumer environmental awareness [12], and a lack of sustained policy incentives [13]. On the production side, cooperation among enterprises remains largely confined to transactional exchanges and has not yet evolved into strategic partnerships [14]. In a game setting characterized by incomplete information, enterprises tend to adopt minimum-compliance strategies based on rational cost–benefit calculus [15]. On the demand side, limited environmental cognition and low consumer trust remain critical barriers to market transformation [16]. Coupled with the absence of effective coordination and value-sharing across the supply chain, the consumer trust deficit severely restricts downstream market demand in the circular economy [17]. On the policy side, current instruments rely heavily on government funding and lack market-driven mechanisms [18].

As resource and environmental constraints tighten, stakeholders across the network are increasingly shifting toward sustainable resource utilization [19,20]. Among these approaches, green innovation cooperation is widely regarded as a crucial pathway for improving circular efficiency and driving the synergistic reduction of pollution and carbon emissions [21]. Green innovation cooperation refers to collaborative research and development (R&D) and the application of green technologies among different entities, facilitated by technology-sharing, complementary advantages, and the sharing of development costs and risks [22]. On the supply side, green innovation encompasses core technologies such as energy conservation and emission reduction, pollution prevention, and green design [23], and is inherently characterized by capital intensity, substantial risk, and strong positive externalities [24]. Consequently, a single actor acting in isolation often struggles to surmount technological bottlenecks and market penetration barriers [25]. This inevitably drives firms to shift from isolated innovation to collaborative innovation paradigms. However, the substantial sunk costs and the lack of robust risk-sharing mechanisms create endogenous obstacles that hinder enterprises from engaging in deep collaboration [26].

On the demand side, capturing the value of green innovation cooperation is impeded by trust deficits and preference heterogeneity. Specifically, faced with information asymmetry regarding product quality, consumers harbor considerable skepticism about the green attributes and reliability of remanufactured products [16]. Under the dual constraints of ambiguous quality perceptions and price sensitivity, market demand becomes endogenously fragile, which substantially undermines the intrinsic incentives of enterprises to pursue deep cooperation [27,28]. Moreover, although the government can reshape enterprise incentive structures and consumer preferences through instruments such as subsidies, regulation, and public advocacy [29], excessive reliance on exogenous incentives (e.g., fiscal subsidies) readily induces strategic opportunistic behavior amid tightening fiscal constraints [25]. Therefore, breaking out of this low-level strategic equilibrium and reconstructing a collaborative governance mechanism for green innovation cooperation are critical to addressing the current predicament.

Although the resource value of e-waste has been increasingly recognized, relatively limited attention has been paid to multi-agent strategic interactions within reverse logistics networks in the context of green innovation cooperation. Accordingly, this study primarily aims to construct a four-party evolutionary game model involving e-waste recycling enterprises, remanufacturing enterprises, government authorities, and consumers. The model is utilized to elucidate the evolutionary trajectories and stability conditions of multi-agent collaborative governance within a green innovation framework and to examine the interactions between policy instruments and market forces. Consequently, this study provides a theoretical foundation and practical implications for optimizing urban-mining resource-recovery systems and improving circularity efficiency. The main issues addressed in this study are as follows:

(1) How can the payoff matrix of the four parties in the green innovation cooperation mechanism be constructed?

(2) How do multi-agent strategic interactions converge toward an evolutionarily stable strategy (ESS), and what conditions and driving factors govern its formation?

(3) How do key parameters such as green-innovation spillover effects, subsidy intensity, and product pricing shape the evolutionary trajectories and systemic stability among multiple stakeholders?

2. Literature review

In the governance of e-waste reverse logistics, the strategic interplay between regulatory intervention and firm behavior constitutes a central issue in institutional design [30]. Government regulation is generally regarded as an important institutional instrument for addressing uncertainty risks in secondary resource markets [31]. Esenduran et al. (2017) [32] developed a remanufacturing competition model involving recyclers and original equipment manufacturers, and analyzed the impact of government-mandated recycling targets on the recycling industry. Zhang et al. [33] demonstrated that differentiated reward–penalty mechanisms not only encourage technology investment among manufacturers but also strengthen incentives for firms to maintain cooperative relationships. Wang and

Huo [34] further noted that regulatory constraints alone are insufficient to fully offset the cost spillover risks inherent in corporate green innovation cooperation. Consequently, subsequent studies have increasingly shifted focus toward external incentive instruments, such as subsidies, taxation, rewards, and penalties. Liu et al. [35] concluded that excessively high subsidies and taxes can lead to resource misallocation and policy dependence, thereby weakening the environmental performance of the recycling system. However, existing studies have largely focused on how regulatory policies affect individual recycling entities, while insufficient attention has been paid to the interdependent effects of governmental decision-making on the behavioral choices of multiple stakeholder groups.

Consumer acceptance of remanufactured products constitutes a key demand-side variable that determines the closed-loop efficiency of reverse logistics systems [36]. Chen et al. [37] argued that green product premiums can convey proactive commitments to environmental protection and green investment by firms to the market, thereby enhancing consumer recognition of and preference for such products. Furthermore, Pretner et al. [38] found that greater transparency and comprehensiveness of green product information significantly enhance consumer willingness to engage in green purchasing. Building on this foundation, some studies have begun to incorporate consumer behavior into multi-agent interaction frameworks. Zhao et al. [39] found that sharing part of subsidy benefits with consumers enables remanufacturing firms to effectively expand the market size of green products, thereby promoting consumer engagement in remanufactured product consumption. However, relatively few studies have examined consumers as independent game participants or analyzed their strategic adjustment mechanisms and their effects on the closed-loop operation of reverse logistics systems.

In response to the limitations of external incentives, scholarly attention has gradually shifted toward internal coordination on the supply side. Deep inter-firm collaboration constitutes an essential foundation for green innovation [40]. However, if the recycling and remanufacturing stages remain disconnected, overall system performance may still be constrained despite substantial demand-side potential [41]. Zhao and Bai [42] noted that corporate green innovation collaborations often exhibit shallow characteristics driven by policy dependence and profit motives. Zhang et al. [43] compared the dynamic evolutionary patterns of innovative manufacturers and incumbent manufacturers in green innovation cooperation. Schøtt and Jensen [44] examined how collaborative practices enhance green innovation performance in supply chains. Yan et al. [29] combined game-theoretic analysis with numerical simulations and further proposed that green innovation subsidies constitute an effective instrument for improving supply-chain profitability. However, the stability of green innovation cooperation depends heavily on the fairness of benefit allocation and the controllability of technological spillovers [45–47]. Wang et al. [48] constructed a two-stage evolutionary game model to investigate the potential spillover effects on incentive mechanisms for reliability investments during the cooperation process between manufacturers and suppliers. Nevertheless, existing studies on inter-firm collaboration remain largely grounded in the transactional logic of traditional supply chains, with insufficient attention paid to the bidirectional nature of technological spillovers, the triggering mechanisms of opportunistic behavior, and the endogenous effects of fairness in benefit allocation within green innovation cooperation.

Regarding complex system optimization and uncertainty analysis, the existing literature has developed a relatively rich methodological framework [49]. Uncertainty in supply-chain networks has been widely examined in fields such as agriculture [50], blood supply [51], and biodiesel [52], and has given rise to diverse analytical approaches for improving supply chain resilience, including fuzzy regression [53], stochastic control [54,55], and game-theoretic models [56,57]. In addition, mixed-integer linear programming models [58,59], four-objective optimization frameworks [60], and hybrid combinatorial algorithms [61] have offered important methodological foundations for multi-objective decision-making under complex uncertainty [62]. However, in reverse logistics networks, participating stakeholders are often constrained by bounded rationality rather than fully rational decision-making. Evolutionary game theory is therefore particularly suitable for this context, as it captures strategic adjustment, behavioral learning, and the formation of dynamic equilibria among heterogeneous stakeholders [63]. Accordingly, recent studies have begun to apply evolutionary game theory to examine the dynamic strategy choices of participants in reverse logistics systems [64,65].

To more accurately capture multi-stakeholder interactions in reverse logistics systems, recent studies have increasingly incorporated multiple stakeholders into evolutionary game frameworks. Kang et al. [66] developed a two-tier supply chain model involving retailers and manufacturers, and used evolutionary game theory to examine how government policy shapes firm behavior. Ma et al. [67] constructed a bilateral evolutionary game model between e-waste remanufacturers and e-commerce platforms. Their results showed that controlling green innovation costs enables firms to sustain their innovation activities. Wang et al. [68] developed a tripartite evolutionary game model to examine the interaction between consumer green preferences and policy incentives. The results showed that these two factors are significantly coupled and jointly determine the equilibrium states and evolutionary trajectories of the system. Guo et al. [69] established a tripartite evolutionary game model involving the government, manufacturers, and consumers, and found that increasing consumer subsidies can strengthen green demand and encourage manufacturers to increase investment in green technologies. Gao and Chen [70] developed a multi-agent coordination model for electronic waste recycling involving local governments, producers, and consumers. Their results showed that stronger linkages between reward–penalty mechanisms and the strategies of participating agents make the system more stable. Existing studies have largely examined dyadic or triadic interactions among governments, recyclers, remanufacturers, and consumers in recycling networks. However, omitting any key stakeholder may obscure the interdependent mechanisms among these actors and underestimate the extent to which multi-stakeholder coordination failures undermine recycling network resilience.

In summary, existing studies have provided an important theoretical foundation for the governance of e-waste reverse logistics, yet several limitations remain. Most existing models remain confined to dyadic or triadic frameworks, leaving the strategic adjustment mechanisms of boundedly rational firms insufficiently explained in the context of green innovation cooperation, especially when government incentives and consumer support jointly shape strategic choices. Against this backdrop, this study makes three main contributions.

First, this study extends the scope of actors considered in conventional dyadic and triadic models by integrating recycling enterprises, remanufacturing enterprises, the government, and consumers into a unified analytical framework.

Second, this study integrates opportunistic behavior, stakeholder-differentiated subsidies, and remanufactured product pricing into an incentive-compatible constraint framework, thereby revealing how policy incentives, inter-firm coordination, market feedback, and cooperation stability are coupled with green innovation cooperation.

Finally, the findings offer theoretical and policy implications for optimizing collaborative governance mechanisms in e-waste reverse logistics, refining stage-specific policy design, and improving the circular utilization of urban mineral resources.

3. Construction of evolutionary game model

3.1. Problem description

The reverse logistics network for e-waste encompasses the entire process through which consumers transfer discarded electronic products to formal recycling channels; recycling enterprises undertake collection, inspection, classification, and preliminary screening; and remanufacturing enterprises carry out disassembly, remanufacturing, and resource recovery. The green innovation cooperation strategy refers to a dynamic collaborative process through which recycling enterprises and remanufacturing enterprises, jointly shaped by government incentives and market demand, optimally coordinate activities related to the collection, classification, identification, disassembly, utilization, technology-sharing, and value realization of e-waste. Recycling and remanufacturing enterprises constitute the core participants in green innovation cooperation. Throughout the cooperative process, both parties jointly allocate tangible and intangible resources, including technology, operational facilities, data assets, and managerial inputs, thereby promoting technological upgrading and facilitating the optimal transformation of innovative outcomes into practical value.

