



Tripartite evolutionary game analysis of collaborative governance in construction and demolition waste management

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Abstract

Construction and demolition waste management remains a critical challenge in China, where low recycling rates and fragmented stakeholder coordination impede the transition toward a circular economy. This study develops a tripartite evolutionary game model involving government regulators, construction enterprises, and recycling enterprises. By integrating replicator dynamics with MATLAB-based simulations and incorporating phased subsidies, penalties, and firm-level cost parameters, the model analyzes the strategic evolution of stakeholder behaviors. Simulation results show that a stable cooperative equilibrium emerges when subsidies for construction and recycling enterprises are set at $E_1 = 50$ and $E_2 = 48$, and the penalty H is at least 50. Under these conditions, the probability of adopting proactive strategies exceeds 0.9 within 50 iterations. While penalties remain consistently effective across all levels of market maturity, the marginal utility of subsidies declines sharply as the resource utilization rate (q) approaches 0.5. Increasing the initial cooperation probability of construction enterprises from 0.5 to 0.8 reduces convergence time by approximately 35%. High sorting costs ($F > 45$) and low resale revenues ($I < 40$) are identified as key barriers to sustained cooperation. Based on these findings, a three-phase policy strategy is proposed: subsidies should be deployed in the early stage to lower entry barriers; penalties should be prioritized during the transition phase; and transaction cost reduction and long-term revenue mechanisms should be emphasized in the mature stage. The study provides both theoretical and practical insights into sustainable governance of construction and demolition waste.

Keywords: Construction and demolition waste, evolutionary game theory, circular economy, subsidy optimization, sensitivity analysis

1. Introduction

China's rapid urbanization and extensive infrastructure development over the past few decades have led to the generation of unprecedented volumes of construction and demolition (C&D) waste^[1]. With annual production exceeding 2.5 billion tons, C&D waste has become one of the largest waste streams in the country^[2]. Its composition is predominantly inert and non-biodegradable, comprising materials such as concrete, bricks, metals, and wood, substances resistant to natural degradation and requiring vast land areas for disposal^[3]. Improper management of C&D waste poses significant environmental risks, including soil contamination^[4], water pollution^[5], and mounting pressure on land resources^[6]. Furthermore, it accelerates the depletion of natural resources, as large quantities of virgin materials are consumed in construction activities, thereby contributing to the unsustainable exploitation of finite resources^[7]. Despite the magnitude and urgency of the issue, China's C&D waste recycling rate remains considerably low. In contrast, developed economies such as the Netherlands, Germany, and Japan have established highly efficient recycling systems, achieving recovery rates several times higher than those in China^[8]. These successes are largely attributed to comprehensive policy frameworks, strict regulatory enforcement, and effective stakeholder coordination, which collectively facilitate resource recovery and waste reduction. In comparison, China's recycling efforts face persistent obstacles^[9], including weak regulatory enforcement, fragmented governance structures, unclear stakeholder incentives, and inadequate recycling and waste management infrastructure.



In response to growing environmental concerns, the Chinese government has introduced a series of policy initiatives aimed at C&D waste^[10]. Key measures include the Circular Economy Promotion Plan (2015), which seeks to guide the country toward a circular economy, and the Guidance on Promoting the Reduction of Construction Waste (2020), which focuses on waste minimization, recycling, and material reuse. Although these policies reflect a clear shift toward more sustainable practices, their practical effectiveness have been uneven. Persistent challenges include unclear stakeholder roles, inadequate financial support for recycling enterprises, and weak enforcement mechanisms. As highlighted by Hua *et al.*^[11], fragmented governance and poor institutional coordination have impeded effective policy implementation across different government and industrial levels. Recycling enterprises encounter numerous operational difficulties, such as high costs associated with collection, sorting, and processing, alongside fluctuations in secondary materials markets^[12,13]. These economic obstacles, coupled with insufficient policy backing, have substantially constrained the growth of a sustainable recycling industry. Additionally, construction firms often hesitate to adopt waste management practices due to weak regulatory frameworks and the lack of economic incentives that would enhance the viability of recycling^[14]. As a result, the C&D waste management system remains inefficient, and recycling rates continue to be low.

Previous research on C&D waste management has primarily employed static methods, including life cycle assessment^[15,16], system dynamics^[17], building information modeling^[18] and cost-benefit analysis^[19], which focus on assessing environmental and economic impacts. While these approaches provide valuable insights into the overall sustainability of C&D waste systems, they often fall short in capturing the dynamic nature of stakeholder interactions, policy changes, and market fluctuations. As highlighted by Peng *et al.*^[20], achieving long-term sustainability in waste management requires a deeper understanding of how stakeholders adjust their strategies over time in response to evolving incentives, regulations, and environmental pressures. This necessitates the development of more dynamic and adaptive models capable of representing the complex interactions and strategic behaviors among multiple stakeholders. In this regard, evolutionary game theory (EGT) presents a promising framework for modeling the behavior of heterogeneous stakeholders under conditions of bounded rationality and strategic interaction^[21]. Unlike traditional game theory, which assumes agents possess complete information and make rational decisions based on fixed payoffs, EGT focuses on the evolution of strategies over time through processes such as imitation, learning, and adaptation^[22]. This approach is especially well-suited for analyzing complex socio-environmental systems like C&D waste management, where stakeholder decisions are influenced by shifting policies, market dynamics, and environmental factors.

This study develops a tripartite evolutionary game model involving government, construction enterprises, and recycling enterprises. The model captures the shift in China's policy approach from direct financial subsidies toward market-based instruments, including penalties, performance-based rewards, and public procurement criteria. By integrating phased subsidy reductions and employing replicator dynamics, the model simulates how changes in incentives and regulatory intensity influence stakeholder strategies and long-term outcomes of the system. This research addresses two critical real-world challenges: (1) how to overcome strategic misalignment among stakeholders to foster sustained cooperation in C&D waste governance ; and (2) what types of dynamic incentive structures can effectively drive this transition without inducing over-dependence or market inefficiencies.

Accordingly, the objectives of this study are threefold:

- (1) To model the behavioral dynamics of key stakeholders in the C&D waste management system using an evolutionary game theory framework;
- (2) To identify the conditions and policy parameters that promote the emergence of stable, cooperative equilibria;
- (3) To provide policy-relevant insights for designing adaptive, phased incentive mechanisms that align with institutional maturity and market responsiveness.

The remainder of this paper is organized as follows. [Section 2](#) reviews the relevant literature on C&D waste governance and applications of EGT. [Section 3](#) details the model structure, including underlying assumptions and payoff configurations. [Section 4](#) presents and discusses the simulation results and their implications. Finally, [Section 5](#) concludes with theoretical contributions, policy recommendations, and suggestions for future research.

2. Literature Review

2.1 Systemic perspectives on C&D waste management

C&D waste management has emerged as a critical focus within environmental systems research but continues to suffer from fragmented implementation and insufficient coordination among stakeholders^[23]. Although extensive research has emphasized the technical and environmental benefits of recycling, real-world practices often fall short of expectations^[24]. Technological studies have demonstrated that recycled aggregates and secondary construction materials can perform comparable to virgin materials, particularly when advanced processing and sorting systems are employed^[25]. However, as Hasibuan *et al.*^[26] pointed out, technological feasibility alone does not guarantee adoption, especially in contexts where collection infrastructure is underdeveloped and quality assurance mechanisms for recycled products are lacking. From an economic standpoint, structural barriers hinder the scalability of recycling efforts. Ding *et al.*^[27] showed that C&D recycling enterprises in China often operate on narrow profit margins,

primarily due to volatile material prices and limited integration into mainstream procurement systems. In a broader context, Bonifazi *et al.*^[28] systematically examined the relationship between urban infrastructure expansion and the exponential growth of C&D waste, underscoring the intertwined environmental and economic challenges posed by conventional disposal methods. From a policy design perspective, scholars such as Hurlimann *et al.*^[29] and Liu *et al.*^[30] have classified national C&D waste management frameworks into three main categories: (1) command-and-control regulations, such as landfill bans; (2) market-based instruments, including tax credits and extended producer responsibility schemes; and (3) voluntary standards. While these instruments have proven effective in many developed economies, Ababio *et al.*^[31] cautioned that their success depends heavily on enforcement capacity, institutional clarity, and the strategic sequencing of policy tools. In the Chinese context, overlapping ministerial jurisdictions and limited local implementation capacity often lead to “policy fatigue” or symbolic compliance rather than substantive recycling outcomes.

Several scholars advocate for a systemic governance approach to C&D waste management. For example, Li *et al.*^[32] found that practices at the construction site-level are deeply embedded in subcontracting norms, project schedules, and informal routines among workers. Similarly, Liu *et al.*^[33] emphasized that waste sorting behavior is rarely shaped solely by regulations; rather, it emerges through negotiations among site managers, waste haulers, and local regulators. These observations align with the institutional framework proposed by Stabler^[34], which posits that informal norms and transaction costs significantly influence the evolution of formal rules. Building on this perspective, recent work by Munaro *et al.*^[35] introduced the concept of “governance inertia” in C&D systems, referring to local actors’ resistance to policy changes due to perceived administrative burdens and exposure to risk. This is consistent with Tan’s^[36] theory of polycentric governance, which suggests that effective environmental management requires iterative, cross-scale learning rather than purely top-down control. Despite the expanding breadth of research, a notable methodological gap remains. As explored by Chen *et al.*^[37] and Mallick *et al.*^[38], even advanced approaches such as life-cycle assessments and cost-benefit analyses often rely on fixed behavioral assumptions, overlooking the adaptive strategies adopted by firms and regulators in response to changing conditions. Most studies remain static in nature and fail to account for the strategic interdependence among actors or the feedback loops that evolve over time. This gap underscores the need for dynamic modeling tools capable of capturing adaptive strategies and multi-actor interactions in complex systems.

