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Evolutionary game analysis of green packaging supply chain cooperative development considering consumer preferences for traceability

Jing Peng[a*], Yutong Shi[a] and Jinfeng Zeng[a]

[a]*School of Economic and Management, Xiamen university of technology, Xiamen, China*

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A B S T R A C T

Promoting green packaging production represents a crucial strategy for the packaging industry in its pursuit of sustainable development. This study constructs a three-party evolutionary game model involving suppliers, manufacturers, and brands to examine their strategic decision-making under various scenarios. Simulation and analysis yield three principal findings. First, the system initially begins at (0,0,0) and may transition to a manufacturer-dominated intermediate state—either (1,1,0) or (0,1,1)—before gradually stabilizing at the equilibrium point (1,1,1). Second, supply chain decision-making is influenced by both internal and external factors. Internal factors include penalty mechanisms, carbon trading allocation, and cooperative concessions, whereas external factors comprise consumer preferences for traceability and the environmental attributes of packaging. Specifically, suppliers are primarily driven by internal factors, manufacturers are predominantly influenced by external factors, and brands are impacted by a combination of both. Third, serving as the central node in the supply chain, manufacturers enable upstream and downstream integration through traceable production, refine cooperative concession mechanisms to enhance brand participation, and harness market signals to promote green transformation and co-production among suppliers. Therefore, the effective management of the green packaging supply chain necessitates the establishment and ongoing refinement of a tripartite active cooperation mechanism. Additionally, cultivating consumer preferences for traceability is essential for advancing the long-term sustainable development of the supply chain.

1. Introduction

In the context of globalization, industrial production remains a fundamental driver of national and regional economic growth, with the packaging industry occupying a pivotal role in this development. However, the pervasive use of non-biodegradable materials and inefficient recycling systems has resulted in substantial packaging waste accumulation, posing significant threats to ecosystems and human health (Lin, 2022). Addressing this challenge necessitates an urgent transition toward green packaging. Green technological innovation, as a core mechanism for reconciling economic growth with environmental sustainability, presents a feasible pathway to establishing a symbiotic relationship between low-carbon practices and sustained economic development (Huo et al., 2024). Green packaging seeks to minimize environmental pollution across the entire life cycle and is integral to the long-term sustainability of the packaging sector (Wu & Zhao, 2024). Despite its evident advantages, the transition to green packaging encounters numerous obstacles. A primary barrier involves information asymmetry between the sales and production segments of the traditional packaging supply chain, which significantly impedes the widespread adoption of green packaging. Therefore, fostering collaboration between producers and retailers, alongside the establishment of a synergistic green packaging supply chain mechanism, is essential to accelerating the industry's green transformation.

The integration of traceability technology presents an innovative approach to enhancing collaboration within the green packaging supply chain. By embedding traceability markers—such as QR codes—into packaging, companies can enable full

* Corresponding author Tel:15160098363
E-mail pjsophie@xmut.edu.cn (J. Peng)
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life-cycle traceability, encompassing raw material sourcing and production processes (Dai et al., 2021). Serving as the central node in the packaging supply chain, manufacturers play a pivotal role in linking upstream and downstream enterprises while facilitating information exchange through traceability technology. For example, Unilever has adopted traceability in its plastic packaging, enabling consumers to scan package labels and access information on plastic sources and recycling options. Similarly, Alibaba has integrated packaging traceability into its green logistics initiative, allowing consumers to scan QR codes on courier packages to obtain information regarding material origins and environmental attributes. This transparent information-sharing mechanism not only enhances consumer environmental awareness but also empowers them to monitor sustainability practices within the supply chain. Moreover, consumer preferences and feedback function as incentives for upstream enterprises to adopt greener production methods, thereby promoting emissions reductions at the source (Zhao et al., 2023a).

In summary, this study develops an evolutionary game model of the green packaging supply chain, incorporating suppliers, manufacturers, and brands. The model comprehensively incorporates key variables, including consumer traceability preferences, packaging greenness, and internal supply chain dynamics. The objective is to investigate the role of traceability technology in driving long-term emissions reduction within the green packaging supply chain and to assess the influence of various factors on supply chain evolution. Accordingly, this study seeks to provide both theoretical underpinnings and practical insights to support the green transformation of the packaging industry. Specifically, the study addresses the following research questions: (1) Can supply chain participants achieve long-term collaborative green development? (2) How do various factors affect their strategic decision-making? (3) In what ways can traceability technology facilitate information sharing and joint emissions reduction across the supply chain?

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature on green packaging supply chain management. Section 3 defines the research problem and formulates the evolutionary game model. Section 4 presents the model analysis. Section 5 conducts numerical simulations and interprets the results. Section 6 discusses the key findings, and Section 7 concludes the study.

2. Literature review

Green packaging design represents a critical strategy for mitigating environmental pollution and promoting sustainable development. Li and Wang (2023) emphasized that green packaging should align with the principles of minimizing material usage, enhancing recyclability, and ensuring biodegradability. Similarly, Li (2022) noted that the integration of green design concepts into product packaging can inherently communicate environmental values, thereby enhancing consumer acceptance. However, Wang et al. (2023) observed that despite broad societal support for eco-friendly packaging, a persistent gap between consumer attitudes and behaviors continues to impede its large-scale adoption. Consequently, consumer preferences for low-carbon products, coupled with their environmental awareness, play a pivotal role in advancing green packaging adoption. Empirical studies indicate that consumer demand for low-carbon products incentivizes firms to adopt greener production practices and supports the realization of carbon-neutral strategies (Ding et al., 2022; Z. Liu et al., 2023). Furthermore, Liu et al. (2021) found that consumers are willing to pay a premium for low-carbon products, motivating retailers to share carbon reduction costs with manufacturers. In addition, consumer demand for transparency concerning sustainable products significantly influences supply chain decision-making, with brand reputation emerging as a key determinant for both manufacturers and suppliers (Bera & Giri, 2024).