In practice, green innovation cooperation often involves substantial heterogeneity between recycling enterprises and remanufacturing enterprises in terms of input intensity, risk exposure, and resource endowments. Such heterogeneity tends to give rise to imbalances in the distribution of cooperative payoffs. Moreover, the two parties develop a complex relationship of asymmetric interdependence: recycling enterprises depend on remanufacturing enterprises for product distribution channels, technical support, and sales conversion, whereas remanufacturing enterprises rely on recycling enterprises for raw material sourcing, quality sorting, and stable supply. This mismatch in dependence intensity directly gives rise to disparities in bargaining power and divergences in benefit claims, thereby exposing cooperative contracts to endogenous instability. In addition, information asymmetry and bounded rationality make it difficult for recycling enterprises and remanufacturing enterprises to fully assess the actual inputs, contract performance, and technological contributions of partner firms, thereby potentially inducing innovation spillover risks and opportunistic behavior. Particularly during the stage of deep cooperation, when binding contractual constraints remain weak, one party may continue to appropriate and exploit previously shared outcomes after deviating from the cooperative agreement or after the cooperative relationship breaks down, thereby converting innovation spillovers into opportunistic gains. Correspondingly, the compliant party not only loses the original synergistic benefits but also bears coordination costs associated with reconstructing cooperative relationships, searching for alternative partners, realigning operational processes, and adjusting production plans [46].

At the regulatory level, the government acts as an external regulator and intervenes in market operations through policy instruments such as fiscal subsidies and green advocacy initiatives, aiming to steer corporate green transformation and cultivate environmental preferences among consumers. Given that the government seeks to balance fiscal constraints with environmental governance, the model specifies its objective function as maximizing aggregate utility, incorporating both reputational benefits and green performance outcomes [47]. On the demand side, consumers make purchase decisions based on an aggregate utility assessment that incorporates cost-effectiveness, functional attributes, and green preferences [71]. The model further incorporates the perceived value gap relative to original products and green opportunity loss to characterize substitution behavior among consumers across different mental accounts. As a core signal of terminal market feedback, consumer demand directly regulates incentives for innovation among enterprises: demand expansion generates positive feedback for capacity expansion and R&D investment, whereas a lack of trust or weak environmental awareness gives rise to market impediments [72].

In summary, under the assumption of bounded rationality, the government, recycling enterprises, remanufacturing enterprises, and consumers continuously update their strategies based on their respective cost-benefit structures, environmental performance, and social utility. The strategic interactions among these actors, described by replicator dynamic equations, jointly shape the co-evolutionary trajectory of the system and determine its operational efficiency as it evolves toward an optimal equilibrium. The specific game relationships among the four parties are illustrated in Figure 1.

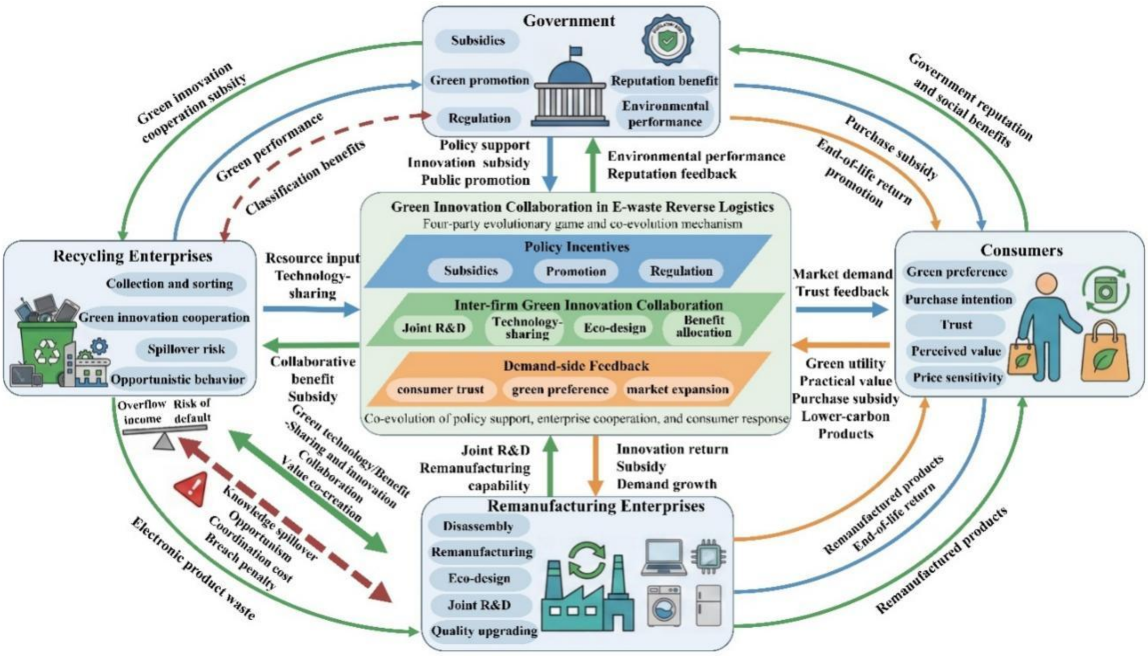

Figure 1. Game relationships among the four parties in the reverse logistics network.

3.2. Basic assumptions of parameters

Based on the preceding theoretical reasoning and review of the relevant literature, this study proposes the following model assumptions. The corresponding variables and their definitions are reported in Table 1.

Assumption 1. When recycling enterprises and remanufacturing enterprises establish green innovation cooperation, they jointly bear the green innovation cost (C_A), of which a proportion (φ) is borne by recycling enterprises and the remaining proportion (1-φ) is borne by remanufacturing enterprises. We denote the cooperative synergy by H_A and allocate it between the two parties according to the sharing ratio θ, where the allocation ratios φ and θ satisfy φ, $\theta \in [0,1]$, thereby ensuring the boundedness and feasibility of the model parameters. Given the asymmetry between the partners in resource control and related dimensions, the dependence intensity of recycling enterprises and remanufacturing enterprises, denoted by L_H and L_Z, respectively, captures the extent to which one party relies on the other in areas such as raw material supply and sales conversion. During the cooperative process, when one party deviates from the cooperative agreement or causes the cooperation to break down, the defaulting party no longer continues to fulfill its cooperative obligations but may still appropriate opportunistic gains, denoted by P_H or P_Z, by exploiting technological knowledge, customer resources, and other assets acquired during the earlier stage of cooperation. Meanwhile, the defaulting party is required to bear a contractual breach penalty M, which is treated as a net cost to the defaulting party and as breach compensation received by the non-defaulting party. This penalty is enforced through the inter-firm cooperation agreement and remains applicable even when the government does not provide supportive policies. Correspondingly, the compliant party bears coordination costs, denoted by K_H or K_Z, such as those associated with adjustments to production plans.

Assumption 2. Under bounded rationality, f denotes the probability that the government adopts a supportive strategy through adaptive adjustment. When the government adopts a supportive strategy, it incurs publicity cost C_F and provides subsidies to the recycling side, the remanufacturing side, and the consumer side, denoted by B_H, B_Z, and B_C, respectively. In this case, government utility consists of environmental performance gains P_F and social reputation or public credibility gains H_F. When the government adopts a non-supportive strategy, it incurs no fiscal expenditure. However, if enterprises still engage in green innovation cooperation voluntarily, the government, as the representative of the public interest, continues to obtain environmental performance gains P_F with positive externalities.

Assumption 3. When consumers adopt a supportive strategy, reflecting their overall support for remanufactured products and circular consumption patterns, they pay the price (V_Z) and obtain product practical value (H_C). If enterprises implement green innovation under this condition, consumers further obtain additional green utility (P_C). In addition, consumers' supportive behavior generates a market expansion effect, causing the demand for recycled and remanufactured products to increase by α and β, respectively, relative to their baseline levels. If consumers adopt a non-supportive strategy, they forgo the purchase, and the market size of enterprises remains at its baseline level (Q_H, Q_Z). In this case, V_H denotes the negative psychological utility consumers experience from abandoning green purchases and enters the utility function of the non-supportive strategy as a negative term.

Table 1. Definitions of variables and parameters.

Parameter symbol	Parameter meaning	Parameter symbol	Parameter meaning
H	E-waste recycling enterprises	Z	E-waste remanufacturing enterprises
F	Government	G	Consumers
C_H	Unit product processing cost for a recycling enterprise	i	Probability of recycling enterprises choosing green innovation cooperation
C_Z	Unit product processing cost for a remanufacturing enterprise	j	Probability of remanufacturing enterprises choosing green innovation cooperation
C_F	Government promotion cost	g	Probability of consumers supporting remanufactured products
C_A	Unit product input cost for green innovation cooperation	f	Probability of government support
V_X	The price at which recycling enterprises sell products to remanufacturing enterprises	L_H	Degree of dependency of recycling enterprises on remanufacturing enterprises

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Parameter symbol	Parameter meaning	Parameter symbol	Parameter meaning
P_F	Green performance resulting from green innovation cooperation	LZ	Degree of dependency of remanufacturing enterprises on recycling enterprises
P_H	Opportunistic gains for recycling enterprises	M	Penalty for breach of contract
P_Z	Opportunistic gains for the remanufacturing enterprise	θ	Allocation ratio of green innovation cooperation results to recycling enterprises
P_C	Green benefits brought to consumers by innovation cooperation	φ	Cost-sharing ratio borne by recycling enterprises
H_F	Government reputation and social benefits	K_H	Coordination cost invested by recycling enterprises
H_C	Practical value obtained by consumers from remanufactured products	K_Z	Coordination cost invested by remanufacturing enterprises
H_A	Revenue from the outcomes of green innovation cooperation	B_H	Subsidy for recycling enterprises engaging in green innovation cooperation
B_Z	Subsidy for remanufacturing enterprises engaging in green innovation cooperation	B_C	Consumer purchase subsidy
Q_H	Actual sales volume of recycled enterprise products	Q_Z	Actual sales volume of remanufacturing enterprise products
V_H	Consumer green opportunity loss	V_Z	Unit market price of remanufactured electronic products
α	Growth rate of the recycling enterprise in product quantity	β	Growth rate of the remanufacturing enterprise in product quantity

3.3. Construction of payoff matrix

Based on the study hypotheses, the logic of strategic choice, and the core benefit claims of the four stakeholders in the e-waste reverse logistics network, the payoff matrix of the four-party game is constructed, as shown in Table 2.

Table 2. Payoff matrix of the four-party evolutionary game.