2.2 Evolutionary game theory in environmental systems

To address the limitations of static or linear analytical tools, EGT has emerged as a powerful approach for simulating how stakeholder strategies evolve over time within complex^[39], multi-agent environmental systems. Unlike classical game theory, which assumes fully rational agents and fixed payoffs, EGT incorporates bounded rationality and adaptive learning, offering a more accurate reflection of behavioral and institutional dynamics in contemporary policy and market environments^[40]. In EGT models, agents revise their strategies through imitation, payoff comparisons, and behavioral diffusion, making the approach particularly well-suited to analyzing how cooperation or non-cooperative behaviors propagates across sectors^[41]. EGT has seen growing application in environmental governance research. For example, Wu *et al.*^[42] examined firms’ responses to emissions trading schemes, finding that stronger enforcement mechanisms and lower abatement costs significantly enhance compliance. Similarly, Cheng *et al.*^[43] demonstrated that high subsidy levels and positive demonstration effects within an industry increase enterprises’ willingness to invest in clean energy technologies. In the context of industrial symbiosis, Zhao *et al.*^[44] showed that effective cooperation in waste exchange networks depends on internal cost-sharing mechanisms and external policy signals. Collectively, these studies highlight EGT’s core advantage: its ability to model environmental policy not as a one-time intervention, but as a dynamic process shaped by strategic feedback and behavioral adaptation.

Extending the application of EGT to the construction sector, several recent studies have examined the behavioral dynamics related to sustainability among key stakeholders. For instance, Ma *et al.*^[45] developed a two-player model involving government regulators and construction enterprises, demonstrating that stricter penalties effectively promote compliance only when monitoring costs are sufficiently low. However, their model omits recycling enterprises, which are critical intermediaries in the C&D waste system by collecting, processing, and reintegrating materials into the economy^[46]. Given their exposure to high fixed costs and uncertain market demand, the economic viability of recycling enterprises significantly influences overall policy effectiveness. The exclusion of this stakeholder group limits the model’s explanatory power and practical relevance in real-world policy contexts. Similarly, Sönnichsen *et al.*^[47] employed a dyadic framework to assess the impact of government incentives on green procurement but assumed static policy conditions, thereby overlooking the transitional and adaptive nature of environmental regulation. In dynamic policy contexts such as China, subsidies are often phased out as markets mature and institutional capacity increases^[48]. Zhao *et al.*^[49] made progress by introducing a declining subsidy mechanism; however, their analysis remains confined to a single stakeholder group. As a result, the model fails to capture the interrelated strategic responses that arise in a multi-actor system, such as how reducing subsidies for recyclers might dampen the motivation of construction companies to conduct on-site waste sorting, or how regulators adjust enforcement strategies in response to weakening compliance.

A key shortcoming of the existing literature is its limited attention to cross-sectoral feedback and institutional dynamics. Abdulai *et al.*^[50] argued that effective environmental governance, particularly in multi-level systems such as C&D waste management,

requires not only economic incentives but also collaborative rule-making, trust-building, and iterative learning. Stofberg *et al.*^[51] further emphasized that long-term cooperation depends on shared performance indicators and institutional alignment, which are often absent in EGT models featuring fixed actor types and static payoff structures. The decentralized nature of C&D waste governance, characterized by multiple autonomous decision-makers and the absence of centralized control, aligns with the principles of polycentric governance theory^[52]. This theory posits that durable cooperation emerges from self-reinforcing behaviors and coordination driven by feedback, both of which EGT is well suited to capture. To address these gaps, this study develops a tripartite evolutionary game model that combines the analytical strengths of EGT with the practical governance requirements of emerging economies transitioning toward a circular economy. The model offers a behaviorally realistic and institutionally grounded framework for analyzing the formation, stability, and potential disruption of sustainable C&D waste systems. It also provides policy-related insights for coordinating multi-participant systems, designing adaptive subsidy schemes, and anticipating long-term challenges such as policy fatigue and rebound effects, all of which are critical to advancing circular development in the built environment.

To bridge these gaps, this study develops a tripartite evolutionary game model that integrates government, construction enterprises, and recycling firms as strategic agents. The model incorporates phased policy transitions to reflect changes in subsidy levels and enforcement intensity. It also accounts for institutional factors such as coordination costs, behavioral inertia, and bounded rationality. This integrative framework enhances the explanatory power of EGT in the context of circular economy transitions. It offers actionable insights for coordinating multi-actor systems, designing adaptive policy mechanisms, and addressing long-term governance challenges such as policy fatigue and rebound effects in C&D waste management.

3. Methodology

3.1 Theoretical foundation

This study applies EGT to examine the dynamic strategic interactions among three core stakeholders in C&D waste management: the government, construction enterprise, and recycling enterprise, as illustrated in Figure 1. Unlike static analytical approaches, EGT incorporates bounded rationality and adaptive learning, enabling it to capture the iterative nature of strategy adjustment driven by payoff feedback^[53]. This makes EGT particularly suitable for analyzing behavioral evolution within complex systems influenced by policy shifts, market fluctuations, and inter-organizational coordination. The modeling framework consists of three key components: (1) construction of a payoff matrix based on realistic parameterization; (2) application of dynamic equations to model strategy evolution over time; and (3) implementation of numerical simulations using MATLAB to observe long-term equilibrium patterns and assess sensitivity to changes in policy parameters. The theoretical soundness of this approach is grounded in the following key aspects:

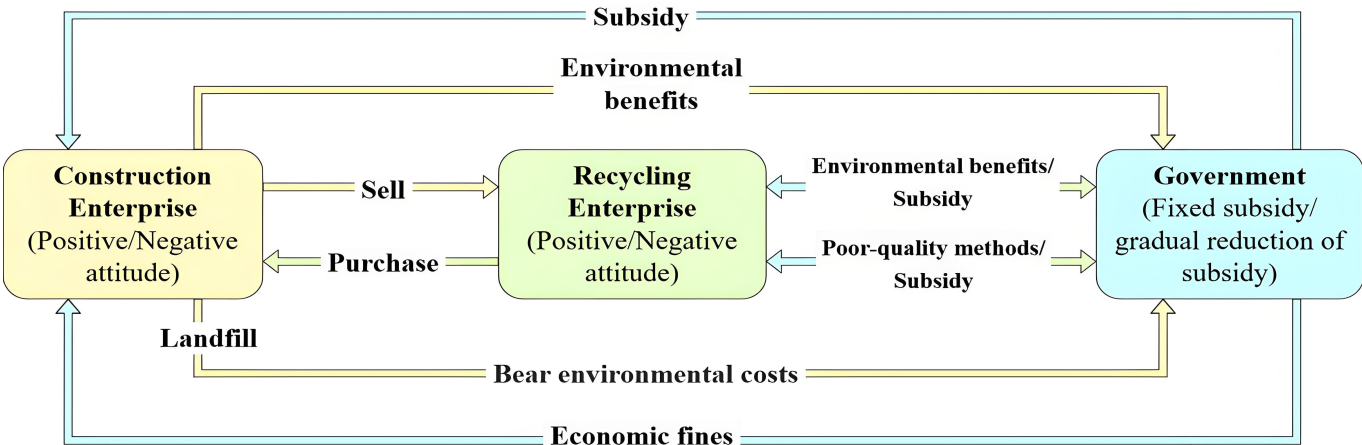


Figure 1. Strategic interaction framework.

- **Incorporation of heterogeneous actors:** The model explicitly includes three interdependent stakeholder groups: government, construction enterprise, and recycling enterprise. Each group has distinct cost structures, compliance incentives, and strategic choices, thereby reflecting the heterogeneity of real-world systems.
- **Dynamic policy simulation:** A phased subsidy reduction mechanism is introduced to simulate the evolution of real-world policy. As market mature, initial financial support is gradually withdrawn, prompting stakeholders to reassess their strategies dynamically. This reflects the broader shift from direct government intervention to market-based regulation. The design of the payoff functions draws upon the policy objectives in China's 14th Five-Year Plan for the Circular Economy (MEE, 2021)^[54] and the EU Circular Economy Action Plan (EU, 2020)^[55].

- **Interdependent behavior modeling:** The model captures payoff interdependencies, wherein the return to any given stakeholder depends not only on their own strategy but also on the evolving behavior of others. For example, stricter enforcement targeting construction firms may enhance the operational viability of recycling enterprises, triggering cascading behavioral adjustments throughout the system.
- **Long-term simulation of replicator dynamics:** By applying replicator dynamics, the model enables an analysis of how system-level equilibrium states emerge, stabilize, or collapse in response to changes in cost structures, policy design, and adaptive learning mechanisms.

3.2 Parameter assumptions and payoff matrix construction

The parameter system in this study is defined through a rigorous synthesis of China’s C&D waste management practices and findings from the existing literature^[56-61].

1) Construction enterprise strategy (x): The strategic behavior of construction enterprises is represented by the probability x of adopting an active recycling strategy, while $(1 - x)$ corresponds to choosing passive landfill disposal. Active recycling involves a costs F , which includes expenses related to waste sorting, transportation, and collaboration with recycling facilities. In contrast, passive strategies incur a lower operational costs f but expose enterprises to potential penalties H . Revenue also differs by strategy: active recycling yields income I from material recovery, whereas passive disposal results in a lower return R . Two additional parameters are introduced to capture system-specific inefficiencies: n reflects the coordination difficulties with passive recyclers, and d represents the indirect costs associated with landfill-based practices.