The adoption of collaborative development strategies within supply chains has emerged as a critical pathway toward sustainable transformation. Zhu et al. (2023) emphasized that the increasing accumulation of packaging waste contributes to severe environmental pollution, necessitating coordinated green governance across all segments of the supply chain. Studies have demonstrated that comprehensive active cooperation among supply chain members enhances both carbon emissions reduction and overall system profitability (Zhang & Qin, 2022). However, Liu et al. (2022) noted that certain firms may exhibit "free-rider" behavior—benefiting from emissions reduction initiatives without bearing the associated costs. To address this issue, contractual mechanisms have become a widely adopted approach for coordinating green supply chain activities. For example, Zhao et al. (2023b) demonstrated that revenue-sharing and cost-sharing contracts effectively align economic incentives and contribute to the reduction of packaging waste. Similarly, Li and Zhu (2023) argued that manufacturers must share the costs and risks associated with green product development with retailers to sustain active and long-term cooperation. Beyond contractual mechanisms, traceability technology serves as a critical enabler of supply chain coordination by facilitating end-to-end tracking from production to consumption. Collart and Canales (2022) underscored the significance of farm-to-fork traceability systems in the food supply chain, noting that such systems not only enhance food safety and reduce waste but also generate direct financial benefits. Likewise, Dong et al. (2023) emphasized that traceability technology enhances transparency, reinforces accountability, and supports more sustainable supply chain management.

Despite its benefits, the high installation cost of traceability technology remains a major barrier to widespread adoption, thereby underscoring the necessity of active cooperation among supply chain members (Ma et al., 2024). Furthermore, firms often disclose authentic traceability information selectively, primarily when it aligns with their strategic interests, thus highlighting the importance of well-structured incentive mechanisms (Ren et al., 2024). Bera and Giri (2024) found that consumer preferences for sustainability and traceability significantly influence the strategic decisions of manufacturers and suppliers, with brand reputation serving as a critical market driver. Similarly, Jiang et al. (2024) observed that in markets characterized by high consumer environmental awareness, traceability technology can act as a catalyst for manufacturers to intensify carbon reduction initiatives. Luo et al. (2024) further emphasized that traceability plays a pivotal role in fostering consumer trust and brand value by reinforcing confidence in product quality and origin. This finding is supported by prior studies indicating that transparent traceability systems enhance consumer trust and promote engagement with sustainable products (Ellahi et al., 2023; Fan et al., 2022).

This study contributes to the existing body of literature in several critical areas. First, it constructs a three-party evolutionary game model to explore the dynamic strategic interactions among suppliers, manufacturers, and brands. Second, it integrates consumer preferences for traceability as a pivotal factor in analyzing their impact on supply chain decision-making. Finally, it investigates the positive role of traceability in facilitating supply chain co-production, thereby offering novel theoretical insights into the sustainable transformation of green supply chains.

3. The Evolutionary Game Model

3.1 Background and problem description

In the three-tier green packaging supply chain, suppliers provide raw materials, manufacturers convert these into packaging, and brands procure the packaging for integration into final consumer products. Within this structure, suppliers have the option to adopt green production practices. Suppliers that opt for green production invest in the research and development of environmentally friendly technologies and sustainable raw materials. Manufacturers, in turn, determine whether to implement traceability systems. Traceability acts as a critical interface between upstream and downstream supply chain participants, necessitating that manufacturers establish standardized protocols and record relevant production data to ensure transparency. Concurrently, brands may choose to collaborate in the promotion of green packaging. Brands engaging in active cooperation assume the responsibility of marketing green packaging to enhance their market presence. Under this cooperative arrangement, manufacturers share revenue with brands according to a pre-established ratio.

3.2 Model Assumptions and Parameter Descriptions

The logical relationships among the three evolutionary game participants supplier, manufacturer, and brand are illustrated in the Fig. 1.

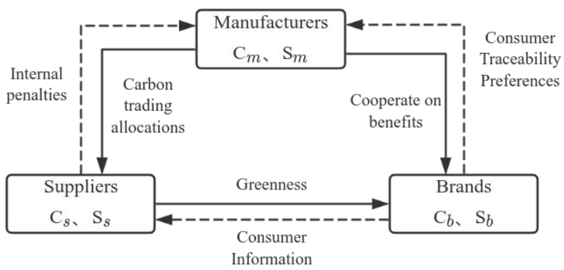

Fig. 1. Game relationship among payoffs for the three parties

Hypothesis 1: The green packaging supply chain involves three primary participants: the supplier (S), manufacturer (M), and brand (B). The supplier can choose between green production and traditional production, with probabilities x and 1-x, respectively. The manufacturer can adopt either traceability production or traditional production, with probabilities y and 1-y. The brand may opt for either active cooperation or negative cooperation, with probabilities z and 1-z. All three participants exhibit bounded rationality, continuously updating their strategies through a learning process over time.

Hypothesis 2: The supplier engages in green production by producing low-carbon, environmentally friendly raw materials and reducing carbon emissions throughout the production process. The degree of packaging greenness is represented by g, where $0 \le g \le 1$. Suppliers that adopt green production incur a production cost C_s and receive a corresponding benefit S_s. If the supplier collaborates with the brand while maintaining traditional production, it incurs a loss of potential consumer groups, denoted as T_1.

Hypothesis 3: The manufacturer engages in traceability production by improving the traceability system, providing traceability codes to consumers, and ensuring compliance with emission standards during the green packaging production process. Implementing traceability incurs a cost C_m and provides a corresponding benefit S_m. If the manufacturer adopts traditional production while the brand engages in cooperation, it incurs a loss of potential consumer groups, denoted as T_2.