			Consumer			
			Support (g)		Do not support (1-g)	
	Government	Remanufacturing enterprises	Provide support (f)	Do not support (1-f)	Provide support (f)	Do not support (1-f)
Recycling enterprises	Engage in innovation cooperation (i)	Engage in innovation cooperation (j)	$\{(1+\alpha)(V_X-C_H+\theta H_A-\varphi C_A)Q_H+B_H,(1+\beta)[V_Z-V_X-C_Z+(1-\theta)H_A-(1-\varphi)C_A]Q_Z+B_Z,H_F+P_F-C_F-B_H-B_Z-B_C,H_C+P_C+C_F+B_C-V_Z\}$	$\{(1+\alpha)(V_X-C_H+\theta H_A-\varphi C_A)Q_H,(1+\beta)[V_Z-V_X-C_Z+(1-\theta)H_A-(1-\varphi)C_A]Q_Z,P_F,H_C+P_C-V_Z\}$	$\{(V_X-C_H+\theta H_A-\varphi C_A)Q_H+B_H,[V_Z-V_X-C_Z+(1-\theta)H_A-(1-\varphi)C_A]Q_Z+B_Z,H_F+P_F-C_F-B_H-B_Z,P_C+C_F-V_H\}$	$\{(V_X-C_H+\theta H_A-\varphi C_A)Q_H,[V_Z-V_X-C_Z+(1-\theta)H_A-(1-\varphi)C_A]Q_Z,P_F,P_C-V_H\}$
		No innovation cooperation (1-j)	$\{(1+\alpha)(V_X-C_H-K_H+M)Q_H+B_H,(1+\beta)(1-L_Z)(V_Z-V_X-C_Z-M+P_Z)Q_Z,H_F-C_F-B_H-B_C,H_C+C_F+B_C-V_Z\}$	$\{(1+\alpha)(V_X-C_H-K_H+M)Q_H,(1+\beta)(1-L_Z)(V_Z-V_X-C_Z-M)Q_Z,0,H_C-V_Z\}$	$\{(V_X-C_H-K_H+M)Q_H+B_H,(1-L_Z)(V_Z-V_X-C_Z-M+P_Z)Q_Z,H_F-C_F-B_H,C_F-V_H\}$	$\{(V_X-C_H-K_H+M)Q_H,(1-L_Z)(V_Z-V_X-C_Z-M+P_Z)Q_Z,0,-V_H\}$

Continued on next page

			Consumer			
			Support (g)		Do not support (1-g)	
	Government	Remanufacturing enterprises	Provide support (f)	Do not support (1-f)	Provide support (f)	Do not support (1-f)
Recycling enterprises	No innovation cooperation (1-i)	Engage in innovation cooperation (j)	$\{(1+\alpha)(1-L_H)(V_X-C_H-M+P_H)Q_H,(1+\beta)(V_Z-V_X-C_Z-K_Z+M)Q_Z+B_Z,H_F-C_F-B_Z-B_C,H_C+C_F+B_C-V_Z\}$	$\{(1+\alpha)(1-L_H)(V_X-C_H-M+P_H)Q_H,(1+\beta)(V_Z-V_X-C_Z-K_Z+M)Q_Z,0,H_C-V_Z\}$	$\{(1-L_H)(V_X-C_H-M+P_H)Q_H,(V_Z-V_X-C_Z-K_Z+M)Q_Z+B_Z,H_F-C_F-B_Z,C_F-V_H\}$	$\{(1-L_H)(V_X-C_H-M+P_H)Q_H,(V_Z-V_X-C_Z-K_Z+M)Q_Z,0,-V_H\}$
		No innovation cooperation (1-j)	$\{(1+\alpha)(V_X-C_H)Q_H,(1+\beta)(V_Z-V_X-C_Z)Q_Z,H_F-C_F,H_C+C_F-V_Z\}$	$\{(1+\alpha)(V_X-C_H)Q_H,(1+\beta)(V_Z-V_X-C_Z)Q_Z,0,H_C-V_Z\}$	$\{(V_X-C_H)Q_H,(V_Z-V_X-C_Z)Q_Z,H_F-C_F,C_F-V_H\}$	$\{(V_X-C_H)Q_H,(V_Z-V_X-C_Z)Q_Z,0,-V_H\}$

4. Solution and analysis of evolutionary game models

4.1. Stability analysis of the recycling enterprise strategy

Let U_i denote the expected payoff of an e-waste recycling enterprise when it adopts the green innovation cooperation strategy and let $U_{1\text{-}i}$ denote its expected payoff when it does not. The average expected payoff is denoted by $\bar{U}_I$. The corresponding expressions are given in equations (1)–(3).

$$U_i=(1+g\alpha)(V_X-C_H-K_H+M)Q_H+jQ_H(1+g\alpha)(K_H+\theta K_H-\varphi C_A-M)+fB_H \tag{1}$$

$$U_{1\text{-}i}=(1+g\alpha)Q_H(V_X-C_H)+jQ_H(1+ga)(L_HM-M-L_HP_H+P_H-L_HV_X+L_HC_H) \tag{2}$$

$$\bar{U}_I=iU_i+(1-i)\ U_{1\text{-}i} \tag{3}$$

The replicator dynamic equation for the strategy selection of recycling enterprises is equation (4):

$$\begin{aligned}F(i)&=\frac{di}{dt}=i(U_i-\bar{U}_I)\\&=i(1-i)\{(1+g\alpha)Q_H[(-K_H+M)+j(\theta H_A-\varphi C_A+K_H-P_H+L_HV_X-L_HC_H+L_HP_H-L_HM)]+fB_H\}\end{aligned} \tag{4}$$

According to the stability theorem for differential equations, the strategy of recycling enterprises is stable only when the following conditions are satisfied: F(i) = 0 and F′ (i) < 0.

Theorem 1. When $j>j^*$, $f>f^*$, and $g>g^*$, recycling enterprises will evolve toward cooperative green innovation as their evolutionarily stable strategy. Conversely, when $j<j^*$, $f<f^*$, and $g<g^*$, non-cooperation emerges as the dominant strategy. At the critical point where $j=j^*$, $f=f^*$, and $g=g^*$, the evolutionarily stable strategy is indeterminate.

Equations (5), (6), and (7) denote the decision probability threshold values for remanufacturing enterprises, governments, and consumers, respectively.

$$j^*=\frac{(1+g\alpha)Q_H(K_H-M)-fB_H}{(1+g\alpha)Q_H(\theta H_A-\varphi C_A+K_H-P_H+L_HV_X-L_HC_H+L_HP_H-L_HM)} \tag{5}$$

$$f^*=\frac{-B_H}{(1+g\alpha)Q_H(-K_H+M)+j(1+g\alpha)(\theta H_A-\varphi C_A+K_H-P_H+L_HV_X-L_HC_H+L_HP_H-L_HM)Q_H} \tag{6}$$

$$g^*=\frac{-fB_H - Q_H[(-K_H+M)+j(\theta H_A-\varphi C_A+K_H-P_H+L_HV_X-L_HC_H+L_HP_H-L_HM)]}{\alpha Q_H[(-K_H+M)+j(\theta H_A-\varphi C_A+K_H-P_H+L_HV_X-L_HC_H+L_HP_H-L_HM)]} \quad (7)$$

Solving the replicator dynamic equation yields the critical thresholds g_1 and g_2 for recycling enterprises. When $j^* = 1$, the threshold is given by $g_1=\frac{fB_H-Q_H(K_H-M)}{\alpha Q_H(K_H-M)}$. When $j^* = 0$, the threshold is given by $g_2=-\frac{Q_H(\theta H_A-\varphi C_A+P_H+L_HV_X-L_HC_H+L_HP_H-L_HM+M)+fB_H}{\alpha Q_H(\theta H_A-\varphi C_A+P_H+L_HV_X-L_HC_H+L_HP_H-L_HM+M)}$. Based on the above stability analysis and the practical range of decision probabilities, the strategy-selection phase diagram of e-waste recycling enterprises is shown in Figure 2(a).

The probabilities of recycling enterprises engaging in green innovation cooperation and not engaging in green innovation cooperation are i_1 and i_2, with volumes of V_{i1} and V_{i2}, respectively, and $R_1=\theta H_A-\varphi C_A+K_H+P_H+L_HV_X-L_HC_H+L_HP_H-L_HM$ as shown in equations (8) and (9):

$$V_{i1}=\int_0^1\int_{g_2}^{g_1} j^*\,dgdi+\int_0^1\int_0^{g_2} dgdi=\frac{1}{R_1}[(K_H-M)(g_1-g2)-\frac{fB_H}{\alpha Q_H}\ln(\frac{1+\alpha g_1}{1+\alpha g_2})]+g_2 \quad (8)$$

$$V_{i2}=1-V_{i1}=1-\frac{1}{R_1}[(K_H-M)(g_1-g2)-\frac{fB_H}{\alpha Q_H}\ln(\frac{1+\alpha g_1}{1+\alpha g_2})]+g_2 \quad (9)$$

Corollary 1. When other parameters are held constant and government subsidies remain within the effective incentive range, an increase in government subsidies or the penalty for breach (M) raises the probability of recycling enterprises choosing green innovation cooperation, whereas an increase in the coordination cost (K_H) reduces this probability.

4.2. Stability analysis of remanufacturing enterprise strategy

The expected payoff of remanufacturing enterprises under the innovation cooperation strategy is denoted by U_j, the expected payoff for not choosing this strategy is $U_{1\text{-}j}$, and the average expected payoff is set as $\bar{U}_J$. The expressions are (10) –(12).

$$U_j=(1+g\beta)Q_Z(V_Z-V_X-C_Z-K_Z+M)+i(1+g\beta)Q_Z[(1\text{-}\theta)H_A-(1-\varphi)C_A+K_Z-M]+fB_Z \quad (10)$$

$$U_{1\text{-}j}=(1+g\beta)Q_Z(V_Z-V_X-C_Z)+i(1+g\beta)Q_Z(-L_ZV_Z+L_ZV_X+L_ZC_Z+L_ZM-L_ZP_Z-M+P_Z) \quad (11)$$

$$\bar{U}_J=jU_j+(1\text{-}j)\,U_{1\text{-}j} \quad (12)$$

The replicator dynamic equation for strategy selection in remanufacturing enterprises is equation (13):

$$\begin{aligned}F(j)&=\frac{dj}{dt}=j(U_j-\bar{U}_J)\\&=j(1\text{-}j)\{(1+g\beta)Q_Z(-K_Z+M)+i(1+g\beta)Q_Z[(1-\theta)H_A-(1-\varphi)C_A+L_Z(V_Z-V_X-C_Z+P_Z-M)+K_Z-P_Z]+fB_Z\}\end{aligned} \quad (13)$$

Theorem 2. When $i > i^*$, $f > f^*$, and $g > g^*$, remanufacturing enterprises tend to adopt cooperative green innovation as their evolutionarily stable strategy. When $i < i^*$, $f < f^*$, and $g < g^*$, remanufacturing enterprises tend not to engage in cooperative green innovation. When $i = i^*$, $f = f^*$, and $g = g^*$, the evolutionarily stable strategy cannot be determined. Equations (14), (15), and (16) denote the decision probability threshold values for recycling enterprises, governments, and consumers, respectively.

$$i^* = \frac{(1+g\beta)Q_Z(K_Z - M) - fB_Z}{(1+g\beta)Q_Z[(1\text{-}\theta)H_A - (1-\varphi)C_A + L_Z(V_Z - V_X - C_Z + P_Z - M) + K_Z - P_Z]} \tag{14}$$

$$f^* = \frac{(1+g\beta)Q_Z(K_Z - M) - i(1+g\beta)Q_Z[(1\text{-}\theta)H_A - (1-\varphi)C_A + L_Z(V_Z - V_X - C_Z + P_Z - M) + K_Z - P_Z]}{B_Z} \tag{15}$$

$$g^* = \frac{-fB_Z - Q_Z(-K_Z + M) - iQ_Z[(1\text{-}\theta)H_A - (1-\varphi)C_A + L_Z(V_Z - V_X - C_Z + P_Z - M) + K_Z - P_Z]}{\beta Q_Z(-K_Z + M) + i\beta Q_Z[(1\text{-}\theta)H_A - (1-\varphi)C_A + L_Z(V_Z - V_X - C_Z + P_Z - M) + K_Z - P_Z]} \tag{16}$$

Solving the replicator dynamic equation yields the critical thresholds f_1 and f_2 for remanufacturing enterprises. When $i^* = 1$, the threshold is given by $f_1 = \frac{(1+g\beta)Q_Z(-K_Z + M)}{B_Z}$. When $i^* = 0$, the threshold is given by $f_2 = \frac{(1+g\beta)Q_Z[(1\text{-}\theta)H_A - (1-\varphi)C_A + L_Z(V_X - V_Z + C_Z + P_Z - M) + M - P_Z]}{B_Z}$. Based on the above stability analysis and the practical range of decision probabilities, the strategy-selection phase diagram of e-waste remanufacturing enterprises is shown in Figure 2(b).