2) Recycling enterprise strategy (y): The strategic behavior of recycling enterprises is represented by the probability y of adopting high-quality processing methods, while $1 - y$ corresponds to low-quality processing. High-quality operations require significant investments K_1 in advanced technologies and skilled labor, whereas low-quality processing minimizes costs to o but exposes enterprises to penalties w . Revenue outcomes differ accordingly: V denotes the premium return from high-quality recycled products, while i represents the lower returns associated with substandard processing.

3) Government strategy (z): The government’s strategic behavior is modeled through a binary choice: implementing fixed subsidies with probability z , or adopting a gradually reducing subsidy strategy with probability $1 - z$. The latter is formalized as a dynamic subsidy reduction function $e(x) = E - pq$, where E represents the initial subsidy amount, q indicates the industry-wide resource utilization rate (reflecting the maturity of circular economy practices), and p is the subsidy reduction coefficient, which determines the rate at which subsidies decline as resource efficiency improves. Environmental outcomes are categorized into three levels: G_1 , G_2 , and G_3 , corresponding to high, medium, and low environmental protection outcomes, respectively, under different strategic combinations. Additionally, the parameter u denotes the environmental remediation cost incurred by the government when stakeholders engage in passive waste management practices.

The interaction of these strategies generates a tripartite payoff matrix encompassing all eight possible combinations derived from the variables z , x , and y , as shown in Table 1. Each cell in the matrix calculates the net payoff for the government, construction enterprises, and recycling enterprises. For instance, in the case of full cooperation ($z = 1, x = 1, y = 1$), the construction enterprises receive a payoff of $I - F + E_1$, recycling enterprises receive $V - K_1 + E_2$, and the government receives $G_1 - E_1 - E_2$. In contrast, passive strategies lead to penalties and environmental remediation costs (u), highlighting the systemic trade-offs among subsidy incentives, operational decisions, and negative externalities. This matrix serves as the foundational basis for replicator dynamics and stability analysis conducted in the subsequent stage of the model.

Table 1. Tripartite payoff matrix under different strategy combinations.

Construction Enterprise	Recycling Enterprise	Government	
		Fixed Subsidy (z)	Gradually Reducing Subsidies (1 - z)
Positive attitude (x)	Positive attitude (y)	$I - F + E_1, V - K_1 + E_2, G_1 - E_1 - E_2$	$I - F + E_1 - pq, V - K_1 + E_2 - pq, G_1 - (E_1 - pq) - (E_2 - pq)$
Negative attitude (1 - y)	$I - F + E_1 - n, i - o - w, G_2 + w - E_1$	$I - F + E_1 - pq - n, i - o - w - c, G_2 + w - E_1 - pq + c$	Negative attitude (1 - x)
Positive attitude (y)	$R - f - H - d, i + E_2 - K_2, G_3 + H - E_2$	$R - f - H - d - c, i - K_2 + E_2 - pq, G_3 + H - E_2 + pq - u + c$	Negative attitude (1 - y)
$R - f - H - d, i - o - (K_2 - K_1) - w, H + w$	$R - f - H - d - c, i - o - (K_2 - K_1) - w - c, H + - u + 2c$		

3.3 Strategic stability and equilibrium analysis

After establishing the parameter assumptions and constructing the payoff matrix, it is essential to analyze strategic stability and identify equilibrium points to gain a deeper understanding of the behavioral trends among the three stakeholder groups and the overall stability of the system. This analysis is based on the replicator dynamics equations. By examining changes in the strategy frequencies of each participant over time and evaluating the system's equilibrium under various conditions^[62], we can uncover the dynamic evolution of decision-making processes within the C&D waste management system.

3.3.1 Strategic stability of each participant

The strategic stability of each participant is analyzed using replicator dynamics equations^[63], which describe how the frequency of a given strategy evolves over time based on its payoff relative to the average payoff within the group.

1) Construction enterprises

Based on the payoff matrix, the expected payoffs of construction enterprises under active recycling (ES_1) and passive landfill disposal (ES_2), as well as the average expected payoff $\overline{ES}$, are calculated as follows:

$$ES_1 = yz(I - F + E_1) + z(1 - y)(I - F + E_1 - n) + y(1 - z)(I - F + E_1 - pq) + (1 - y)(1 - z)(I - F + E_1 - pq - n) \quad (1)$$

$$ES_2 = yz(R - f - H - d) + (1 - y)z(R - f - H) + y(1 - z)(R - f - H - d - c) + (1 - y)(1 - z)(R - f - H - c) \quad (2)$$

$$\overline{ES} = xES_1 + (1 - x)ES_2 \quad (3)$$

The replication-dynamic equation $F(x)$ and its derivative are given by:

$$F(x) = \frac{dx}{dt} = x(ES_1 - \overline{ES}) = -x(x - 1)(E_1 - F + H + I - R + c + d + f - n - cz - pq + ny + pqz) \quad (4)$$

$$\frac{dF(x)}{dx} = (1 - 2x)(E_1 - F + H + I - R + c + d + f - n - cz - pq + ny + pqz) \quad (5)$$

To simplify the expression, let $G(y) = E_1 - F + H + I - R + c + f - n - cz - pq + ny + pqz$. According to the stability theorem of differential equations, for the probability x of construction enterprise adopting a positive attitude toward resource utilization of construction waste to be stable, the following conditions must be satisfied: $F(x) = 0$ and $\frac{dF(x)}{dx} < 0$. For convenience in the subsequent discussion, define $y_1 = \frac{F - E_1 - H - I + R - c - f + n + pq - z(pq - c)}{n}$ and $z_1 = \frac{F - E_1 - H - I + R - c + pq - f + n}{pq - c}$.

Proposition 1: If $z > z_1$, then $x = 1$ is an evolutionarily stable strategy. If $z < z_1$, the stability of x depends on the value of y : when $y = y_1$, all values of x are stable; when $y < y_1$, $x = 0$ is stable; and when $y > y_1$, $x = 1$ is stable. This indicates that a high probability of fixed government subsidies encourages construction enterprises to adopt a positive recycling attitude. Conversely, when the probability of fixed subsidies is low, the construction enterprises' decisions are influenced by the behavior of recycling enterprises.

2) Recycling enterprises

For recycling enterprises, the expected payoffs under active processing (ES_3) and passive processing (ES_4), as well as the average expected payoff $\overline{ES}$, are calculated as follows:

$$ES_3 = xz(V - K_1 + E_2) + x(1 - z)(V - K_1 + E_2 - pq) + z(1 - x)(i + E_2 - K_2) + (1 - x)(1 - z)(V - K_1 + E_2 - pq) \quad (6)$$

$$ES_4 = xz(i - o - w) + x(1 - z)(i - o - w - c) + z(1 - x)(i - o(K_2 - K_1) - w) + (1 - x)(1 - z)(i - o - (K_2 - K_1) - w - c) \quad (7)$$

$$\overline{ES} = yES_3 + (1 - y)ES_4 \quad (8)$$

The replication-dynamic equation $F(y)$ and its derivative are:

$$F(y) = \frac{dy}{dt} = y(ES_3 - \overline{ES}) = -y(y - 1)(E_2 - K_1 + c + o + w + Vx - cz - ix - pq + pqz) \quad (9)$$

$$\frac{dF(y)}{dx} = (1 - 2y)(E_2 - K_1 + c + o + w + Vx - cz - ix - pq + pqz) \quad (10)$$

To simplify the expression, define $J(x) = E_2 - K_1 + c + o + w + Vx - cz - ix - pq + pqz$. According to the stability theorem of differential equations, for the probability y of recycling enterprise adopting a positive attitude toward resource utilization of construction waste to be stable, the following conditions must hold: $F(y) = 0$ and $\frac{dF(y)}{dx} < 0$. For convenience, define $x_1 = \frac{K_1 - E_2 - c - o - w + pq - (pq - c)z}{V - i}$ and $z_2 = \frac{K_1 - E_2 - c - o - w + pq}{pq - c}$.

Proposition 2: If $z > z_2$, $y = 1$ is an evolutionarily stable strategy. If $z < z_2$, the stability of y depends on x : when $x = x_1$, all values of y are stable; when $x < x_1$, $y = 0$ is stable; and when $x > x_1$, $y = 1$ is stable. This indicates that a high probability of fixed government subsidies encourages recycling enterprises to adopt active strategies. When the probability of fixed subsidies is low, recycling enterprises' decisions are influenced by the behavior of construction companies.

3) Government

The expected payoffs of the government under fixed subsidy (ES_5) and gradually reduced subsidy (ES_6) strategies, as well as the average expected payoff $\overline{ES}$ are:

$$ES_5 = xy(G_1 - E_1 + E_2) + x(1 - y)(G_2 + w - E_1) + y(1 - x)(G_3 + H - E_2 - u) + (1 - x)(1 - z)(H + w - u) \quad (11)$$

$$ES_6 = xy(G_1 - (E_1 - pq) - (E_2 - pq)) + x(1 - y)(G_2 + w - (E_1 - pq) + c) + y(1 - x)(G_3 + H - E_2 + pq - u + c) + (1 - x)(1 - z)(H + w - u + 2c) \quad (12)$$

$$\overline{ES} = zES_5 + (1 - z)ES_6 \quad (13)$$

The replication dynamic equation $F(z)$ and its derivative are:

$$F(z) = \frac{dz}{dt} = y(E S_5 - \overline{ES}) = -z(z - 1)(cx - 2c + cy - pqx - pqy + u - ux) \quad (14)$$

$$\frac{dF(z)}{dx} = (1 - 2z)(cx - 2c + cy - pqx - pqy + u - ux) \quad (15)$$

To simplify the expression, define $U(y) = cx - 2c + cy - pqx - pqy$. According to the stability theorem of differential equations, for the probability z of the government adopting a fixed subsidy strategy to be stable, the following conditions must hold: $F(z) = 0$ and $\frac{dF(z)}{dx} < 0$. For convenience in discussion, define $y_2 = \frac{(c - pq - u)x - 2c + u}{pq - c}$, and $x_2 = \frac{2c - u}{c - pq - u}$.