Hypothesis 4: When the supplier adopts green production and the manufacturer implements traceability, their investments indirectly enhance the brand's market positioning and overall value, generating a benefit denoted as S_b for the brand. If the brand chooses to cooperate, it must invest in establishing traceability integration through collaboration with the manufacturer, thereby incurring an additional cost C_b. In contrast, non-cooperating brands do not bear responsibility for the manufacturer's emission reduction efforts and thus avoid this cost. However, manufacturer-led traceability results in a partial revenue concession to the cooperating brand, denoted as R_b. Non-cooperating brands, on the other hand, suffer the loss of potential consumer segments T_1 and T_2, due to the supplier's adoption of green production and the manufacturer's implementation of traceability, respectively.

Hypothesis 5: When the supplier adopts green production, the manufacturer adopts traceability, and the brand actively cooperates, the total benefit generated by the green packaging supply chain is denoted as W. This benefit is distributed among the three parties in proportions φ_1, φ_2 and φ_3, when $\varphi_1+\varphi_2+\varphi_3=1$.

Hypothesis 6: Consumers' preference for traceability is denoted by μ ($0\leqslant\mu\leqslant1$). This preference is reflected in consumer behavior, whereby individuals specifically seek products packaged with environmentally friendly materials and verify the carbon footprint of product origins using traceability codes to ensure alignment with their environmental values.

Hypothesis 7: To regulate carbon emissions during raw material production, the government implements a carbon allowance trading policy for the green packaging supply chain. The total carbon allowance is denoted as E, enabling firms to buy or sell surplus carbon emission rights at a unit price of 1 in the trading market. Under traditional production, the supplier emits E_0 units of carbon, while green production reduces emissions to $(1-g)E_0$. When the manufacturer adopts traceability, consumer-side supervision further compels upstream suppliers to reduce emissions, resulting in a final carbon emission level of $(1-\mu)(1-g)E_0$. The corresponding carbon trading revenue, calculated as $E-(1-\mu)(1-g)E_0$, is distributed between the supplier and the manufacturer in proportions θ_1 and θ_2, respectively, where $\theta_1+\theta_2=1$. If the manufacturer follows traditional production practices, it neither gains carbon trading benefits nor incurs related costs, underscoring the critical role of traceability in maximizing both environmental and economic gains.

Hypothesis 8: To enhance carbon emission reduction within the green packaging supply chain, an internal penalty mechanism is established between the supplier and the manufacturer. If one party adopts green or traceability technology while the other continues traditional production, the non-compliant party incurs a penalty F, which serves as compensation to the proactive member. This mechanism incentivizes both suppliers and manufacturers to align their strategies with sustainable practices, fostering mutual commitment to emission reduction. By imposing financial consequences on non-cooperative behavior, the system encourages proactive cooperation and accelerates the transition toward a low-carbon, traceable supply chain.Combining the above assumptions, the payoff matrix for suppliers, manufacturers, and brands in this evolutionary game model is shown in Table 1.

Table 1
Tripartite evolutionary game payoff matrix

		Suppliers	
		Green Production *x*	Traditional Production 1-*x*
Manufacturers Traceability Production *y*	Brands Active Cooperation *z*	$\varphi_1 W - C_s + S_s + \theta_1[E-(1-\mu)(1-g)E_0]$ $\varphi_2 W + S_m - C_m - R_b + \theta_2[E-(1-\mu)(1-g)E_0]$ $\varphi_3 W + R_b + S_b - C_b$	$-T_1 - F + \theta_1[E-(1-\mu)E_0]$ $S_m - C_m - R_b + F + \theta_2[E-(1-\mu)E_0]$ $R_b - C_b$
	Brands Positive Cooperation 1-*z*	$-C_s + S_s + \theta_1[E-(1-\mu)(1-g)E_0]$ $S_m - C_m + \theta_2[E-(1-\mu)(1-g)E_0]$ $S_b - T_1 - T_2$	$-F + \theta_1[E-(1-\mu)E_0]$ $S_m - C_m + F + \theta_2[E-(1-\mu)E_0]$ $-T_2$
Manufacturers Traditional Production1-*y*	Brands Active cooperation *z*	$-C_s + F + [E-(1-g)E_0]$ $-F - T_2$ $-C_b$	$-T_1 + (E-E_0)$ $-T_2$ $-C_b$
	Brands Positive Cooperation 1-*z*	$-C_s + F + [E-(1-g)E_0]$ $-F$ $-T_1$	$(E-E_0)$ 0 0

4. Model Analysis

4.1 Model Solution

Let E_{x_1} and E_{x_2} denote the expected returns for suppliers adopting the "green production" and "traditional production" strategies, respectively, with E_x representing the average return. Based on the game's payoff matrix, the expected and average returns for suppliers under both strategies can be computed accordingly.

$$\begin{aligned} E_{x1} &= yz\{\varphi_1 W - C_s + S_s + \theta_1[E-(1-\mu)(1-g)E_0]\} + y(1-z)\{-C_s + S_s + \theta_1[E-(1-\mu)(1-g)E_0]\} \\ &\quad + (1-y)z\{-C_s + F + [E-(1-g)E_0]\} + (1-y)(1-z)\{-C_s + F + [E-(1-g)E_0]\} \end{aligned} \tag{1}$$

$$\begin{aligned} E_{x2} &= yz\{-T_1 - F + \theta_1[E-(1-\mu)E_0]\} + y(1-z)\{-F + \theta_1[E-(1-\mu)E_0]\} + (1-y)z[-T_1 + (E-E_0)] \\ &\quad + (1-y)(1-z)(E-E_0) \end{aligned} \tag{2}$$

$$E_x = xE_{x1} + (1-x)E_{x2} \tag{3}$$

Analogously, let E_{y_1} and E_{y_2} denote the expected returns for the manufacturer under the "traceability production" and "traditional production" strategies, respectively, with E_y denoting the average expected return.