Let j_1 and j_2 denote the probabilities that remanufacturing enterprises choose and do not choose green innovation cooperation, respectively. The corresponding phase-space volumes are represented by V_{j1} and V_{j2}. Furthermore, let $R_2 = (1+g\beta)Q_Z[(1\text{-}\theta)H_A - (1-\varphi)C_A + L_Z(V_Z - V_X - C_Z + P_Z - M) + K_Z - P_Z]$. The phase-space volumes associated with the two strategic choices can then be derived and are given in equations (17) and (18).

$$V_{j1} = \int_0^1 \int_{f_2}^{f_1} i^* df dj + \int_0^1 \int_0^{f_2} df dj = \frac{f_1 - f_2}{R_2}[R_2 - \frac{B_Z}{2}(f_1 + f_2)] \tag{17}$$

$$V_{j2} = 1 - V_{j1} = 1 - \frac{f_1 - f_2}{R_2}[R_2 - \frac{B_Z}{2}(f_1 + f_2)] \tag{18}$$

Corollary 2. Ceteris paribus, the likelihood that remanufacturing enterprises engage in green innovation cooperation increases with government subsidies (B_Z) and the penalty for breach (M), but decreases with the coordination cost (K_Z).

4.3. Analysis of government strategy stability

Let U_f denote the expected payoff of the government under the supportive strategy, $U_{1\text{-}f}$ denote the expected payoff under the non-supportive strategy, and $\overline{U_F}$ denote the average payoff. The corresponding expressions are given in equations (19), (20), and (21), respectively.

$$U_f = H_F + ijP_F - C_F - iB_H - jB_Z - (ig + jg - ijg)B_C \tag{19}$$

$$U_{1-f} = ijP_F \tag{20}$$

$$\bar{U}_F = fU_f + (1-f)U_{1-f} \quad (21)$$

The replicator dynamic equation for government strategy selection is equation (22):

$$F(f) = \frac{df}{dt} = f(U_f - \bar{U}_F) = f(1-f)[H_F - C_F - iB_H - jB_Z - (ig + jg - ijg)B_C] \quad (22)$$

Theorem 3. When $i > i^*$, $j > j^*$, and $g > g^*$, the government tends to provide support for green innovation cooperation as its evolutionarily stable strategy. When $i < i^*$, $j < j^*$, and $g < g^*$, the government tends not to support green innovation cooperation. When $i = i^*$, $j = j^*$, and $g = g^*$, the evolutionarily stable strategy cannot be determined. Equations (23), (24), and (25) denote the decision probability threshold values for recycling enterprises, remanufacturing enterprises, and consumers, respectively.

$$i^* = \frac{H_F - C_F - jB_Z - jgB_C}{B_H + gB_C - jgB_C} \quad (23)$$

$$j^* = \frac{H_F - C_F - iB_H - igB_C}{B_Z + gB_C - igB_C} \quad (24)$$

$$g^* = \frac{H_F - C_F - iB_H - jB_Z}{(i + j - ij)B_C} \quad (25)$$

Solving the replicator dynamic equation yields the critical thresholds g_1 and g_2 for governments. When $i^* = 1$, the threshold is given by $g_2 = \frac{H_F - C_F - jB_Z - B_H}{B_C}$. When $i^* = 0$, the threshold is given by $g_1 = \frac{H_F - C_F - jB_Z}{jB_C}$. Based on the above stability analysis and the practical range of decision probabilities, the strategy-selection phase diagram of governments is shown in Figure 2(c).

Let f_1 and f_2 denote the probabilities that the government adopts supportive and non-supportive strategies toward green innovation cooperation among enterprises, respectively. The corresponding phase-space volumes, denoted by V_{f1} and V_{f2}, are given in equations (26) and (27).

$$\begin{aligned} V_{f1} &= \int_0^1 \int_{g_2}^{g_1} i^* \, dg df + \int_0^1 \int_0^{g_2} dg df \\ &= \frac{1-j}{2} g_1 + \frac{1+j}{2} g_2 - \frac{B_H}{2B_C} + \frac{(H_F - C_F + B_Z - B_H) + j(H_F - C_F - B_Z)}{2B_C} \ln\left(\frac{B_H + g_1 B_C (1-j)}{B_H + g_2 B_C (1-j)}\right) \end{aligned} \quad (26)$$

$$V_{f2} = 1 - V_{f1} = 1 - \frac{1-j}{2} g_1 + \frac{1+j}{2} g_2 - \frac{B_H}{2B_C} + \frac{(H_F - C_F + B_Z - B_H) + j(H_F - C_F - B_Z)}{2B_C} \ln\left(\frac{B_H + g_1 B_C (1-j)}{B_H + g_2 B_C (1-j)}\right) \quad (27)$$

Corollary 3. Ceteris paribus, the likelihood that the government supports green innovation cooperation among enterprises decreases with subsidy expenditures (B_H, B_Z) but increases with the reputational and social benefits obtained by the government (H_F).

4.4. Stability analysis of the consumer strategy

Assuming the expected payoff for consumers who choose to support remanufactured products is denoted as U_g, the expected payoff for those who do not is denoted as $U_{1\text{-}g}$, and the average expected payoff is denoted as $\bar{U}_G$. The corresponding expressions are presented in equations (28), (29), and (30), respectively.

$$U_g = H_C + ijP_C + fC_F + ifB_C + jfB_C - ijfB_C - V_Z \tag{28}$$

$$U_{1-g} = ijP_C + fC_F - V_H \tag{29}$$

$$\bar{U}_G = gU_g + (1-g)U_{1\text{-}g} = gH_C + ijP_C + fC_F + g(V_H - V_Z) - V_H + igfB_C + jg\text{f}B_C - ij\text{f}gB_C \tag{30}$$

The replicator dynamic equation for consumer strategy selection is equation (31):

$$F(g) = \frac{dg}{dt} = g(U_g - \bar{U}_G) = g(1-g)(H_C + ifB_C + jfB_C - ijfB_C + V_H - V_Z) \tag{31}$$

Theorem 4. When $i > i^*$, $j > j^*$, and $f > f^*$, consumers tend to purchase remanufactured products as their evolutionarily stable strategy. When $i < i^*$, $j < j^*$, and $f < f^*$, consumers tend not to purchase remanufactured products. When $i = i^*$, $j = j^*$, and $f = f^*$, the evolutionarily stable strategy cannot be determined. Equations (32), (33), and (34) denote the decision probability threshold values for recycling enterprises, remanufacturing enterprises, and the government, respectively.

$$i^* = \frac{V_Z - H_C - V_H - jfB_C}{fB_C(1\text{-}j)} \tag{32}$$

$$j^* = \frac{V_Z - H_C - V_H - ifB_C}{fB_C(1\text{-}i)} \tag{33}$$

$$f^* = \frac{V_Z - H_C - V_H}{B_C(i + j - ij)} \tag{34}$$

Solving the replicator dynamic equation yields the critical thresholds f_1 and f_2 for consumers. When $j^* = 1$, the threshold is given by $f_1 = \frac{V_Z - H_C - V_H}{B_C}$. When $j^* = 0$, the threshold is given by $f_2 = \frac{V_Z - H_C - V_H}{iB_C}$. Based on the above stability analysis and the practical range of decision probabilities, the strategy-selection phase diagram of consumers is shown in Figure 2(d).

The probabilities of consumers choosing to support versus not support remanufactured products are denoted as g_1 and g_2, with the corresponding volumes denoted as V_{g1} and V_{g2}, respectively. These relationships are formalized in equations (35) and (36).

$$V_{g1} = \int_0^1 \int_{j_2}^{j_1} j^* \, df dg + \int_0^1 \int_0^{j_2} df dg = \frac{V_Z - H_C - V_H}{B_C(1-i)} \ln\left(\frac{j_1}{j_2}\right) - \frac{i(j_1 - j_2)}{1-i} + j_2 \tag{35}$$

$$V_{g2} = 1\text{-}V_{g1} = 1 - \frac{V_Z - H_C - V_H}{B_C(1-i)} \ln\left(\frac{j_1}{j_2}\right) - \frac{i(j_1 - j_2)}{1-i} - j_2 \tag{36}$$

Corollary 4. The probability that consumers support remanufactured products is positively associated with their practical application value and green opportunity loss (V_H), and negatively associated with their market price (V_Z).

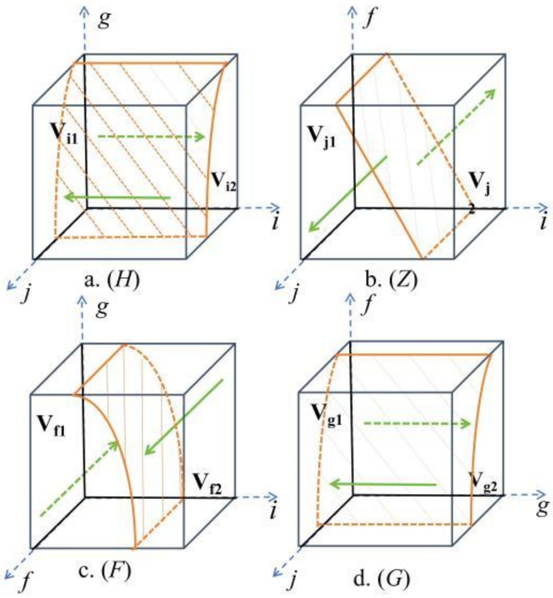


Figure 2. Strategy evolution phase diagrams of the four parties.