Proposition 3: If $x > x_2$, then $z = 0$ is an evolutionarily stable strategy. If $x < x_2$, the stability of $y = y_2$, all values of z are stable; when $y < y_2$, $z = 1$ is stable; and when $y > y_2$, $z = 0$ is stable. This suggests that when construction enterprises are more likely to adopt a positive approach, the government tends to reduce subsidies. Conversely, if construction enterprises are less cooperative, the government's decision is influenced by the behavior of recycling enterprises.

3.3.2 Stability analysis of system equilibrium points

After analyzing the strategic stability of each individual participant, it is essential to further examine the equilibrium states of the overall system. By setting $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$, eight pure-strategy equilibrium points are identified, from $E_1(0,0,0)$ to $E_8(1,1,1)$. To assess the stability of these equilibrium points, the Jacobian matrix J is constructed as follows:

$$J = \begin{bmatrix} \lambda_1 & nx(1 - x) & x(c - pq)(x - 1) \\ -y(V - i)(1 - y) & \lambda_2 & y(c - pq)(y - 1) \\ z(z - 1)(u - c + pq) & z(c - pq)(1 - z) & \lambda_3 \end{bmatrix} \quad (16)$$

In this matrix, λ_1 , λ_2 , and λ_3 are the eigenvalues derived from the earlier expressions. The stability of each equilibrium point is determined by the signs of these eigenvalues. The conditions for determining evolutionary stability are presented in Table 2.

Table 2. Conditions for determining evolutionary stable points.

Equilibrium Point	Eigenvalue	Stability Condition
$E_1(0,0,0)$	$\lambda_1 = E_1 - F + H + I - R + c + f - pq;$ $\lambda_2 = K_1 - E_2 - c - o - w + pq;$	$F + R + n > E_1 - pq + H + I + c;$ $K_1 > E_2 - pq + c + o + w;$

	$\lambda_3 = u - c - pq.$	$u < 2c.$
$E_2(0,1,0)$	$\lambda_1 = E_1 - F + H + I - R + c + f - pq;$ $\lambda_2 = K_1 - E_2 - c - o - w + pq;$ $\lambda_3 = u - c - pq.$	$F + R > E_1 - pq + H + I + c;$ $K_1 < E_2 - pq + c + o + w;$ $u < c + pq.$
$E_3(0,0,1)$	$\lambda_1 = E_1 - F + H + I - R + f - n;$ $\lambda_2 = E_2 - K_1 + o + w;$ $\lambda_3 = 2c - u.$	$F + R + n > E_1 + H + I + f;$ $K_1 > E_2 + o + w;$ $u > 2c.$
$E_4(0,1,1)$	$\lambda_1 = E_1 - F + H + I - R + f;$ $\lambda_2 = K_1 - E_2 - o - w;$ $\lambda_3 = c - u + pq.$	$F + R > E_1 + H + I + f;$ $K_1 < E_2 + o + w;$ $u > c + pq.$
$E_5(1,0,0)$	$\lambda_1 = F - E_1 - H - I + R - c - f + n + pq;$ $\lambda_2 = E_2 - K_1 + V + c - i + o + w - pq;$ $\lambda_3 = -c - pq.$	$F + R + n < E_1 - pq + H + I + c + f;$ $K_1 + i > E_2 - pq + V + c + o + w.$
$E_6(1,1,0)$	$\lambda_1 = F - E_1 - H - I + R - c - f + pq;$ $\lambda_2 = K_1 - E_2 - V - c + i - o - w + pq;$ $\lambda_3 = -2pq.$	$F + R < E_1 - pq + H + I + c + f;$ $K_1 + i < E_2 - pq + V + c + o + w.$
$E_7(1,0,1)$	$\lambda_1 = F - E_1 - H - I + R - f + n;$ $\lambda_2 = E_2 - K_1 + V - i + o + w;$ $\lambda_3 = c + pq > 0.$	Unstable point
$E_8(1,1,1)$	$\lambda_1 = F - E_1 - H - I + R - f;$ $\lambda_2 = K_1 - E_2 - V + i - o - w;$ $\lambda_3 = 2pq > 0.$	Unstable point

Based on the above analysis of equilibrium points and the Jacobian matrix, the following propositions are proposed:

Proposition 4: When $F + R > E_1 - pq + H + I + c + f$, $K_1 > E_2 - pq + c + o + w$, and $u < 2c$, the stable point is $E_1(0,0,0)$. When $F + R + n > E_1 + H + I + f$, $K_1 > E_2 + o + w$, and $u > 2c$, the stable point is $E_3(0,0,1)$. This indicates that high costs for enterprises lead to passivity, and the government's strategy is affected by environmental costs.

Proposition 5: When $F + R > E_1 - pq + H + I + c + f$, $K_1 < E_2 - pq + c + o + w$, and $u < c + pq$, the stable point is $E_2(0,1,0)$. When $F + R > E_1 + H + I + f$, $K_1 < E_2 + o + w$, and $u > c + pq$, the stable point is $E_4(0,1,1)$. These results indicate that recycling enterprises are more likely to adopt active strategies when their costs are low, while construction enterprises may still remain passive. The government must strike a balance between environmental damage, fines, and subsidies.

Proposition 6: When $F + R + n < E_1 - pq + H + I + c + f$ and $K_1 + I > E_2 - pq + V + c + o + w$, the stable point is $E_5(1,0,0)$. When $F + R < E_1 - pq + H + I + c + f$ and $K_1 + I < E_2 - pq + V + c + o + w$, the stable point is $E_6(1,1,0)$. These findings show that positive economic returns can motivate construction enterprises to engage in proactive waste management. The optimal state, represented by $E_6(1,1,0)$, enables the government to reduce subsidies while fostering a market-driven recycling ecosystem.

4. Results and Discussion

4.1 Evolutionary trajectories and equilibrium scenarios

The development of a tripartite evolutionary game model offers a comprehensive theoretical framework for analyzing the complex interactions among government, construction enterprises, and recycling enterprises. The in-depth analysis of conditions governing the system's evolutionary stable points (Table 2) provides critical insights. Notably, it identifies not only the optimal equilibrium state $E_6(1,1,0)$ but also several persistent 'policy traps' that reflect common real-world implementation failures. One such trap is the 'governance deadlock' represented by $E_1(0,0,0)$, where prohibitive high operational costs prevent stakeholders from engaging in any proactive behavior. Another is the 'perpetual subsidy trap' of $E_3(0,0,1)$, in which public funds are continuously allocated without complementary enforcement measures, leading to minimal behavioral change. Overcoming such systemic inertia requires a well-calibrated policy mix that combines high-impact initial incentives with credible penalties, thereby reshaping the underlying cost-benefit structure of stakeholder decision-making. In contrast, the model also reveals a subtler but equally problematic scenario: the 'supply chain disconnect' in $E_5(1,0,0)$. In this case, the upstream proactivity of construction enterprises is rendered ineffective due

to passive engagement by the downstream recycling sector. This bottleneck cannot be resolved through generic incentives alone. Instead, it calls for targeted interventions to enhance market connectivity, such as standardizing waste-derived products and creating stable demand through green procurement mandates.

To verify the robustness of the proposed theoretical framework and to examine the influence of various parameters on stakeholder behavior, a numerical simulation is conducted using MATLAB2016b. While the theoretical analysis considers all equilibrium points, the simulation analysis is deliberately focused on the evolutionary path toward the ideal stable state, which consists of a proactive attitude, proactive attitude, and a gradually reducing subsidy strategy. This combination represents the central policy objective. The initial parameter values for the numerical simulation are summarized in Table 3. A detailed justification for each parameter, grounded in empirical evidence and an analysis of prevailing regulatory and market conditions, is provided in Table S1 to ensure full transparency. Given the current challenges in China’s construction waste management^[64], the initial probabilities for strategy selection are set at $x = 0.5$, $y = 0.5$, and $z = 0.5$. This setup is intended to reflect a market in a state of transition, where stakeholders have not yet established firm long-term strategies.

Table 3. Initial parameter settings.

F	E_1	E_2	H	I	V	i	p	q	K_1	c	f	R	o	w	n	u
45	50	48	50	50	70	40	48	0.5	50	3	30	40	25	30	10	20

The simulation results demonstrate that the tripartite system ultimately stabilizes at an equilibrium in which both construction and recycling enterprises adopt proactive strategies, while the government gradually withdraws from direct subsidization. As shown in Figure 2, the probabilities of proactive strategies by construction enterprises (x) and recycling enterprises (y) increase over time, whereas the probability of the government adopting a fixed subsidy strategy (z) declines. This reflects the dynamic nature of incentive-driven evolution: once behavioral momentum is established, dependence on policy stimuli diminishes. These results support the theoretical argument for time-bound government intervention. Subsidies function most effectively as transitional tools that ignite self-reinforcing behavioral patterns. This finding is consistent with the experiences of countries such as Germany and Japan, where governments initially provided substantial subsidies to jump-start the recycling industry and later phased out support as enterprises internalized sustainable practices^[65]. In contrast, similar transitions have stalled in some emerging economies where subsidy reductions were introduced prematurely or were not aligned with enterprise readiness^[66]. In the early stages of promoting construction waste recycling, government subsidies can serve as a powerful catalyst. For example, they can help recycling enterprises overcome high initial investment barriers associated with establishing advanced waste-processing facilities. Financial support from the government can encourage market entry and operational initiation. For construction enterprises, subsidies can offset the costs of waste sorting and transportation, making recycling a more viable alternative to landfilling. As the market matures and enterprises accumulate experience in sustainable practices, government subsidies can be gradually reduced. This approach not only fosters market self-sufficiency but also ensures the efficient use of public resources.