$$\begin{aligned} E_{y1} &= xz\{\varphi_2 W + S_m - C_m - R_b + \theta_2[E-(1-\mu)(1-g)E_0]\} + x(1-z)\{S_m - C_m + \theta_2[E-(1-\mu)(1-g)E_0]\} \\ &\quad + (1-x)z(-F-T_2) + (1-x)(1-z)(-F) \end{aligned} \tag{4}$$

$$E_{y2} = xz\{S_m - C_m - R_b + F + \theta_2[E-(1-\mu)E_0]\} + x(1-z)\{S_m - C_m + F + \theta_2[E-(1-\mu)E_0]\} + (1-x)z(-T_2) \tag{5}$$

$$E_y = yE_{y1} + (1-y)E_{y2} \tag{6}$$

Similarly, let E_{z_1} and E_{z_2} denote the expected returns for the brand adopting the "active cooperative" and "negative cooperative" strategies, with E_z denoting the average expected return.

$$E_{z1} = xy(\varphi_3 W + R_b + S_b - C_b) + x(1-y)(-C_b) + (1-x)y(R_b - C_b) + (1-x)(1-y)(-C_b) \tag{4}$$

$$E_{z2} = xy(S_b - T_1 - T_2) + x(1-y)(-T_1) + (1-x)y(-T_2) \tag{5}$$

$$E_z = zE_{z1} + (1-z)E_{z2} \tag{6}$$

The core objective of the evolutionary game is to identify the Evolutionary Stable Strategy (ESS) and examine the system's replicator dynamics. Based on Equations (1)-(9), the replicator dynamic equations for the system are derived.

$$F(x) = (1-x)x\{-Cs + F + E_0 g + y[Ss - E_0 g(1-\theta_1+\mu\theta_1)] + zT_1 + \varphi_1 Wyz\} \tag{10}$$

$$F(y) = (1-y)y\{-C_m + F + S_m + \theta_2[\mathrm{E} - E_0(1-\mu)(1-gx)] + (-R_b + T_2 + \varphi_2 Wx)z\} \tag{11}$$

$$F(z) = z(1-z)[-C_b + xT_1 + (R_b + T_2 + \varphi_3 Wx)y] \tag{12}$$

4.2 Tripartite Evolutionary Stability Analysis

Following Friedman's method, the ESS can be determined by performing a local stability analysis of the system's Jacobian matrix.

$$J = \begin{bmatrix} \begin{array}{l}(1-2x)\{-C_s + F - E_0 g + \varphi_1 Wyz \\ +y[S_s - E_0 g(1-\theta_1+\mu\theta_1)] + zT_1\}\end{array} & [x(1-x)(S_s + E_0 g(-1+\theta_1-\theta_1\mu) + \varphi_1 Wz)] & x(1-x)(T_1 + \varphi_1 Wy) \\ y(1-y)[\theta_2 E_0 g(1-\mu) - \varphi_2 Wz] & \begin{array}{l}(1-2y)\{-C_m + \theta_2[\mathrm{E} - E_0(1-\mu)(1-gx)] \\ + F + S_m + (-R_b + T_2 + \varphi_2 Wx)z\}\end{array} & y(1-y)(R_b - T_2 - \varphi_2 Wx) \\ z(1-z)(T_1 + \varphi_3 Wy) & z(1-z)(R_b + T_2 + \varphi_3 Wx) & (1-2z)[-C_b + xT_1 + (R_b + T_2 + \varphi_3 Wx)y] \end{bmatrix} \tag{13}$$

Ritzberger and Weibull assert that the ESS is a pure strategy when the condition of information asymmetry holds in asymmetric games. Thus, it suffices to analyze eight local equilibrium points: $D_1(0,0,0)$, $D_2(0,0,1)$, $D_3(0,1,0)$, $D_4(0,1,1)$, $D_5(1,0,0)$, $D_6(1,0,1)$, $D_7(1,1,0)$, $D_8(1,1,1)$, which satisfy F(x)=0, F(y)=0, and F(z)=0 in Equations (10)-(12). Each equilibrium point is substituted into the Jacobian matrix to compute the corresponding eigenvalues. According to the Lyapunov stability criterion, if all eigenvalues are negative, the strategy set is deemed stable. Otherwise, the strategy set is classified as either unstable or a saddle point. The eigenvalues of the Jacobian matrix for each equilibrium point are presented in Table 2, while the corresponding ESS are summarized in Table 3.

Table 2
Equilibrium Point Eigenvalue

Equilibrium point	Eigenvalue λ1	Eigenvalue λ2	Eigenvalue λ3
$D_1(0,0,0)$	gE_0+F-C_s	$\theta_2[E-(1-\mu)E_0]+F-C_m+S_m$	$-C_b$
$D_2(0,0,1)$	$gE_0+F-C_s+T_1$	$\theta_2[E-(1-\mu)E_0]+F-C_m+S_m-R_b+T_2$	C_b
$D_3(0,1,0)$	$\theta_1 gE_0+F-C_s+S_s$	$-\theta_2[E-(1-\mu)E_0]-F+C_m-S_m$	$R_b-C_b+T_2$
$D_4(0,1,1)$	$\theta_1 gE_0+F-C_s+S_s+\varphi_1 W+T_1$	$-\theta_2[E-(1-\mu)E_0]-F+C_m-S_m+R_b-T_2$	$-R_b+C_b-T_2$
$D_5(1,0,0)$	$-gE_0-F+C_s$	$\theta_2[E-(1-\mu)(1-g)E_0]+F-C_m+S_m$	$-C_b+T_1$
$D_6(1,0,1)$	$-gE_0-F+C_s-T_1$	$\theta_2[E-(1-\mu)(1-g)E_0]+F-C_m+S_m-R_b+\varphi_2 W+T_2$	C_b-T_1
$D_7(1,1,0)$	$-\theta_1 gE_0-F+C_s-S_s$	$-\theta_2[E-(1-\mu)(1-g)E_0]-F+C_m-S_m$	$R_b-C_b+\varphi_3 W+T_1+T_2$
$D_8(1,1,1)$	$-\theta_1 gE_0-F+C_s-S_s-\varphi_1 W-T_1$	$-\theta_2[E-(1-\mu)(1-g)E_0]-F+C_m-S_m+R_b-\varphi_2 W-T_2$	$-R_b+C_b-\varphi_3 W-T_1-T_2$