4.5. Stability analysis of strategy combination

Within the framework of multi-agent collaborative governance, Lyapunov's first method is adopted to determine the stability of the strategy profiles of all game participants [73]. Accordingly, the Jacobian matrix of the four-party evolutionary game is derived, as shown in equation (37). By evaluating the Jacobian matrix at each candidate equilibrium point, the specific expressions of its entries are obtained and reported in Table 3.

$$J=\begin{pmatrix} \frac{\partial F(i)}{\partial i} & \frac{\partial F(i)}{\partial j} & \frac{\partial F(i)}{\partial \mathrm{f}} & \frac{\partial F(i)}{\partial g} \\ \frac{\partial F(j)}{\partial i} & \frac{\partial F(j)}{\partial j} & \frac{\partial F(j)}{\partial \mathrm{f}} & \frac{\partial F(j)}{\partial g} \\ \frac{\partial F(\mathrm{f})}{\partial i} & \frac{\partial F(\mathrm{f})}{\partial j} & \frac{\partial F(\mathrm{f})}{\partial \mathrm{f}} & \frac{\partial F(\mathrm{f})}{\partial g} \\ \frac{\partial F(g)}{\partial i} & \frac{\partial F(g)}{\partial j} & \frac{\partial F(g)}{\partial \mathrm{f}} & \frac{\partial F(g)}{\partial g} \end{pmatrix}=\begin{pmatrix} a_{11}a_{12}a_{13}a_{14} \\ a_{21}a_{22}a_{23}a_{24} \\ a_{31}a_{32}a_{33}a_{34} \\ a_{41}a_{42}a_{43}a_{44} \end{pmatrix} \tag{37}$$

Table 3. Expressions of the Jacobian matrix.

Parameter	Expression
a_{11}	$(1-2i)\{(1+g\alpha)Q_H[(-K_H+M)+j(\theta H_A-\varphi C_A+K_H-P_H+L_HV_X-L_HC_H+L_HP_H-L_HM)]+fB_H\}$
a_{12}	$i(1\text{-}i)(1+g\alpha)Q_H(\theta H_A-\varphi C_A+K_H-P_H+L_HV_X-L_HC_H+L_HP_H-L_HM)$
a_{13}	$i(1\text{-}i)B_H$
a_{14}	$i(1\text{-}i)\alpha Q_H[(-K_H+M)+j(\theta H_A-\varphi C_A+K_H-P_H+L_HV_X-L_HC_H+L_HP_H-L_HM)]$
a_{21}	$j(1\text{-}j)(1+g\beta)Q_Z[(1-\theta)H_A-(1-\varphi)C_A+L_Z(V_Z-V_X-C_Z+P_Z-M)+K_Z-P_Z]$
a_{22}	$(1-2j)\{(1+g\beta)Q_Z(-K_Z+M)+i(1+g\beta)Q_Z[(1-\theta)H_A-(1-\varphi)C_A+L_Z(V_Z-V_X-C_Z+P_Z-M)+K_Z-P_Z]+fB_Z\}$
a_{23}	$j(1-j)B_Z$
a_{24}	$j(1-j)\beta Q_Z\{(M-K_Z)+i[(1-\theta)H_A-(1-\varphi)C_A+L_Z(V_Z-V_X-C_Z+P_Z-M)+K_Z-P_Z]\}$
a_{31}	$f(1-f)(-B_H-gB_C+jgB_C)$
a_{32}	$f(1-f)(-B_Z-gB_C+igB_C)$
a_{33}	$(1\text{-}2f)[H_F-C_F-iB_H-jB_Z-(ig+jg-ijg)B_C]$
a_{34}	$f(1-f)(-iB_C-jB_C+ijB_C)$
a_{41}	$g(1-g)(1-j)fB_C$
a_{42}	$g(1-g)(1-i)fB_C$
a_{43}	$g(1-g)(i+j-ij)B_C$
a_{44}	$(1\text{-}2g)(H_C+ifB_C+jfB_C-ijfB_C+V_H-V_Z)$

According to this stability criterion, an equilibrium is asymptotically stable and can be identified as an ESS if all eigenvalues of the corresponding Jacobian matrix have negative real parts. If at least one eigenvalue (λ) has a positive real part, the equilibrium is unstable and therefore cannot be regarded as an ESS. If all nonzero eigenvalues (λ) have negative real parts while one or more eigenvalues are equal to zero, the stability of the equilibrium cannot be determined directly using this criterion. The pure strategy solution of the four-party evolutionary game is shown in Table 4.

Table 4. Stability analysis of the pure strategy solution of the four-party evolutionary game.

Number	Equilibrium point	Jacobian matrix eigenvalues	Eigenvalue signs	Stability
1	(0, 0, 0, 0)	$(M-K_H)Q_H,(M-K_Z)Q_Z,H_F-C_F,H_C+V_H-V_Z$	+, +, #, #	instability
2	(0, 0, 0, 1)	$(1+\alpha)(M-K_H)Q_H,(1+\beta)(M-K_Z)Q_Z,H_F-C_F,V_Z-H_C-V_H$	+, +, #, #	instability
3	(0, 0, 1, 0)	$(M-K_H)Q_H+B_H,(M-K_Z)Q_Z+B_Z,C_F-H_F,H_C+V_H-V_Z$	+, +, #, #	instability
4	(0, 1, 0, 0)	$(L_HV_X-L_HC_H+L_HP_H-L_HM-P_H+\theta H_A-\varphi C_A+M)Q_H$, $(K_Z-M)Q_Z,H_F-C_F-B_Z,H_C+V_H-V_Z$	+, -, #, #	instability
5	(1, 0, 0, 0)	$(K_H-M)Q_H,Q_Z[(1-\theta)H_A-(1-\varphi)C_A+L_Z(V_Z-V_X-C_Z+P_Z-M)+M-P_Z]$, $H_F-C_F-B_H,H_C+V_H-V_Z$	-, +, #, #	instability
6	(0, 0, 1, 1)	$(1+\alpha)(M-K_H)Q_H+B_H,(1+\beta)(M-K_Z)Q_Z+B_Z,C_F-H_F,V_Z-H_C-V_H$	+, +, #, #	instability
7	(0, 1, 0, 1)	$(1+\alpha)Q_H[\theta H_A-\varphi C_A+M-P_H+L_H(V_X-C_H+M+P_H)]$, $(1+\beta)(K_Z-M)Q_Z,H_F-C_F-B_H-B_Z,V_Z-H_C-X_H$	+, -, #, #	instability

Continued on next page

Number	Equilibrium point	Jacobian matrix eigenvalues	Positive and negative	Stability
8	(1, 0, 0, 1)	$(1+\alpha)(K_H-M)Q_H,(1+\beta)Q_Z[M-P_Z+(1-\theta)H_A-(1-\varphi)C_A$ $+L_Z(V_Z-V_X-C_Z+P_Z-M)],H_F-C_F-B_H-B_C,V_Z-H_C-V_H$	-, +, #, #	instability
9	(0, 1, 1, 0)	$Q_H[\theta H_A-\varphi C_A+L_H(V_X-C_H+P_H-M)-P_H+M]+B_H,$ $(K_Z-M)Q_Z-B_Z,C_F-H_F+B_Z,B_C+V_H-V_Z+H_C$	+, -, #, #	instability
10	(1, 0, 1, 0)	$(K_H-M)Q_H-B_H,Q_Z[(1-\theta)H_A-(1-\varphi)C_A+M-P_Z$ $+L_Z(V_X-V_Z-C_Z+P_Z-M)]+B_Z$ $C_F-H_F+B_H,H_C+V_H-V_Z$	-, +, #, #	instability
11	(1, 1, 0, 0)	$Q_H[-\theta H_A+\varphi C_A-M+P_H+L_H(-V_X+C_A+C_H-P_H+M)],$ $Q_Z[-(1-\theta)H_A+(1-\varphi)C_A-M+P_Z+L_Z(V_X-V_Z+C_Z-P_Z+M)],$ $H_F-C_F-B_H-B_Z,H_C+V_H-V_Z$	-, -, #, #	ESS under condition ①
12	(0, 1, 1, 1)	$(1+\alpha)Q_H[\theta H_A-\varphi C_A+M-P_H+L_H(V_X-C_H+P_H-M)]+B_H,$ $(1+\beta)Q_Z(K_Z-M)-B_Z,C_F-H_F+B_Z+B_C,V_Z-H_C-B_C-V_H$	+, -, #, #	instability
13	(1, 0, 1, 1)	$(1+\alpha)(K_H-M)Q_H-B_H,$ $(1+\beta)Q_Z[(1-\theta)H_A-(1-\varphi)C_A+M-P_Z+L_Z(V_Z-V_X-C_Z+P_Z-M)]$ $+B_Z,C_F-H_F+B_H+B_C,V_Z-H_C-B_C-V_H$	-, +, #, #	instability
14	(1, 1, 0, 1)	$(1+\alpha)Q_H[-\theta H_A+\varphi C_A-M+P_H-K_H+L_H(-V_X+C_H-P_H+M)],$ $(1+\beta)Q_Z[-(1-\theta)H_A+(1-\varphi)C_A-M+P_Z+L_Z(V_X-V_Z+C_Z-P_Z+M)],$ $H_F-C_F-B_H-B_Z-B_C,V_Z-H_C-V_H$	-, -, #, #	ESS under condition ②
15	(1, 1, 1, 0)	$Q_H[-L_HV_X+L_HC_H-L_HP_H+L_HM-M+P_H-\theta H_A+\varphi C_A]-B_H,$ $Q_Z[P_Z-M-(1-\theta)H_A+(1-\varphi)C_A+L_Z(V_X-V_Z+C_Z-P_Z+M)]-B_Z,$ $C_F-H_F+B_Z+B_H,H_C+V_H-V_Z+B_C$	-, -, #, #	ESS under condition ③
16	(1, 1, 1, 1)	$(1+\alpha)Q_H(-\theta H_A+\varphi C_A-M+P_H+L_H(-V_X+C_H-P_H+M)-B_H,$ $(1+\beta)Q_Z[-(1-\theta)H_A+(1-\varphi)C_A-M+P_Z+L_Z(V_X-V_Z+C_Z-P_Z+M)]-B_Z,$ $C_F-H_F+B_H+B_Z+B_C,V_Z-H_C-V_H-B_C$	-, -, #, #	ESS under condition ④

#: Parameter-dependent eigenvalue before imposing the corresponding stability condition.

Condition ①: $H_F-C_F-B_H-B_Z\le 0,H_C+V_H-V_Z\le 0$;

Condition ②: $H_F-C_F-B_H-B_Z-B_C\le 0,V_Z-H_C-V_H\le 0$;

Condition ③: $C_F-H_F+B_H+B_Z\le 0,H_C+V_H-V_Z+B_C\le 0$;

Condition ④: $C_F-H_F+B_H+B_Z+B_C\le 0,V_Z-H_C-V_H-B_C\le 0$.

Because Conditions ①–④ are difficult to satisfy simultaneously, the system converges to only one type of ESS under a given single-parameter setting, thereby providing a theoretical basis for the subsequent local analysis of a unique equilibrium state. The results further identify four potential types of ESSs.