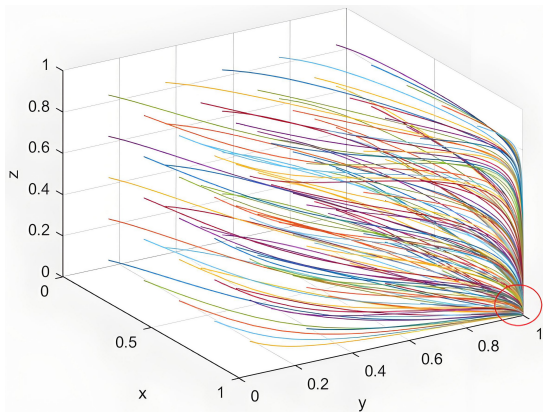


Figure 2. Evolutionary trajectories of strategy probabilities (x , y , z) over time.

4.2 Influence of initial strategic conditions

The initial distribution of stakeholder strategies plays a crucial role in shaping the evolutionary trajectory of the construction waste management system, as illustrated in Figure 3. Figure 3a shows that when construction enterprises begin with a high probability of adopting a proactive recycling strategy (a higher value of x), the system tends to evolve more efficiently toward a cooperative and sustainable equilibrium. This findings aligns with experiences from Finland and South Korea, where early and strong engagement of construction actors in on-site waste sorting accelerated systemic progress^[67,68]. As primary producers of construction waste, early

involvement by construction enterprises in source-level waste sorting reduces the complexity and costs associated with downstream processing. This facilitates recycling enterprises in adopting high-quality treatment methods, which corresponds to an increase in y (Recycling Enterprise Strategy), as shown in Figure 3b. Enhanced collaboration between these two stakeholders improves operational efficiency and reduces the overall system's reliance on government intervention. Figure 3c illustrates that with stronger private-sector synergy, the government is more likely to transition from a fixed subsidy model to a gradually decreasing subsidy strategy, reflected by a decline in z (Government Strategy). This adjustment leads to more rational allocation of public resources and promotes the development of a self-regulating market.

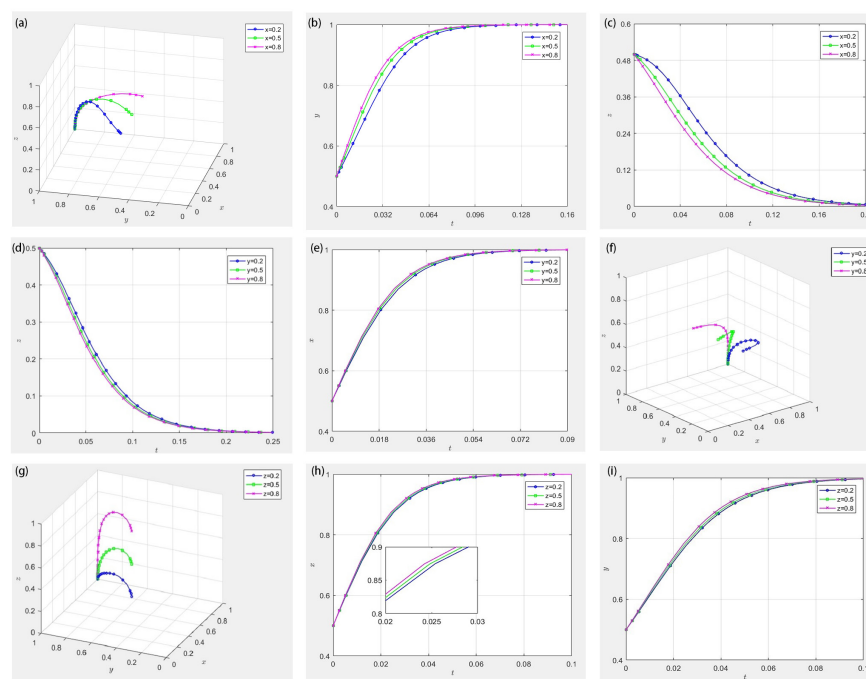


Figure 3. Influence of initial strategy probabilities on system evolution.

However, when the government begins with a high probability of implementing a fixed subsidy policy, represented by a higher initial value of z as shown in Figure 3d, it may temporarily reduce financial barriers for recycling enterprises and stimulate early-stage development. Nevertheless, if such subsidies are maintained without being adjusted to reflect market maturity, they can lead to long-term inefficiencies. Similar concerns have been raised in studies from Brazil and India, where prolonged subsidies resulted in distorted enterprise incentives and diminished motivation for technological innovation^[69]. Recycling enterprises may become overly dependent on external financial support, reducing their willingness to enhance competitiveness or adopt advanced technologies. Moreover, Figure 3e shows that when x is initially low, indicating that construction enterprises are passive in recycling efforts, the limited availability of well-classified waste disrupts the input flow necessary for recycling operations. This, in turn, reduces the efficiency of the entire system. As demonstrated in Figure 3f, even when y is high, the lack of upstream cooperation constrains potential gains, highlighting the critical role of construction enterprises in shaping the dynamics and performance of the entire system.

In addition, Figure 3g illustrates that recycling enterprises respond more sensitively to changes in government strategy than construction enterprises. A reduction in z often leads to a decline in y , indicating that recyclers are more vulnerable to the withdrawal of subsidies. This heightened sensitivity suggests that recycling enterprises occupy a structurally weaker position within the system and require coordinated support to maintain stability. When both x and z are low, as shown in Figure 3h, recycling enterprises face compounded constraints resulting from inadequate upstream collaboration and insufficient policy support. Under such conditions, they may be forced to scale back operations or even exit the market. These findings underscore the necessity of simultaneous strategic commitment from all stakeholders to ensure systemic resilience. Finally, Figure 3i demonstrates the role of regulatory enforcement beyond financial incentives. Stronger regulations can directly increase x by motivating construction enterprises to engage more actively in waste sorting. Improvements in construction practices, in turn, enhance the quality of input materials available to recycling enterprises, encouraging a corresponding rise in y . This interplay between regulatory measures and enterprise behavior strengthens system cohesion and accelerates the transition toward a circular economy. Empirical evidence from Singapore supports this perspective, showing that robust enforcement mechanisms and clear defined accountability frameworks significantly improve compliance and foster stakeholder cooperation^[70].

4.3 Sensitivity analysis of subsidy and penalty parameters

Figure 4 investigates the system's sensitivity to financial incentives and reveals how stakeholder behaviors are differentially influenced by subsidies and penalties across varying levels of market maturity. When the construction waste recycling market is at an early stage, characterized by a low resource utilization rate (q), subsidies play a crucial role in shaping enterprise decision-making. As shown in Figure 4a, an increase in E_1 , the subsidy provided to construction enterprises, substantially promotes the adoption of proactive behaviors, indicated by a rise in x . At this stage, financial support effectively lowers the perceived cost-risk ratio associated with waste sorting, encouraging enterprises to actively engage in sustainable practices. This finding is consistent with Wang *et al.*^[71], who argued that early-stage fiscal incentives are essential to overcoming behavioral inertia and investment aversion in construction firms. However, as the market matures and q increases, the marginal effectiveness of E_1 diminishes. This observation aligns with the principle of diminishing returns^[72], suggesting that beyond a certain threshold of market development, enterprises become less reliant on external subsidies and more responsive to internal cost-benefit considerations. A similar pattern is observed in Figure 4b, where increases in E_2 , the subsidy directed to recycling enterprises, initially raise the likelihood of adopting high-quality processing methods, resulting in higher values of y . As noted by Green *et al.*^[73], static subsidy schemes often fail to accommodate evolving operational conditions and may lead to rent-seeking behaviors in mature markets. These findings support a dynamic policy adjustment approach, whereby financial incentives are gradually replaced by efficiency gains and competitive market mechanisms as the system advances toward maturity.

In contrast to subsidies, penalties maintain a consistently strong influence on enterprise strategies across all stages of market development. Figure 4c reveals that raising the base penalty H for construction enterprises that fail to meet environmental standards effectively raises the probability of proactive behavior, thereby increasing x . This observation aligns with the findings of Mazzucato *et al.*^[74], who emphasized that negative incentives, particularly when clearly enforced, serve as more powerful behavioral drivers under conditions of bounded rationality. Additional insights are presented in Figure 4d, which compares the behavioral effects of H and auxiliary fines c on construction enterprises. The result suggest that simple and unambiguous sanctions are more effective in shaping behavior than layered or complex penalty structures. This finding is consistent with Barak-Corren *et al.*^[75], who argued that clarity and immediacy in enforcement mechanisms significantly enhance compliance in environmental governance settings. From a policy design perspective, these findings underscore the importance of aligning incentive mechanisms with the evolving maturity of the market. Subsidies such as E_1 and E_2 are particularly effective during the early stages of system development, where they serve to lower financial entry barriers and stimulate initial participation. However, as the system matures, policy reliance should gradually shift toward well-defined and enforceable penalties, especially H , which offer a stable and credible deterrent against non-compliant behavior. This phased approach enhances regulatory efficiency and facilitates long-term behavioral adaptation among both construction and recycling enterprises.