(1) **Initial Stage:** Isolation

Corollary 1: When $gE_0+F-C_s+T_1<0$, $\theta_1 gE_0+F-C_s+S_s+\varphi_1 W+T_1<0$, $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m<0$, the eigenvalues of $D_1(0,0,0)$ are all negative, indicating that this point is an ESS. The corresponding stable strategies are traditional production, traditional production, and negative cooperation.

In the early stage of the green packaging supply chain, the cost of green production for suppliers is significantly higher than that of traditional production. This is primarily due to challenges such as underdeveloped technologies and insufficient supply chain support, thereby raising the complexity and cost of green production, represented by C_s. Given $gE_0+F-C_s+T_1<0$ and $\theta_1 gE_0+F-C_s+S_s+\varphi_1 W+T_1<0$, suppliers continue to opt for traditional production. Simultaneously, manufacturers lack standardized frameworks for implementing traceability technology and do not possess mature systems to support such integration, thereby hindering the full realization and diffusion of traceability-related supply chain benefits. Owing to limited information and operational experience, manufacturers remain cautious about assuming additional costs, leading $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m-R_b+T_2<0$ and other manufacturers to stick with traditional production. Meanwhile, brands exhibit limited awareness of supply chain collaboration and have not yet recognized the potential of active cooperation to significantly enhance overall supply chain efficiency.

Conclusion 1: At this stage, suppliers, constrained by the relatively higher costs of green raw materials compared to traditional alternatives, continue to adopt conventional production methods. Manufacturers, hindered by limited understanding and technical capacity related to traceability systems, also favor traditional production. Brands, lacking awareness of the strategic value of collaboration in supply chain development, refrain from engaging in active cooperation. Consequently, a misalignment emerges between the long-term benefits of sustainable transformation and the short-term profit-oriented goals of supply chain members. This disconnect results in diminished motivation among supply chain participants to pursue the sustainability transition.

(2) **Start-up Stage:** Development Driven by a Single Supply Chain Member

Corollary 2-1: When $gE_0+F-C_s+T_1<0$, $\theta_1 gE_0+F-C_s+S_s+\varphi_1 W+T_1<0$, $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$ and $R_b-C_b+\varphi_3 W+T_1+T_2<0$, the eigenvalues of $D_3(0,1,0)$ are all negative, indicating that this point is an ESS. The corresponding stable strategies are traditional production, traceability production, and negative cooperation.

As consumer preference for traceability increases significantly, manufacturers recognize that implementing traceability technology can effectively reduce upstream emissions. At this stage, the cost of traceability is effectively offset by subsidies or other compensatory mechanisms $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$. Suppliers may depend on manufacturers' traceability initiatives to drive emission reductions, lacking sufficient awareness and motivation for independent green production. Brands, on the other hand, evaluate the cost of active cooperation and ultimately choose passive collaboration. Although passive cooperation entails bearing a share of potential consumer group losses, these are offset by the benefits derived from the manufacturer's traceability efforts, leading brands to favor a negative cooperation strategy.

Corollary 2-2: When $gE_0+F-C_s+T_1>0$, $\theta_1 gE_0+F-C_s+S_s+\varphi_1 W+T_1>0$, $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m<0$ and $R_b-C_b+\varphi_3 W+T_1+T_2<0$, the eigenvalues of $D_5(1,0,0)$ are all negative, indicating that this point is an ESS. The corresponding stable strategies are green production, traditional production, and negative cooperation.

Suppliers recognize that proactive emission reduction not only lowers carbon allowance expenditures but also yields corresponding benefits, thereby making green production costs more manageable $gE_0+F-C_s>0$ and $\theta_1 gE_0+F-C_s+S_s>0$. Meanwhile, manufacturers acknowledge that suppliers are adopting green production methods and assume that upstream carbon emission reductions have reached a sufficient threshold. As a result, they therefore lack motivation to adopt traceability technology for additional emission reductions. Moreover, internal penalty mechanisms obligate manufacturers to share in the penalty costs, further discouraging their willingness to invest in traceability implementation. Brands largely depend on manufacturers to enable upstream—downstream integration via traceability technology. However, when manufacturers continue to follow traditional production practices, a persistent lack of awareness regarding the value of active cooperation among supply chain members remains.

Conclusion 2: As the green packaging industry develops, supply chain members at the production stage gradually develop low-carbon awareness. However, they often lack a unified commitment to sustainable transformation and tend to depend on one another rather than independently pursuing sustainable practices. This mutual dependence leads to strategic misalignment—when suppliers adopt green production, manufacturers often maintain traditional production practices, and when manufacturers implement traceability production, suppliers may revert to traditional methods. Additionally, due to limited information exchange and inadequate market feedback, brands exhibit a weak inclination toward cooperation and are less likely to engage in collaborative initiatives.

(3) **Development Stage:** Joint Development by Both Parties

Corollary 3-1: When $gE_0+F-C_s>0$, $\theta_1 gE_0+F-C_s+S_s>0$, $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$ and $R_b-C_b+\varphi_3 W+T_1+T_2<0$, the eigenvalues of $D_7(1,1,0)$ are all negative. The corresponding stable strategies are green production, traceability production, and negative cooperation.