5. Results and analysis

5.1. Explanation of parameter settings

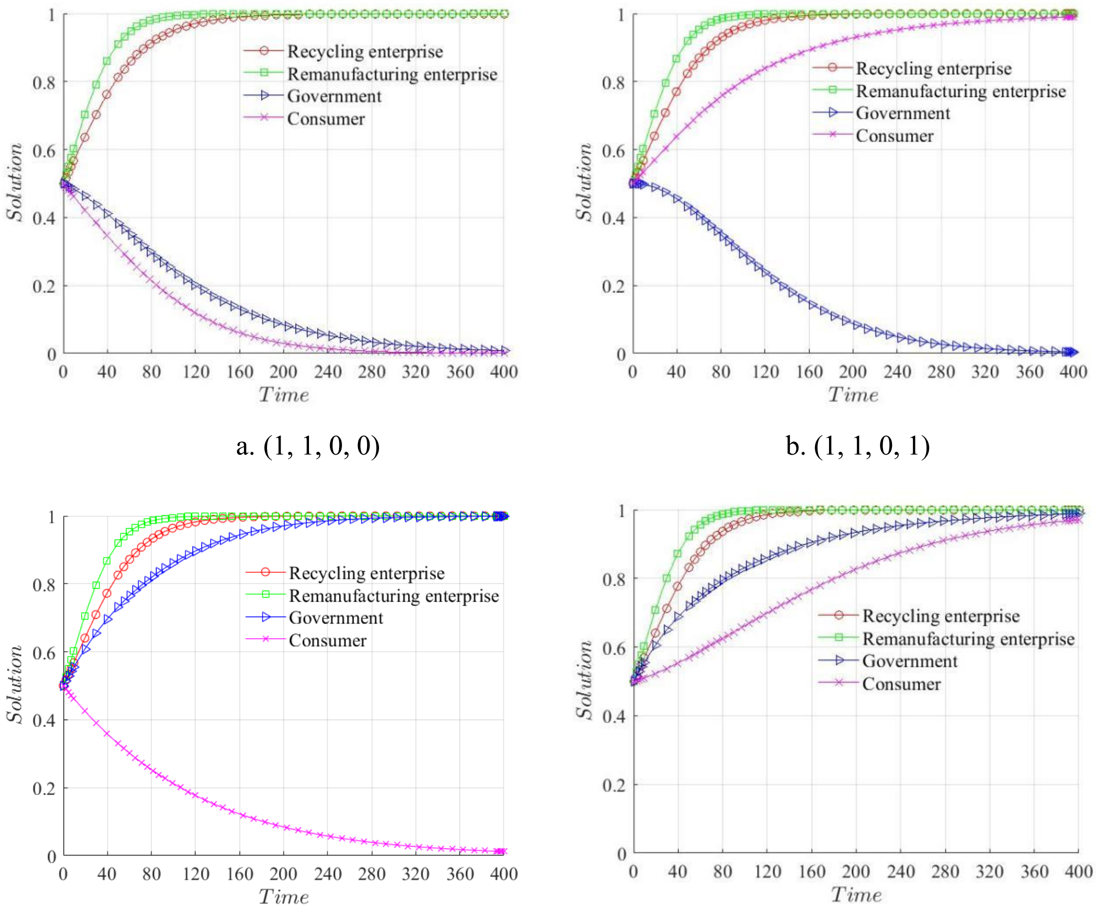
To examine the evolutionary characteristics of the strategic choices of the four parties under different constraints, this study conducts numerical simulations and performs sensitivity analysis on the key parameters affecting the stability of the evolutionary game model. The initial probabilities of participation in the green innovation cooperation mechanism are set to i, j, f, g = (0.5, 0.5, 0.5, 0.5) for recycling enterprises, remanufacturing enterprises, the government, and consumers, respectively. In the simulation results, time is plotted on the horizontal axis, and the proportion of agents adopting the cooperative strategy is plotted on the vertical axis, thereby illustrating the evolutionary trajectory of agent strategies over time and their associated stability properties.

To ensure the consistency of parameter calibration, this study adopts a single waste mobile phone as the baseline analytical unit, and all parameters are derived through a hierarchical mapping from industry-level statistics to unit-level representations. Cost-related parameters are calibrated based on the *China Recycling Resources Recovery Industry Development Report (2025)* [7] and empirical data from recycling and remanufacturing enterprises, resulting in $C_H = 800$ yuan/unit, $C_Z = 400$ yuan/unit, and $C_A = 300$ yuan/unit. The structural and behavioral parameters of the model are assigned based on second-hand mobile phone transaction data, enterprise financial data, and the actual industry interdependence documented in the *2024 China Second-hand E-commerce Market Data Report* [74]. Specifically, $H_A = 500$ yuan/unit is converted based on the 20%–25% collaborative value-added space corresponding to the average transaction price of a second-hand mobile phone. $\theta = 55\%$ and $\varphi = 45\%$ are set according to the allocation of cooperative outcomes in practical cooperation cases. $P_H = 200$ yuan/unit, $P_Z = 150$ yuan/unit are calculated based on 20% of the normal per-unit profit margin of enterprises. $L_H = 70\%$ and $L_Z = 60\%$ are determined with reference to the product circulation and resource dependence proportions of the two parties. $K_H = 100$ yuan/unit and $K_Z = 80$ yuan/unit correspond to 50%–60% of the opportunistic gains. $M = 250$ yuan/unit is set with reference to industry fund subsidy standards and the requirement for effective breach deterrence. This value is approximately 1.4 times the average opportunistic gain of the two parties.

Revenue- and market-related parameters are determined based on publicly available transaction data from second-hand mobile-phone trading platforms (e.g., Zhuanzhuan and Aihuishou) and consumer behavior survey data, yielding $V_X = 1000$ yuan/unit, $H_C = 1500$ yuan/unit, $V_Z = 2000$ yuan/unit, $V_H = 300$ yuan/unit, and $P_C = 300$ yuan/unit. Scale and proportion parameters are set according to industry recycling capacity statistics and standard modeling assumptions, resulting in $Q_H = 10000$ units, $Q_Z = 10000$ units, $\alpha = 30\%$, and $\beta = 20\%$. Policy-related parameters are calibrated based on the *Administrative Measures for the Collection and Use of the Waste Electrical and Electronic Equipment Treatment Fund*, which specify standardized subsidy and penalty mechanisms for WEEE recycling systems in China, leading to $C_F = 20$ yuan/unit, $B_H = 100$ yuan/unit, $B_Z = 100$ yuan/unit, $B_C = 100$ yuan/unit, $P_F = 200$ yuan/unit, and $H_F = 400$ yuan/unit.

5.2. Possible ESS point evolution path analysis

This study employs numerical simulation to perform grouped adjustments of key parameters, including H_F, V_X, and V_H, while holding all other parameters constant. The parameter settings are specified as follows: for the ESS (1,1,0,0), the initial values are set to $H_F = 100$, $V_X = 1000$, and $V_H = 200$; for the ESS (1, 1, 0, 1), they are set to $H_F = 160$, $V_H = 600$ and $V_X = 1000$; for the ESS (1, 1, 1, 0), they are set to $H_F = 400$, $V_X = 1000$, and $V_H = 300$; and for the ESS (1, 1, 1, 1), they are set to $H_F = 500$, $V_X = 1200$, and $V_H = 600$. Figure 3 illustrates the evolutionary trajectories of system strategies under these scenarios.



a. (1, 1, 0, 0) b. (1, 1, 0, 1)

c. (1, 1, 1, 0) d. (1, 1, 1, 1)

Figure 3. Evolution paths at different equilibrium points.

When Condition ① is satisfied, recycling and remanufacturing enterprises generate strong endogenous momentum for cooperation through knowledge-sharing and resource complementarity. As a result, their probabilities of cooperation rise rapidly during the early stage of the simulation and subsequently stabilize at a high level, as shown in Figure 3(a). However, the persistent absence of government intervention and consumer participation creates a vacuum of external incentives and a demand-side bottleneck. Consequently, the system ultimately converges to a self-organized local equilibrium sustained solely by inter-firm collaboration. This equilibrium is therefore defined as a "market-limited" scenario, which is commonly observed during the early stages of formal recycling system development or in regions with insufficient institutional support [67]. Although substantial gains from collaborative innovation may induce enterprises to cooperate spontaneously, the absence of positive external feedback prevents the system from achieving broader coordination. As a result, the system remains locked in a low-level steady-state trap and becomes vulnerable to technological spillover risks and imbalances in benefit distribution.

When Condition ② is satisfied, the sustained increase in consumer preference for the supportive strategy generates a positive market signal, which encourages enterprises to strengthen cooperative behavior in anticipation of higher expected payoffs. This process gives rise to a virtuous feedback loop of demand pull, trust accumulation, and collaborative reinforcement, ultimately driving up the probabilities of enterprises adopting cooperative strategies, as shown in Figure 3(b). This equilibrium is therefore characterized as a "consumer-driven" scenario, which is commonly observed during the market diffusion stage of remanufactured products in first- and second-tier cities [16]. In these settings, green consumer segments are relatively concentrated, and platform-based sales channels and quality certification mechanisms are relatively mature; however, local fiscal subsidies and targeted regulatory frameworks have not yet been fully established. Once consumer trust is eroded or consumer willingness to pay declines, inter-firm cooperative alliances may readily dissolve because of excessive exposure to market risk. This scenario suggests that, although demand-side trust mechanisms play a critical role in driving green innovation cooperation, they are insufficient on their own to sustain the long-term robustness of the system.

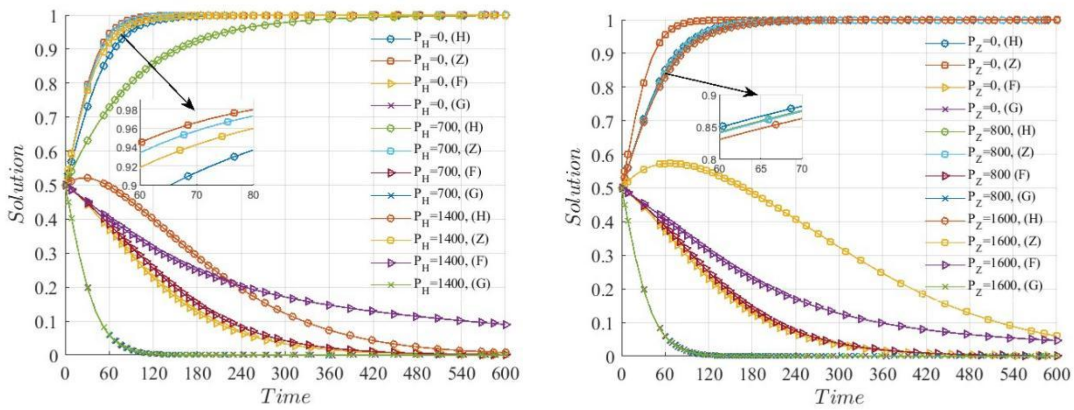
When Condition ③ is satisfied, high-intensity government subsidies exert a pronounced triggering effect during the early stage of evolution, causing the probabilities of enterprises engaging in inter-firm cooperation to increase rapidly and reach a high-level steady state in the intermediate stage, as shown in Figure 3(c). However, this steady state is driven primarily by policy incentives rather than market feedback. As the marginal effect of subsidies gradually diminishes, the system begins to transition toward endogenous stability; nevertheless, because consumer acceptance remains insufficient, the demand side continues to constitute a binding bottleneck. This equilibrium is therefore defined as a "policy-guided" scenario, which commonly occurs when government-led promotion is relatively strong, but consumer awareness and market acceptance have not yet been fully established [75]. This evolutionary trajectory further highlights the necessity of exogenous incentives during the initial phase of system formation, while also revealing that such incentives will ultimately face sustainability constraints if they cannot be transformed into endogenous market demand.