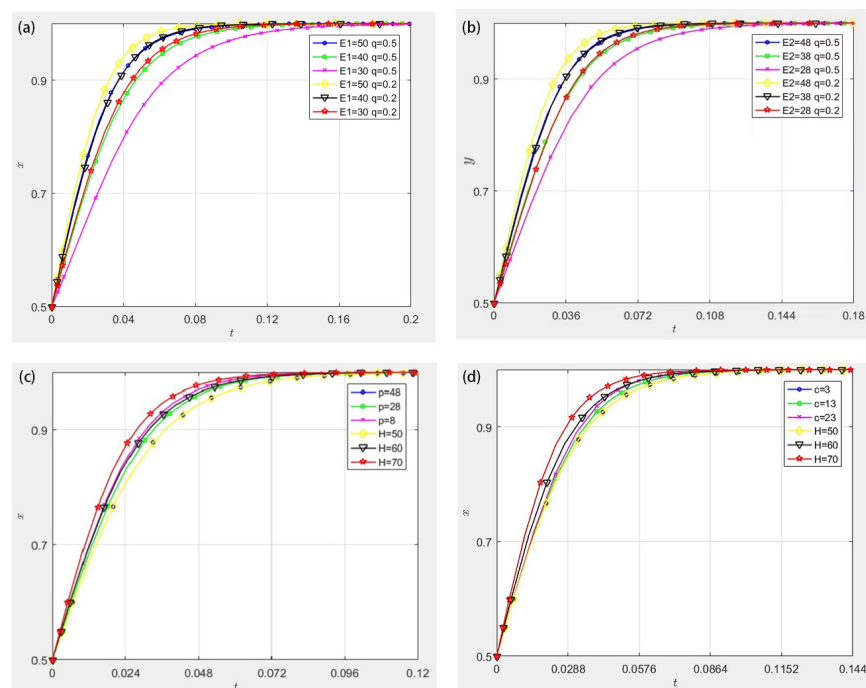


Figure 4. Sensitivity of strategic behavior to subsidy and penalty parameters.

4.4 Internal economic drivers of behavior

Beyond external policy levers, internal economic structures also play a critical role in shaping stakeholder decision-making, as shown in Figure 5. For construction enterprises, Figure 5a demonstrates that high waste classification costs (F) and low levels of inter-organizational cooperation (n) significantly hinder the adoption of proactive recycling behaviors, resulting in a lower value of x . Elevated sorting costs reduce the economic attractiveness of recycling, while weak cooperation mechanisms increase transaction and coordination costs between construction and recycling enterprises. These findings are consistent with observations by Ma *et al.*^[76], who noted that the absence of standardized on-site sorting systems and fragmented communication channels significantly impede source-level recycling performance in Chinese construction projects. Similarly, Yu *et al.*^[77] identified transaction inefficiencies and unclear role definitions among stakeholders as key barriers to implementing circular construction practices in European contexts. In contrast, Figure 5b illustrates that increasing resale revenue (l) and lowering the subsidy reduction coefficient (p) can help mitigate these internal deterrents. Higher revenue expectations motivate enterprises to invest in resource utilization, as the anticipated financial returns outweigh operational burdens. At the same time, a lower p indicates a more prolonged subsidy schedule, even as market maturity improves, thereby reducing the perceived long-term financial risks associated with inter-enterprise cooperation. These insights align with the findings of Tan *et al.*^[78], who emphasized that stable material recovery markets and predictable price signals are essential for encouraging upstream participation in waste separation activities.

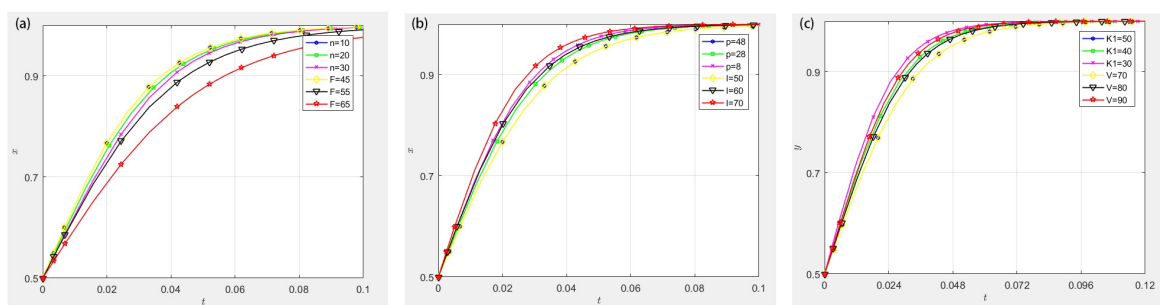


Figure 5. Effects of internal cost-reward structures on strategic decision-making.

For recycling enterprises, Figure 5c reveals that internal operational constraints, particularly processing costs (K_1) and opportunity costs (R), exert greater influence on strategic decisions than revenue incentives. High K_1 values reduce profit margins and discourage recyclers from investing in high-quality processing. Similarly, when R is high, the relative attractiveness of alternative investments lowers recyclers' willingness to commit to long-term waste treatment strategies, thereby decreasing y . This is consistent with findings by Wu *et al.*^[79], who reported that under conditions of high uncertainty and low net returns, recycling enterprises tend to prioritize short-term flexibility over long-term ecological performance. These dynamics suggest that reducing structural cost burdens may lead to more significant behavioral improvements than marginal increases in revenue-based incentives. From an infrastructure and policy standpoint, this implies that improving logistics efficiency, streamlining cooperation mechanisms, and lowering transaction costs are essential for supporting enterprise engagement in recycling. For example, upgrading waste collection and sorting infrastructure can help reduce F and K_1 , while the establishment of digital coordination platforms or standardized industry practices can improve n , facilitating smoother cooperation across the supply chain. Such interventions address the root causes of reluctance and promote a more resilient and cost-effective circular economy system.

These results support the implementation of a staged and actor-sensitive policy framework. In the early stages of market development, fixed subsidies are essential for overcoming behavioral inertia and risk aversion among enterprises. Such financial support can provide the necessary impetus for both construction and recycling enterprises to invest in sustainable waste management practices. For instance, the government may subsidize the purchase of advanced waste-sorting equipment for construction enterprises or support the research and development of innovative recycling technologies for recycling firms. During the transitional stage, as the market begins to mature, regulatory focus should gradually shift toward targeted penalties. These penalties serve to reinforce compliance expectations and ensure continued adherence to sustainable practices. For example, construction enterprises that fail to meet waste-reduction targets may be penalized, thereby encouraging the adoption of improved waste management strategies. In the mature phase of market development, government efforts should prioritize reducing system-level transaction costs and facilitating stable, long-term revenue mechanisms through market-based instruments such as contractual agreements and innovation support. For example, promoting long-term contracts between construction and recycling enterprises can provide mutual stability, enhance market predictability, and encourage sustained investment in recycling technologies. To maximize policy effectiveness, measures should be tailored to the specific roles and cost structures of each stakeholders group. For construction enterprises, this may involve reducing waste disposal costs and simplifying compliance procedures. For recycling enterprises, policies should aim to improve market access and enhance the quality and competitiveness of recycled products.

5. Conclusion

This study presents an evolutionary game-theoretic model to explore the dynamic interactions among construction enterprises, recycling enterprises, and government regulators in the field of construction and demolition waste resource utilization. By integrating bounded rationality, phased subsidy mechanisms, penalty enforcement, and firm-level economic variables, the model effectively captures the adaptive decision-making processes of heterogeneous stakeholders under changing policy environments. The simulation results indicate that a cooperative equilibrium can be achieved when enterprises adopt proactive strategies and the government progressively withdraws from direct subsidy provision. This outcome depends on the strategic deployment of early-stage incentives alongside consistent regulatory enforcement. In the initial stages of market development, subsidies play a pivotal role in reducing financial risks and encouraging participation. However, as behavioral norms become established and the market matures, the marginal effectiveness of subsidies declines. In contrast, penalties remain consistently effective, serving as a stable deterrent against non-compliance. These findings highlight the importance of transitioning from subsidy-driven incentives to enforcement-based mechanisms as the system evolves.

The analysis further demonstrates that the initial behavioral inclinations of stakeholders, particularly construction enterprises, significantly influence the speed and direction of system convergence. As upstream actors, construction firms exert considerable influence on coordination dynamics and the regulatory responses of other stakeholders. Early adoption of proactive waste practices by these actors can produce positive spillover effects, thereby accelerating the emergence of a stable and self-regulating system. Policymakers should therefore take into account the role of key actors and initial market conditions when designing and sequencing interventions. Moreover, the study finds that internal enterprise economics, such as sorting costs, resale revenues, and coordination barriers, play a critical role in shaping strategic decisions. Addressing these structural constraints through investments in infrastructure, standardization of waste classification processes, and enhanced inter-firm communication may prove more effective in sustaining long-term cooperation than reliance on financial incentives alone.

The findings lead to concrete recommendations for policymakers and industry practitioners aiming to promote a circular economy in the construction sector. A uniform policy approach is unlikely to succeed. Instead, governments should adopt an adaptive, multi-stage strategy. During the initial market incubation phase, high-impact tools such as direct subsidies and tax credits are necessary to lower entry barriers and stimulate investment in sorting and recycling. As the market matures and behaviors begin to stabilize, policy should enter a behavioral consolidation phase, gradually phasing out subsidies while reinforcing penalties for non-compliance to avoid dependency. In the system optimization phase, the focus should shift from direct financial instruments to reducing systemic transaction costs through measures such as standardizing waste classification, creating digital material exchange platforms, and investing in shared infrastructure. Given the pivotal role of construction enterprises, early policies should be tailored to them, including targeted grants, training programs, and public recognition to create positive demonstration effects. Ultimately, sustainable change hinges on making recycling economically viable. This necessitates creating strong market pull through instruments such as GPP mandates, quality certification systems for secondary materials, and support for long-term contracts between suppliers and users.