Suppliers recognize that the long-term development of the supply chain cannot be sustained by the efforts of a single entity but instead requires coordinated action among all stakeholders. Their decision to adopt green raw materials not only ensures compliance with carbon emission standards but also contributes to long-term profit growth $gE_0+F-C_s>0$ and $\theta_1 gE_0+F-C_s+S_s>0$. In response, manufacturers acknowledge that implementing traceability technology enhances the integration of supply chain segments. Improved information interoperability not only increases overall supply chain profitability but also reduces the adverse effects of internal penalty mechanisms, as mutual engagement in sustainability efforts minimizes potential losses. Furthermore, traceability production by manufacturers exerts pressure on suppliers to pursue further emission reductions, with effectiveness improving as suppliers adopt greener production practices $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$. Meanwhile, brands display "free-rider" behavior in this context, reaping the benefits of upstream green production and emission reductions without bearing the costs of active cooperation. Although passive cooperation may result in the loss of certain consumer groups, the short-term financial benefits weaken their motivation to actively engage in collaborative initiatives.

Corollary 3-2: When $gE_0+F-C_s>0$, $\theta_1 gE_0+F-C_s+S_s>0$, $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m<0$ and $R_b-C_b+\varphi_3 W+T_1+T_2>0$, the eigenvalues of $D_6(1,0,1)$ are all negative. The corresponding stable strategies are green production, traditional production, and active cooperation.

Suppliers recognize that adopting green production materials not only ensures compliance with carbon emission standards but also contributes to long-term profit growth. Meanwhile, brands acknowledge that the potential losses associated with negative cooperation become more pronounced when suppliers engage in green production. The strategic rationale for manufacturers remains consistent with that discussed in Corollary 2-2 and is therefore omitted here. However, this equilibrium point is less frequently observed, as brands tend to collaborate more closely with manufacturers than directly with suppliers.

Corollary 3-3: When $gE_0+F-C_s<0$, $\theta_1 gE_0+F-C_s+S_s<0$, $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$ and $R_b-C_b+\varphi_3 W+T_1+T_2>0$, the eigenvalues of $D_4(0,1,1)$ are all negative. The corresponding stable strategies are traditional production, traceability production, and active cooperation.

Manufacturers recognize that implementing traceability technology can effectively integrate various segments of the supply chain. The rationale for suppliers is consistent with that presented in Corollary 2-1 and is therefore omitted here. Meanwhile, brands acknowledge that although partnering with a manufacturer who adopts traceability technology incurs additional costs, the potential consumer loss resulting from negative cooperation significantly outweighs these expenses. At this stage, the presence of $-C_b+T_1>0$ partial concessions from manufacturers further strengthens their commitment to active cooperation.

Conclusion 3: As the green packaging supply chain evolves, production-side members increasingly recognize the importance of joint development and tend to promote long-term supply chain growth through the adoption of advanced technologies. According to Corollary 3-1, suppliers will opt for green production and manufacturers will implement traceability. However, brands may still refrain from cooperation due to the short-term benefits associated with "free-riding" behavior. In contrast, Corollary 3-3 suggests that brands may choose to cooperate in order to expand market share when manufacturers implement traceability. This indicates that traceability adoption by manufacturers can incentivize either suppliers or brands to engage in active cooperation during the developmental stage. Therefore, manufacturers play a pivotal role in facilitating collaborative development within the green packaging supply chain.

(4) **Maturity Stage:** Cooperative Development

When $gE_0+F-C_s>0$, $\theta_1 gE_0+F-C_s+S_s>0$, $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$ and $R_b-C_b+\varphi_3 W+T_1+T_2>0$, the eigenvalues of $D_8(1,1,1)$ are all negative, indicating that this point is an ESS. The corresponding stable strategies are green production, traceability production, and active cooperation.

As the development of green packaging stabilizes, supply chain members become more mature and recognize that long-term growth cannot be achieved without mutual collaboration. During this phase of synchronized development, both suppliers and manufacturers opt to transition toward sustainable production practices. Over time, brands also come to understand that the short-term benefits of "free-riding" behavior are unsustainable for long-term success. As consumer loss resulting from negative cooperation gradually offsets the advantages of opportunistic strategies, brands are increasingly motivated to participate in active cooperation—not only to support their own growth but also to contribute to the overall stability of the supply chain. The implementation of traceability technology by manufacturers further strengthens upstream and downstream linkages, enhancing information interoperability across the supply chain. Through traceability systems, suppliers can obtain valuable market insights, which in turn stimulate greater adoption of green production practices and contribute to more effective carbon emissions reduction. Concurrently, brands actively cooperate with manufacturers to access production-side information, enabling them to more effectively target consumers with green preferences.

Conclusion 4: The maturity of the green packaging supply chain fundamentally depends on the establishment of stable and collaborative relationships among its members. Traceability technology acts as a critical enabler in promoting coordinated production and supports the comprehensive transformation of the supply chain, positioning it as the optimal strategy for long-term sustainability. As a result, suppliers adopt green production methods, manufacturers implement traceability systems, and brands actively participate in collaborative initiatives.