When Condition ④ is satisfied, policy incentives, inter-firm collaboration, and consumer support generate a strong synergistic amplification effect. The probabilities of all participating agents adopting supportive strategies increase jointly during the early stage, enter a highly synchronized state in the intermediate stage, and ultimately converge to a global steady state in the later stage, as shown in Figure 3(d). This equilibrium is therefore defined as an "ideal collaborative" scenario, which is typically observed during the mature stage of collaborative development [47]. At this stage, institutional provisions, technological support, and market acceptance are simultaneously strengthened. Policy instruments and market mechanisms achieve functional complementarity: policy interventions lower the threshold for innovation, while market demand absorbs the green premium. As a result, the system exhibits strong resilience and self-sustaining dynamics. This finding reveals the emergence of a co-evolutionary mechanism among policy, technology, and demand, thereby demonstrating the fundamental importance of this mechanism for the long-term optimization of the reverse logistics system.

5.3. Sensitivity analysis of key parameters

5.3.1. Spillover effects on cooperation stability

The spillover effect refers to the opportunistic gains obtained by an enterprise that breaches the cooperative contract and accesses the technology or resources of its partner [76]. To examine the underlying mechanism of spillover effects, this study conducts a sensitivity analysis with respect to P_H and P_Z under the "market-limited" scenario, corresponding to the ESS (1, 1, 0, 0), in which both government intervention and consumer participation are absent. The results for P_H and P_Z are presented in Figures 4(a) and 4(b), respectively. Specifically, $P_H = 0$ and $P_Z = 0$ denote the benchmark case without opportunistic gains, $P_H = 700$ and $P_Z = 800$ represent the critical boundaries determined by the endogenous stability conditions of the model, and $P_H = 1400$ and $P_Z = 1600$ are used to characterize an extreme-case scenario where opportunistic gains are substantially amplified under strong spillover effects.



(a) The impact of spillover effects on recycling enterprises

(b) The impact of spillover effects on remanufacturing enterprises

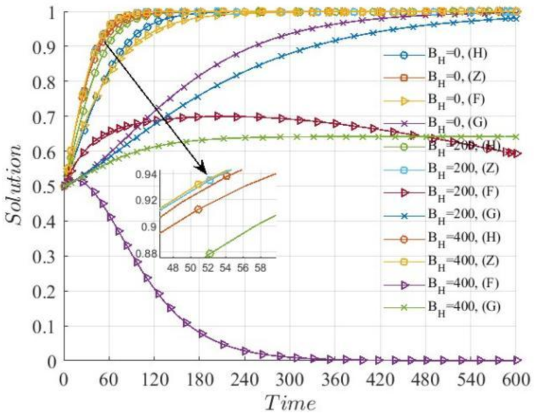
Figure 4. Effects of enterprise spillovers on four-party decisions.

The influence of spillover gains on cooperation stability exhibits a clear nonlinear threshold pattern. When spillover gains remain within a relatively low range, namely, $P_H \leq 700$ and $P_Z \leq 800$, the net payoff differences of enterprises remain positive, that is, $U_i - U_{1-i} > 0$ and $U_j - U_{1-j} > 0$. In this case, the net synergistic benefits generated by long-term cooperation continue to exceed the short-term payoffs from defection, allowing the system to eventually converge to a stable cooperative equilibrium. As spillover gains continue to increase, the net payoff differences gradually narrow, and the evolutionary trajectories of enterprises that choose green innovation cooperation become progressively flatter.

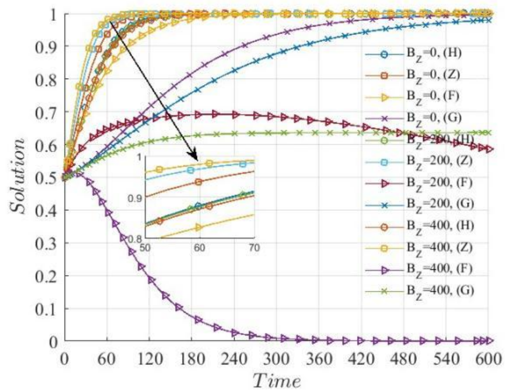
Furthermore, when spillover effects exceed the critical threshold, namely, $P_H \geq 1400$ and $P_Z \geq 1600$, the high short-term opportunistic gains from defection fundamentally alter the incentive-compatibility constraints faced by enterprises. As a result, the net payoff of the non-cooperation strategy exceeds that of the cooperation strategy, that is, $U_i - U_{1-i} < 0$ and $U_j - U_{1-j} < 0$. At this stage, the foundation of trust underlying green innovation cooperation rapidly collapses, and the evolutionary trajectory of the system quickly converges to a non-cooperative equilibrium. This phenomenon is frequently observed in collaborative innovation networks characterized by inadequate intellectual property protection, weak contractual enforcement, and ambiguous boundaries for sharing innovation outcomes [41]. For example, in the early stage of the EU WEEE system, insufficient intellectual property protection enabled small- and medium-sized enterprises to extensively replicate their partners' technologies, ultimately leading to the collapse of technological alliances and the failure of cooperation [77]. Under bounded rationality and incomplete information, the structural resilience of reverse logistics networks depends largely on whether cooperative benefits can consistently outweigh opportunistic gains. Accordingly, intellectual property contracts, modular design, and graded data-sharing are needed to curb opportunistic appropriation, raise defection costs, and sustain system stability.

5.3.2. Government subsidies and strategic evolution

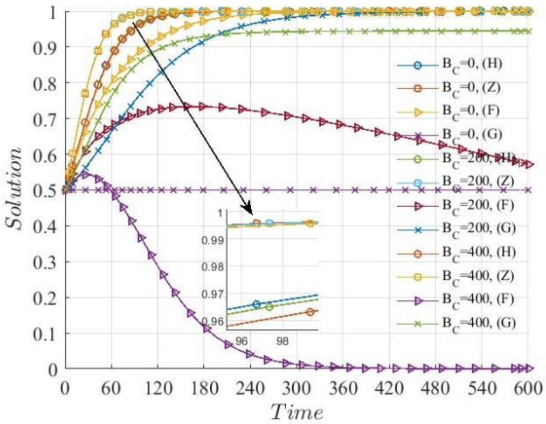
Government subsidies, as a key external moderating factor, directly reshape the distribution of benefits and the evolutionary trajectory of the reverse logistics network. To uncover the underlying mechanism, this study conducts sensitivity simulations under the “ideal collaborative” scenario, represented by the ESS (1, 1, 1, 1), with a focus on the intensity of supply-side subsidies (B_H, B_Z) and demand-side subsidies (B_C). The corresponding evolutionary trajectories are shown in Figure 5.



(a) Effects of recycling-enterprise subsidies on four-party strategic evolution



(b) Effects of remanufacturing-enterprise subsidies on four-party strategic evolution



(c) Effects of consumer subsidies on four-party strategic evolution

Figure 5. Effects of government subsidies on four-party decisions.

As shown in Figure 5(a) and (b), relative to the no-subsidy benchmark, a moderate subsidy level ($B_H = 200$, $B_Z = 200$) substantially accelerates the convergence of enterprises’ cooperative strategies toward a high-level steady state, thereby playing an important catalytic role. However, when the subsidy level is further increased ($B_H = 400$, $B_Z = 400$), its marginal incentive effect declines markedly, exhibiting a typical pattern of diminishing marginal payoffs from subsidies. If green innovation cooperation among enterprises is exposed to external perturbations, sustained high-level subsidies, such as $B_H = 400$ and $B_Z = 400$, may be required to offset the basic costs of cooperation. Under such circumstances, fiscal pressure on the government may continue to accumulate. When subsidy costs exceed the reputational benefits and environmental performance gains generated by policy support, the government may tend to withdraw from the supportive strategy, thereby exposing the ideal collaborative ESS (1, 1, 1, 1) to the risk of instability. This suggests that subsidies primarily function as a mechanism for risk-hedging and cost-sharing during the initial stage of cooperation. As inter-firm cooperation matures, endogenous synergistic payoffs gradually supersede external incentives as the dominant driving force, giving rise to a declining marginal incentive effect of subsidies.

As shown in Figure 5(c), consumer-side government subsidies (B_C) exhibit a non-monotonic incentive effect. A moderate subsidy level ($B_C = 200$) can effectively reduce the green premium, stimulate consumer willingness to purchase remanufactured products, and accelerate the convergence of enterprise strategies toward green innovation cooperation. However, excessive subsidies ($B_C = 400$) lead to a decline in the stable level of consumer support, with the convergence value falling to approximately 0.95, thereby weakening the final steady-state level of support. Meanwhile, an increase in subsidy intensity reduces the probability of the government adopting a supportive strategy. This indicates that excessive consumer subsidies may weaken policy incentives and increase the risk of instability in the multi-agent coupled dynamic system by disrupting strategic coordination among stakeholders. Therefore, structural resilience depends not only on the parameter thresholds themselves but also on the effectiveness of information transmission and the coordination of expectations among agents.

5.4. Pricing mechanisms and system equilibrium

5.4.1. Analysis of the impact of internal transfer prices

The pricing mechanism, as the central lever linking supply and demand, directly determines the efficiency of value allocation and the stability of coordination within the reverse logistics network [78]. Figure 6 presents the simulation results for the effect of the internal transfer price (V_X) on the system's evolutionary trajectory.

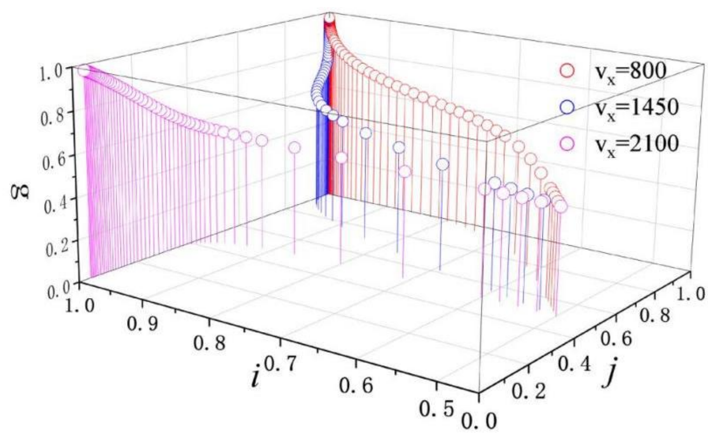


Figure 6. The impact of internal transfer pricing on agent decision-making.

The transaction price (V_X) between recycling enterprises and remanufacturing enterprises functions as a benefit-allocation mechanism linking the recycling and remanufacturing segments of the system. Its impact on system stability exhibits pronounced interval heterogeneity and two-way constraining effects. Within the low-price range, for example, when $V_X = 800$, convergence toward the green innovation cooperation strategy is relatively slow. Although a low internal transfer price reduces the input costs incurred by remanufacturing enterprises, it substantially compresses the profit margins of recycling enterprises, making it difficult for them to cover the costs associated with collection, sorting, and front-end collaborative investment. Under these conditions, the internal distribution of benefits becomes severely imbalanced, and the system can be sustained only with external policy support.