While this model offers valuable insights, it also has limitations that open avenues for future research. The current model assumes homogeneity within each stakeholder group. In practice, construction enterprises vary significantly in size, ownership structure, technological capacity, and risk tolerance. For example, large state-owned firms may be more responsive to reputational incentives and regulatory pressure, whereas small and medium-sized private firms are more sensitive to direct financial costs. These behavioral differences could shape distinct evolutionary pathways or generate multiple local equilibria. In addition, variations in regional policy enforcement intensity, logistical infrastructure, and market accessibility may affect strategic responses across different geographic contexts. Future studies could incorporate heterogeneity in firm size, technological readiness, or risk aversion to better reflect real-world complexities. Furthermore, the framework could be expanded by integrating spatial dimensions to capture regional differences in enforcement and transportation costs. Finally, calibrating the model using empirical data from a specific cities or region would enhance its predictive accuracy and policy relevance for sustainable urban development and waste governance.

Supplementary materials

The supplementary material for this article is available at: [Supplementary materials](#).

Declarations

Authors contribution

Zheng C: Conceptualization, methodology, data curation, formal analysis, writing-original draft.

Qiao G: Software, validation, investigation, writing-review & editing.

Hao JL: Supervision, writing-review & editing, project administration.

Di Sarno L: Methodology, formal analysis, writing-review & editing.

Mannis A: Supervision, software, validation.
Wen Z: Data curation, resources, visualization.
Xu B: Conceptualization, writing-review & editing.
Wang L: Methodology, formal analysis.

Conflicts of interest

Leins Wang works for the company Happy Assembly Technology. Jianli Hao is an Associate Editor of *Journal of Building Design and Environment*. The other authors declare no conflicts of interest.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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References

1. Ma M, Tam VW, Le KN, Butera A, Li W, Wang X. Comparative analysis on international construction and demolition waste management policies and laws for policy makers in China. *J Civ Eng Manag*. 2023;29(2):107-130. [DOI]
2. Gao Y, Wang J, Xu X. Machine learning in construction and demolition waste management: Progress, challenges, and future directions. *Autom Constr*. 2024;162:105380. [DOI]
3. Lyu Y, Xiong N, Liang Y, Lin S, Wang J. Estimation of construction and demolition waste and assessment of disposal facility location: An integrated material flow analysis and geographic information system approach. *Resour Conserv Recycl*. 2025;218:108226. [DOI]
4. Balali A, Gholami S, Javanmardi M, Valipour A, Yunusa-Kaltungo A. Assessment of heavy metal pollution in the soil of a construction and demolition waste landfill. *Environ Nanotechnol Monit Manag*. 2023;20:100856. [DOI]
5. Wang Q, Liu Y. Beautifying urban environment: Smart city construction and sustainable pollution control in China. *J Environ Manage*. 2024;371:123262. [DOI]
6. Yang S, Liu J, Bi X, Ning Y, Qiao S, Yu Q, et al. Risks related to heavy metal pollution in urban construction dust fall of fast-developing Chinese cities. *Ecotoxicol Environ Saf*. 2020;197:110628. [DOI]
7. Zhang Y, Teoh BK, Zhang L. Data-driven optimization for mitigating energy consumption and GHG emissions in buildings. *Environ Impact Assess Rev*. 2024;107:107571. [DOI]
8. Hu Q, Su P, Xiong F. Dynamic game strategies for construction and demolition waste recycling with learning and reference effects. *Environ Impact Assess Rev*. 2021;89:106592. [DOI]
9. Ma W, Hao JL, Zhang C, Guo F, Di Sarno L. System dynamics-life cycle assessment causal loop model for evaluating the carbon emissions of building refurbishment construction and demolition waste. *Waste Biomass Valor*. 2022;13:4099-4113. [DOI]
10. Yu Y, Junjan V, Yazan DM, Iacob ME. A systematic literature review on Circular Economy implementation in the construction industry: a policy-making perspective. *Resour Conserv Recycl*. 2022;183:106359. [DOI]
11. Hua C, Chen L, Liu C, Yang C. The effect of incentive policies on the diffusion of construction and demolition waste recycling: A government perspective. *Waste Manag Res*. 2025;43(1):50-61. [DOI]
12. Santos G, Esmizadeh E, Riahinezhad M. Recycling construction, renovation, and demolition plastic waste: review of the status quo, challenges and opportunities. *J Polym Environ*. 2024;32:479-509. [DOI]
13. Zhao W, Wang K, Guo F, Hao JL, Zhang Q, Qi J. Unraveling barriers to digital twin adoption under Construction 4.0: A DEMATEL-ISM-

- MICMAC approach. *J Build Des Environ.* 2025;3:202438. [DOI]
14. Lin W, Zhang J, Yu M, Tan R. Cooperation dilemmas in construction and demolition waste recycling: From understanding to navigating. *Int J Prod Econ.* 2025;283:109580. [DOI]
 15. Hao JL, Zhao W, Gong G, Ma W, Li L, Zhang Y. Catalyzing sustainability through prefabrication: Integrating BIM-LCA for assessing embodied carbon in timber formwork waste. *Sustain Chem Pharm.* 2024;41:101698. [DOI]
 16. Zhang J, Huang Z, Zhu Z, Yang S, Wei J. Research progress of the recycled aggregate concrete in life cycle assessment. *J Build Des Environ.* 2024;2:32570. [DOI]
 17. Zhao W, Hao JL, Gong G, Ma W, Zuo J, Di Sarno L. Decarbonizing prefabricated building waste: Scenario simulation of policies in China. *J Clean Prod.* 2024;458:142529. [DOI]
 18. Pan Y, Zhang L. Modeling and analyzing dynamic social networks for behavioral pattern discovery in collaborative design. *Adv Eng Inform.* 2022;54:101758. [DOI]
 19. Biancardo SA, Gesualdi M, Savastano D, Intignano M, Henke I, Pagliara F. An innovative framework for integrating Cost-Benefit Analysis (CBA) within Building Information Modeling (BIM). *Socioecon Plann Sci.* 2023;85:101495. [DOI]
 20. Peng L, Cao WJ. Measuring circularity in the construction industry: A systematic literature review from the stakeholder perspective. *J Clean Prod.* 2025;496:144805. [DOI]
 21. Li M, Han C, Shao Z, Meng L. Exploring the evolutionary mechanism of the cross-regional cooperation of construction waste recycling enterprises: A perspective of complex network evolutionary game. *J Clean Prod.* 2024;434:139972. [DOI]
 22. Zhu Q, Zhang X, Pan Y, Liu X. Optimizing environmental regulation policies for digital transformation in energy enterprises in China: An evolutionary game theory approach. *J Environ Manage.* 2024;370:122935. [DOI]
 23. Ma W, Yuan H, Hao JL. A bibliometric visual analysis of the system dynamics approach for construction and demolition waste management. *Clean Waste Syst.* 2022;1:100004. [DOI]
 24. Naghibalsadati F, Gitifar A, Richter A, Tasnim A, Ng KTW. Uncovering key themes in modular construction waste management and exploring their impact and centrality. *Results Eng.* 2025;25:104550. [DOI]
 25. Marín-Cortés S, Fernández-Álvarez M, Enríquez E, Fernández JF. Experimental characterization data on aggregates from construction and demolition wastes for the assistance in sorting and recycling practices. *Constr Build Mater.* 2024;435:136798. [DOI]
 26. Hasibuan GCR, Al Fath MT, Yusof N, Dewi RA, Syafridon GGA, Jaya I, et al. Integrating circular economy into construction and demolition waste management: A bibliometric review of sustainable engineering practices in the built environment. *Case Stud Chem Environ Eng.* 2025;11:101159. [DOI]
 27. Ding Z, Wang X, Zou PXW. Barriers and countermeasures of construction and demolition waste recycling enterprises under circular economy. *J Clean Prod.* 2023;420:138235. [DOI]
 28. Bonifazi G, Grosso C, Palmieri R, Serranti S. Current trends and challenges in construction and demolition waste recycling. *Curr Opin Green Sustain Chem.* 2025;53:101032. [DOI]
 29. Hurlimann A, March A, Bush J, Moosavi S, Browne GR, Warren-Myers G. Climate change transformation in built environments—A policy instrument framework. *Urban Clim.* 2024;53:101771. [DOI]
 30. Liu H, Shang H, Yu J. Why waste sorting implementation remains ineffective: A theoretical analysis based on the generation process of waste sorting behavior in China. *Waste Manag.* 2025;201:114812. [DOI]
 31. Ababio BK, Lu W, Agyekum K, Ghansah FA. Enhancing circular construction through procurement: A conceptual stakeholder-centric collaborative framework for sustainable outcomes. *Environ Impact Assess Rev.* 2025;112:107784. [DOI]
 32. Li L, Zuo J, Du L, Chang R. What influences the on-site recycling behaviour of C&D plastic waste in Australia? An action determination model approach. *J Environ Manage.* 2024;371:123158. [DOI]
 33. Liu J, Chen Y, Wang X. Factors driving waste sorting in construction projects in China. *J Clean Prod.* 2022;336:130397. [DOI]
 34. Stabler D, Hakala H, Huikkola T, Menton AL. Aligning servitization and circularity: The role of institutional confluence in sustainable business models. *J Clean Prod.* 2024;462:142666. [DOI]
 35. Munaro MR, Tavares SF. A review on barriers, drivers, and stakeholders towards the circular economy: The construction sector perspective. *Clean Responsible Consum.* 2023;8:100107. [DOI]
 36. Tan XC, Kong LS, Gu BH, Zeng A, Niu MM. Research on the carbon neutrality governance under a polycentric approach. *Adv Clim Change Res.* 2022;13:159-168. [DOI]
 37. Chen C. Development of green business strategies through green dynamic capabilities and environmental regulation: Empirical evidence from the construction sector. *J Clean Prod.* 2024;438:140826. [DOI]
 38. Mallick PK, Salling KB, Pigosso DCA, McAloone TC. Designing and operationalising extended producer responsibility under the EU Green Deal. *Environ Chall.* 2024;16:100977. [DOI]
 39. Eghbali MA, Rasti-Barzoki M, Altmann J. An evolutionary game-theoretic approach to analysis the green innovation chain dynamics under government policies. *Technol Soc.* 2024;77:102568. [DOI]
 40. Chao Y, Deng N, Du Y, Yao G, Zhou Z. Promoting carbon neutrality through ultra-low energy buildings in China: Evidence from evolutionary game theory. *Habitat Int.* 2025;156:103281. [DOI]
 41. Lv Y, Yang J, Sun X, Wu H. Evolutionary game analysis of stakeholder privacy management in the AIGC model. *Oper Res Perspect.* 2025;14:100327. [DOI]
 42. Wu J, Zhao Y, Fan S, Zhao Z, Zuo S, Wang J. Study on the diffusion of China certified emission reduction scheme under carbon trading