Table 3
Evolutionary Stability Point

Equilibrium point	Eigenvalue Symbol	Stability	Prerequisite
$D_1(0,0,0)$	- - -	ESS	$gE_0+F-C_s+T_1<0$ $\theta_1 gE_0+F-C_s+S_s+\varphi_1 W+T_1<0$ $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m-R_b+T_2<0$
$D_2(0,0,1)$	Uncertain Uncertain Uncertain	Uncertain	/
$D_3(0,1,0)$	- - -	ESS	$gE_0+F-C_s+T_1<0$ $\theta_1 gE_0+F-C_s+S_s+\varphi_1 W+T_1<0$ $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$ $R_b-C_b+\varphi_3 W+T_1+T_2<0$
$D_4(0,1,1)$	- - -	ESS	$gE_0+F-C_s+T_1<0$ $\theta_1 gE_0+F-C_s+S_s+\varphi_1 W+T_1<0$ $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$ $-C_b+T_1>0$
$D_5(1,0,0)$	- - -	ESS	$gE_0+F-C_s>0$ $\theta_1 gE_0+F-C_s+S_s>0$ $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m-R_b+T_2<0$ $R_b-C_b+\varphi_3 W+T_1+T_2<0$
$D_6(1,0,1)$	- - -	ESS	$gE_0+F-C_s>0$ $\theta_1 gE_0+F-C_s+S_s>0$ $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m-R_b+T_2<0$ $-C_b+T_1>0$
$D_7(1,1,0)$	- - -	ESS	$gE_0+F-C_s>0$ $\theta_1 gE_0+F-C_s+S_s>0$ $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$ $R_b-C_b+\varphi_3 W+T_1+T_2<0$
$D_8(1,1,1)$	- - -	ESS	$gE_0+F-C_s>0$ $\theta_1 gE_0+F-C_s+S_s>0$ $\theta_2[E-(1-\mu)E_0]+F-C_m+S_m>0$ $R_b-C_b+\varphi_3 W+T_1+T_2>0$

5. Numerical Simulation

To intuitively demonstrate the evolutionary dynamics and behavioral patterns of key stakeholders—while validating the results of the evolutionary stability analysis—this study utilizes MATLAB for numerical simulations. In this section, the optimal stable strategy $D_8(1,1,1)$, observed during the development process, is selected for analysis. Model parameters are assigned based on the satisfaction of four key inequalities $gE_0 + F - C_s > 0$, $\theta_1 gE_0 + F - C_s + S_s > 0$, $\theta_2[E-(1-\mu)E_0] + F - C_m + S_m > 0$ and $R_b - C_b + \varphi_3 W + T_1 + T_2 > 0$ to ensure theoretical consistency. To improve the generalizability of the findings, the simulation data are adjusted accordingly. These parameter values do not represent real-world quantities but instead reflect the relative magnitudes of the variables. The initial parameter settings are provided in Table 4.

Table 4
Parameter value setting

Parameters	Numerical Value	Parameters	Numerical Value	Parameters	Numerical Value
E_0	60	E	50	T_2	6
C_s	20	R_b	8	θ_1	0.5
C_m	20	F	10	θ_2	0.5
C_b	10	W	20	φ_1	0.3
S_s	25	μ	0.8	φ_2	0.4
S_m	30	g	0.6	φ_3	0.3
S_b	8	T_1	6		

As shown in Fig. 2, after 125 evolutionary iterations under various initial conditions, the system converges to the stable equilibrium $D_8(1,1,1)$, thereby validating Conclusion 4. This result confirms that the numerical simulations are consistent with the theoretical analysis of strategy stability, supporting the model's robustness. To facilitate a more precise analysis of each participant's strategic evolution and minimize the impact of differing initial strategy probabilities, the initial probability for suppliers adopting green production, manufacturers implementing traceability, and brands engaging in active cooperation is uniformly set to 0.2. Based on this configuration, we investigate the influence of key factors on the strategic evolution of supply chain participants, including consumer preference for traceability (μ), the degree of greenness (g), the internal penalty coefficient (F), the carbon trading allocation ratios (θ_1, θ_2), and the manufacturer's concession (R_b).

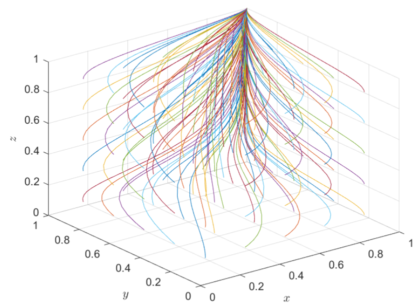

Fig. 2. System Evolution Results

5.1 Impact of Internal Factors on the Evolutionary Dynamics of the System

5.1.1 Internal Penalty Coefficients F

To investigate the impact of the internal penalty coefficient F on the evolutionary outcomes in the three-party game, this study assigns F values of 3, 7, 10, 13, and 16. The corresponding simulation results are presented below. Fig. (a) illustrates how variations in F influence the system's steady-state behavior, with convergence observed from the equilibrium point (0, 1, 1) to (1, 1, 1) as F increases. Figures (b)-(d) show that the internal penalty coefficient significantly affects the evolutionary speed of each supply chain participant. Specifically, a higher F accelerates the adoption of green production (x=1) by suppliers, traceability production (y=1) by manufacturers, and active cooperation (z=1) by brands. In contrast, when F is too low, suppliers tend to persist with traditional production methods. Notably, suppliers display high sensitivity to changes in the internal penalty coefficient, transitioning to green production only when F exceeds a critical threshold (F=7), thereby exerting sufficient cost pressure. Accordingly, a properly calibrated internal penalty coefficient can serve as an effective mechanism for promoting collaborative production across the green packaging supply chain.