When the internal transfer price remains within a moderate range, such as $V_X = 1450$, the minimum revenue requirements of recycling enterprises are well-aligned with the maximum willingness to pay of remanufacturing enterprises. This alignment satisfies the incentive compatibility constraints of both parties and leads to the optimal evolutionarily stable state. Even under external environmental perturbations, both types of enterprises can maintain green innovation cooperation through cooperative benefits and stable expectations. Conversely, when the transfer price rises further to a high level, for example, when $V_X = 2100$, the cost burden on remanufacturing enterprises is substantially aggravated. Their expected profits become insufficient to cover innovation investment and market risks, prompting them to withdraw from green innovation cooperation before recycling enterprises. Once the internal allocation of payoffs within the value chain exceeds the feasible boundary of coordination, structural imbalance is likely to occur, causing the system to shift rapidly from a coordinated steady state to an unstable state characterized by downstream chain disruption. Therefore, the system can maintain strong structural robustness under bounded rationality and incomplete information only when the internal transfer price remains within a mutually acceptable collaborative range.

5.4.2. Analysis of the impact of market pricing on remanufactured products

The terminal market price (V_Z), as a key signal linking the supply of remanufactured products with consumer demand, directly regulates market penetration and profit distribution along the industrial chain [12]. The simulation results shown in Figure 7 reveal how the market pricing mechanism affects the evolutionary stability of the system.

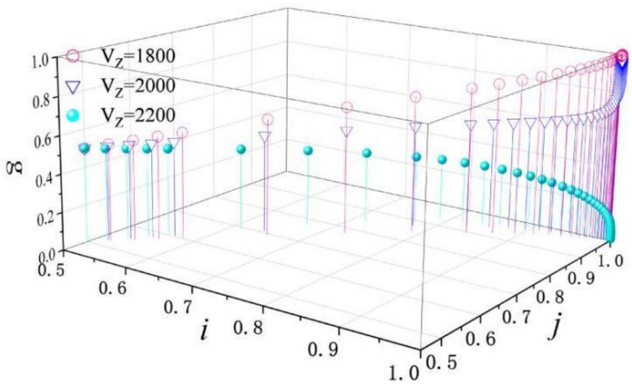


Figure 7. The impact of market pricing of remanufactured products on agent decision-making.

The terminal market transaction price of remanufactured products exerts a nonlinear and stage-specific influence on the evolutionary stability of the system, characterized by a pattern of low-price penetration, medium-price stabilization, and high-price inhibition. In the low-price range, for example, when $V_Z = 1800$, remanufactured products can rapidly cross the market-entry threshold by virtue of their favorable cost-performance advantages. The resulting expansion in demand further reinforces enterprises' willingness to cooperate through sales growth, thereby generating an initial market-pull effect. However, excessively low prices substantially compress the marginal payoffs of remanufacturing enterprises and constrain their ability to accumulate sufficient capital for sustained R&D, quality control, and brand-trust building, all of which are essential for maintaining long-term green technological upgrading.

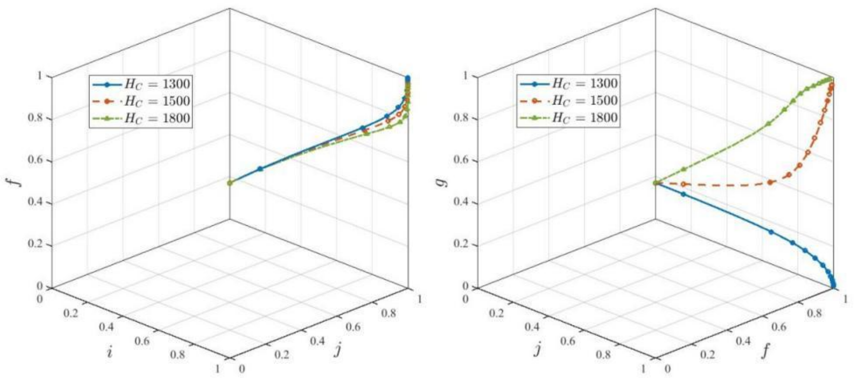
Within a moderate price range, for example, when $V_Z = 2000$, the system achieves a more favorable balance between consumer willingness to pay and enterprise profitability objectives. On the one hand, a moderate price level sustains a high degree of market acceptance and ensures effective demand-side uptake. On the other hand, sufficient profit margins provide remanufacturing enterprises with stable incentives for innovation, thereby supporting technological upgrading on the supply side. The resulting incentive compatibility between the supply and demand sides enhances system stability to its highest level, allowing the evolutionary trajectory to reach its most robust state.

Notably, when the reverse logistics network is exposed to extreme external perturbations, an increase in V_Z may be required to maintain normal operation. However, when the selling price exceeds the upper limit of perceived value among consumers, such as $V_Z = 2200$, the gap between perceived value and the selling price continues to widen, and the proportion of consumers choosing the supportive strategy declines significantly. Although enterprises may still have strong incentives to cooperate because of expected high profits, insufficient effective demand in the terminal market leads to a supply–demand mismatch characterized by excess supply. As a result, the system ultimately struggles to maintain the ideal collaborative state.

5.5. Sensitivity analysis of the perceived practical value of consumers

To further examine the influence of demand-side factors on the evolutionary stability of the system, this study conducts a sensitivity analysis of the practical value H_C obtained by consumers from remanufactured products, while keeping all other parameters unchanged. The simulation results are shown in Figure 8.

As shown in Figure 8(a), as H_C increases, the convergence speed of green innovation cooperation strategies adopted by recycling enterprises and remanufacturing enterprises gradually accelerates. This result indicates that higher perceived value among consumers can strengthen market demand expectations and, through demand-side feedback, enhance the incentives for enterprises to cooperate. Meanwhile, the convergence speed of the government support strategy slows down, suggesting that as market acceptance gradually improves, the system becomes less dependent on direct fiscal subsidies. As shown in Figure 8(b), H_C exerts a more pronounced effect on the evolution of consumer strategies. When the practical value of remanufactured products is insufficient to offset consumer concerns regarding product quality and reliability, as illustrated by the case of $H_C = 1300$, consumers ultimately converge toward the non-supportive strategy. When $H_C = 1500$, positive feedback begins to emerge on the demand side, and the consumer support strategy gradually evolves toward a higher level. When $H_C = 1800$, the consumer support strategy converges more rapidly to a high-level stable state. This result indicates that a higher perceived utilization value can significantly enhance consumer willingness to purchase and support remanufactured products, thereby promoting the evolution of the system toward a more stable collaborative governance state.



(a) Evolutionary effects of H_C on i, j, and f (b) Evolutionary effects of H_C on i, f, and g

Figure 8. Sensitivity analysis of consumer practical value on four-party strategy evolution.

Modeling consumer preferences as static parameters makes it difficult to fully capture dynamic changes in the willingness of consumers to pay in evolving markets. However, as green innovation cooperation between recycling enterprises and remanufacturing enterprises continues to deepen, the continuous improvement of green information disclosure and consumption experience will reduce consumer concerns, thereby increasing consumers' perceived value.

6. Conclusion

From the perspective of green innovation cooperation, this study constructs a four-party evolutionary game model involving recycling enterprises, remanufacturing enterprises, the government, and consumers. The model captures the strategic interaction logic and collaborative evolution mechanism among multiple agents under bounded rationality and conflicting interests. By deriving replicator dynamic equations and conducting eigenvalue analysis of the Jacobian matrix, this study identifies four evolutionarily stable strategy combinations. Furthermore, by combining numerical simulations with sensitivity analysis, this study systematically examines how key parameters related to spillover gains, government subsidies, and market pricing affect evolutionary trajectories and the stability of system equilibria. The main findings are summarized as follows:

(1) The system evolution yields four typical stable scenarios, namely, "market-limited", "consumer-driven", "policy-guided", and "ideal collaborative". The first three correspond respectively to stage-specific stable states characterized by demand-side bottlenecks, inadequate policy provision, and delayed consumer response. The results indicate that the system can converge to a high-level coordinated steady state only when government incentives, inter-firm green innovation cooperation, and consumer support are simultaneously strengthened. Therefore, policy support, inter-firm cooperation contracts, consumer trust-building measures, and market promotion mechanisms for remanufactured products should be improved in a coordinated manner to facilitate the gradual transition of the system from a low-level stage-specific equilibrium to a stable state of collaborative governance.

(2) Spillover risks in green innovation cooperation exert a pronounced threshold effect on cooperative stability. Within the threshold range, cooperation remains sustainable, although the convergence process is relatively slow. However, once the threshold boundary is exceeded, the incentive-compatible relationship between enterprises is disrupted, the probability of cooperation declines sharply, and the system is likely to shift from a cooperative steady state to an unstable state. The stability of green innovation cooperation depends on the dynamic balance among technology sharing, benefit distribution, and default penalty enforcement. The opportunism-triggering threshold derived from the model provides a quantitative basis for enterprises to reasonably define knowledge-sharing boundaries, breach penalty intensity, and cooperative benefit-sharing rules.

(3) The incentive effect of government subsidies exhibits a stage-dependent evolutionary pattern. While subsidies exert a pronounced driving effect in the early stage of cooperation, their marginal effectiveness gradually declines as cooperation becomes increasingly endogenous. In the absence of a dynamic adjustment mechanism aligned with the stage of market development, prolonged fixed subsidies tend to breed corporate subsidy dependence and undermine the long-term sustainability of policy interventions. Therefore, moderate subsidies may be provided at the initial stage to lower the participation threshold for enterprises. During the market diffusion stage, government subsidies should be linked to performance indicators related to green innovation cooperation. At the mature stage, policy support should gradually shift toward indirect instruments, such as tax incentives, green credit, and credit supervision. For enterprises with insufficient innovation performance or subsidy arbitrage, subsidies should be reduced or phased out in a timely manner to avoid policy dependence and the misallocation of fiscal resources.

(4) The market pricing mechanism serves as a pivotal coordination instrument for benefit allocation. Both the internal transfer price and the terminal market price exhibit well-defined effective boundaries. When prices deviate from these ranges, incentive misalignment between upstream and downstream actors or demand-side contraction is likely to occur, thereby undermining the overall collaborative stability of the reverse logistics network. The effective price ranges derived from the model provide a quantitative basis for inter-firm transfer pricing negotiations, the setting of industry price guidance ranges, and the construction of third-party price coordination mechanisms.

(5) Consumer trust and green preferences generate system-level dynamic feedback and exhibit path dependence. Enhancing consumer environmental awareness and building demand-side trust generate positive market signals to supply-side enterprises, thereby facilitating the transition of the system toward a highly coordinated steady state. In practice, a third-party quality certification system should be established for remanufactured products to enhance the market acceptance of such products.

However, this study still has certain limitations. The model parameters are mainly specified based on theoretical assumptions and existing literature, and the characterization of stable scenarios still relies on a deterministic evolutionary framework. Future research may further incorporate stochastic perturbation mechanisms and empirical data calibration to examine the applicability boundaries and structural resilience of the ideal collaborative state under external shocks.

Author contributions

Shuming Liu: Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis. Xiang Liu: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Funding acquisition, Conceptualization. Xianghua Liu: Writing – review &

editing, Supervision, Resources, Conceptualization. Ziquan Li: Software, Methodology, Investigation. Jiahui Huang: Visualization, Formal analysis. Qiuzhi He: Visualization, Software, Methodology, Investigation.

Use of Generative-AI tools declaration

In the preparation of this work, the authors used Generative AI tools such as ChatGPT to assist in improving the clarity of the language. All AI-assisted content was carefully reviewed and revised by the authors, who take full responsibility for the final version of the manuscript.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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