- mechanism: Based on the tripartite evolutionary game model. *Energy*. 2025;322:135643. [DOI]
43. Cheng L, Peng P, Huang P, Zhang M, Meng X, Lu W. Leveraging evolutionary game theory for cleaner production: strategic insights for sustainable energy markets, electric vehicles, and carbon trading. *J Clean Prod*. 2025;145682. [DOI]
44. Zhao X, Xue Y, Ding L. Implementation of low carbon industrial symbiosis systems under financial constraint and environmental regulations: An evolutionary game approach. *J Clean Prod*. 2020;277:124289. [DOI]
45. Ma W, Hao JL. Enhancing a circular economy for construction and demolition waste management in China: A stakeholder engagement and key strategy approach. *J Clean Prod*. 2024;450:141763. [DOI]
46. Yuan H, He L, Wu H, Zuo J. Differentiated subsidy mechanism for promoting construction and demolition waste recycling. *J Clean Prod*. 2023;405:137051. [DOI]
47. Sönnichsen SD, Clement J. Review of green and sustainable public procurement: Towards circular public procurement. *J Clean Prod*. 2020;245:118901. [DOI]
48. Liu Y, Zuo J, Pan M, Ge Q, Chang R, Feng X, et al. The incentive mechanism and decision-making behavior in the green building supply market: A tripartite evolutionary game analysis. *Build Environ*. 2022;214:108903. [DOI]
49. Zhao W, Hao JL, Gong G, Fischer T, Liu Y. Applying digital technologies in construction waste management for facilitating sustainability. *J Environ Manage*. 2025;373:123560. [DOI]
50. Abdulai IA, Fuseini MN, File DJMB. Making cities clean with collaborative governance of solid waste infrastructure in Ghana. *Clean Waste Syst*. 2024;8:100150. [DOI]
51. Stoffberg N, Ciulli F, Bridoux F, Hawlitschek F. Value co-creation in sharing service ecosystems: The role of institutional arrangements and social norms. *J Clean Prod*. 2025;492:144663. [DOI]
52. Ateeq M, Zhang N, Zhao W, Gu Y, Wen Z, Zheng C, et al. Enhancing construction waste transportation management using Internet of Things (IoT): An evaluation framework based on AHP-FCE method. *Buildings*. 2025;15:1381. [DOI]
53. Cheng L, Huang P, Zou T, Zhang M, Peng P, Lu W. Evolutionary game-theoretical approaches for long-term strategic bidding among diverse stakeholders in large-scale and local power markets: Basic concept, modelling review, and future vision. *Int J Electr Power Energy Syst*. 2025;166:110589. [DOI]
54. Progress on Environment and Development Policies in China and Impact of CCICED's Policy Recommendations (2023). In: *Green Empowerment and High Quality Development*. Springer. Singapore. [DOI]
55. Paleari S. The EU policy on climate change, biodiversity and circular economy: Moving towards a Nexus approach. *Environ Sci Policy*. 2024;151:103603. [DOI]
56. Zheng J, Tan R, Yu M, Tang Z, Zhang J. Optimal decisions of construction and demolition waste recycling based on reference green effect under different subsidy models. *Comput Ind Eng*. 2024;196:110479. [DOI]
57. Zhou Y, He Z, Zhao S. How do government subsidies affect the strategic choices of enterprises and individuals in agricultural waste recycling? *Sustain Prod Consum*. 2021;28:1687-1698. [DOI]
58. Li X, Liu X, Huang Y, Li J, He J. Theoretical framework for assessing construction enterprise green innovation efficiency and influencing factors: Evidence from China. *Environ Technol Innov*. 2023;32:103293. [DOI]
59. Ding Z, Huang X, Wang X, Zuo J. Assessment of promotional strategies for construction and demolition waste recycled products based on hybrid simulation system. *Environ Impact Assess Rev*. 2025;112:107814. [DOI]
60. Hao JL, Yu S, Tang X, Wu W. Determinants of workers' pro-environmental behaviour towards enhancing construction waste management: Contributing to China's circular economy. *J Clean Prod*. 2022;369:133265. [DOI]
61. Wu W, Lyu Y, Zheng C, Hao JL, Shen S, Yu S. Digital supervision in construction pollution control: Utilizing advanced information models for enhanced supervision and sustainability. *Environ Technol Innov*. 2025;37:104038. [DOI]
62. Allah Abadi AF, Ataee-pour M. Evaluating public-private partnerships in mining: An evolutionary game theory approach to strategic dynamics and regulatory impacts. *Resour Policy*. 2025;104:105575. [DOI]
63. Cheng L, Yu F, Huang P, Liu G, Zhang M, Sun R. Game-theoretic evolution in renewable energy systems: Advancing sustainable energy management and decision optimization in decentralized power markets. *Renew Sustain Energy Rev*. 2025;217:115776. [DOI]
64. Du W, Yuan H. Investigation of the relationship between economic growth and mismanaged construction waste: Evidence from 268 cities in China. *J Clean Prod*. 2024;482:144205. [DOI]
65. Xu L, Kim SY, Xiong J, Yan J, Huang H. Playing catch-up: how less developed nations can jump-start technology innovation. *J Bus Strategy*. 2018;41:49-57. [DOI]
66. Zavorská Z, Bykova A, Grieveson R, Hanzl-Weiss D, Sankot O. Industrial policy for a new growth model: A toolbox for EU-CEE countries [Internet]. Vienna: The Vienna Institute for International Economic Studies (wiiw); 2023. Available from: <https://wiiw.ac.at/industrial-policy-for-a-new-growth-model-a-toolbox-for-eu-cee-countries-dlp-6582.pdf>
67. Kim J. Construction and demolition waste management in Korea: recycled aggregate and its application. *Clean Technol Environ Policy*. 2021;23:2223-2234. [DOI]
68. Jaakkola M. Recycling municipal solid waste in the European Union: a multiple-case study exploring key success factors and commonalities among top performers [Internet]. 2023. Available from: <https://aaltoodoc.aalto.fi/items/e323034f-e65f-4ead-8206-317e2f6d3b1d>
69. Guo YM, Li X. The impact of greater VAT tax neutrality on total factor productivity: Evidence from China's VAT credit refund reform in 2018. *Econ Anal Policy*. 2023;78:922-936. [DOI]

70. Riyadh DH, Supriati BC, Lopez TC. Transparency and Policy Implementation in the Public Sector in Singapore. *J Public Policy Gov.* 2023;7(3):1-12. [DOI]
71. Wang W, Hao S, Zhong H, Sun Z. How to promote carbon emission reduction in buildings? Evolutionary analysis of government regulation and financial investment. *J Build Eng.* 2024;89:109279. [DOI]
72. Chen Y, Subhan M, Ahmad G, Adil M, Zamir MN. Unveiling the linkages among digital technology, economic growth, and carbon emissions: A resource management perspective. *Resour Policy.* 2024;91:104868. [DOI]
73. Green F, Gambhir A. Transitional assistance policies for just, equitable and smooth low-carbon transitions: who, what and how? *Clim Policy.* 2020;20:902-921. [DOI]
74. Mazzucato M, Kattel R, Ryan-Collins J. Challenge-driven innovation policy: Towards a new policy toolkit. *J Ind Compet Trade.* 2020;20:421-437. [DOI]
75. Barak-Corren N, Kariv-Teitelbaum Y. Behavioral responsive regulation: Bringing together responsive regulation and behavioral public policy. *Regul Gov.* 2021;15:S163-S182. [DOI]
76. Ma W, Liu T, Hao JL, Wu W, Gu X. Towards a circular economy for construction and demolition waste management in China: Critical success factors. *Sustain Chem Pharm.* 2023;35:101226. [DOI]
77. Yu S, Hao JL, Di Sarno L, Ma W, Guo N, Liu Y. Enhancing pro-environmental behaviour of employees towards renovation waste for a circular economy: The role of external supervision and corporate environmental responsibility. *Sustain Chem Pharm.* 2023;33:101103. [DOI]
78. Tan K, Xu , Fang , Yi , Zelong , Li C. Optimising resource recovery from construction waste material reverse supply chain coordination games. *Int J Syst Sci Oper Logist.* 2025;12:2458176. [DOI]
79. Wu W, Xie L, Hao JL. An integrated trading platform for construction and demolition waste recovery in a circular economy. *Sustain Chem Pharm.* 2022;25:100597. [DOI]

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