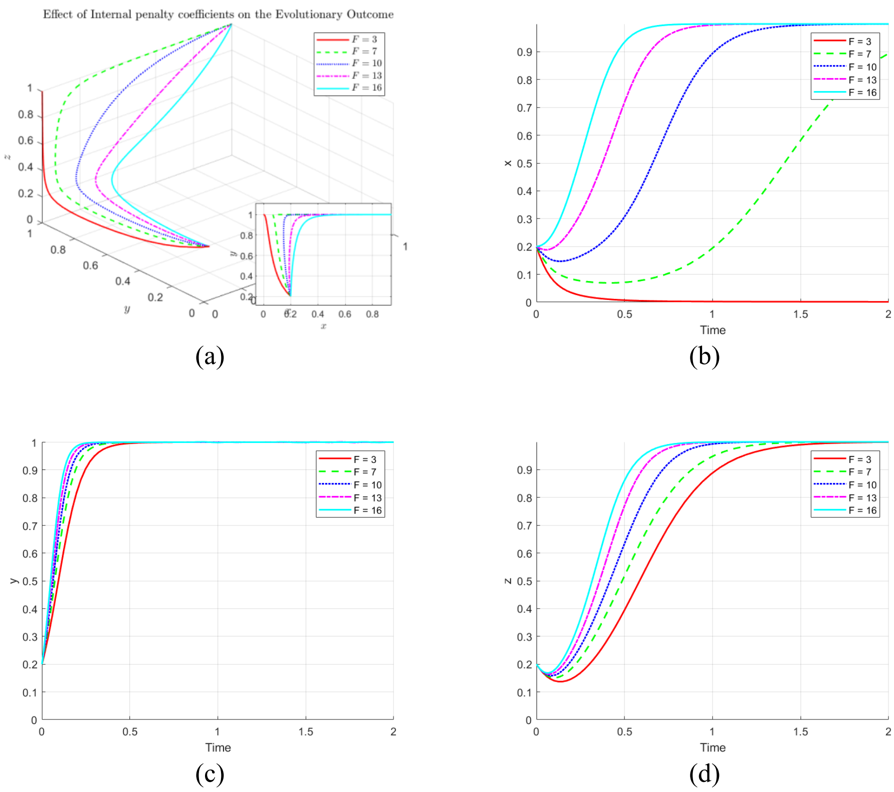

Fig. 3. Impact of Internal Penalty Coefficients on the Supply Chain

5.1.2 Carbon Trading Allocation Ratios θ_1 and θ_2

To analyze the impact of the carbon trading allocation ratios θ_1 and θ_2 on the outcomes of the three-party evolutionary game, different value pairs are assigned: (0.1, 0.9), (0.3, 0.7), (0.5, 0.5), (0.7, 0.3), and (0.9, 0.1). The corresponding simulation results are presented in Fig. 4.

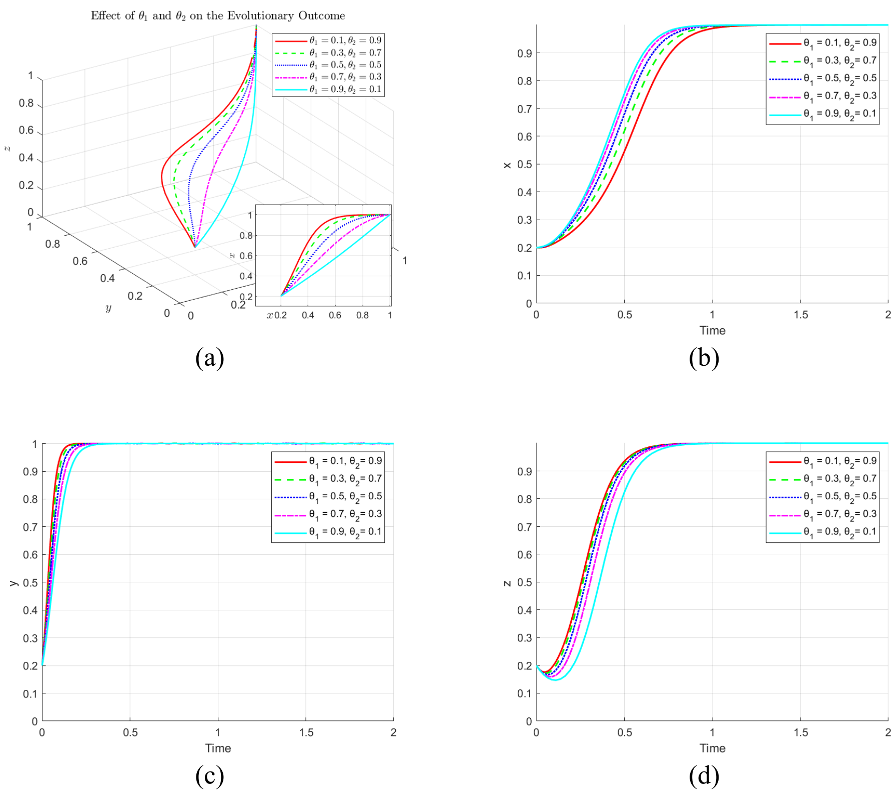

Fig. 4. Impact of Carbon Trading Allocation Ratios on the Supply Chain

The results indicate that variations in the carbon trading allocation ratios do not affect the system's steady-state outcome, which ultimately converges to the equilibrium point (1, 1, 1). However, figures (b)-(d) reveal that these ratios significantly influence the speed of strategic evolution for each supply chain participant. When either the manufacturer or supplier receives a higher share of carbon trading allowances, the transition to green production (x=1, y=1) occurs at a markedly faster pace, while the brand's evolution trend remains closely aligned with that of the manufacturer. This alignment arises from the cooperative relationship between brands and manufacturers, where the latter's production decisions directly influence the former's strategy. A higher allocation ratio enables participants to earn additional revenue by selling surplus carbon emission allowances, thereby accelerating the adoption of their preferred strategy. Therefore, rational allocation of carbon trading ratios is essential for promoting collaborative emission reductions among supply chain members.

5.1.3 Impact of Manufacturer Concessions on System Evolutionary Outcomes

To examine the impact of the manufacturer's concession R_b on the outcomes of the three-party evolutionary game, different values are assigned to R_b : 1, 5, 8, 13, and 16. The corresponding simulation results are presented in the figure below.

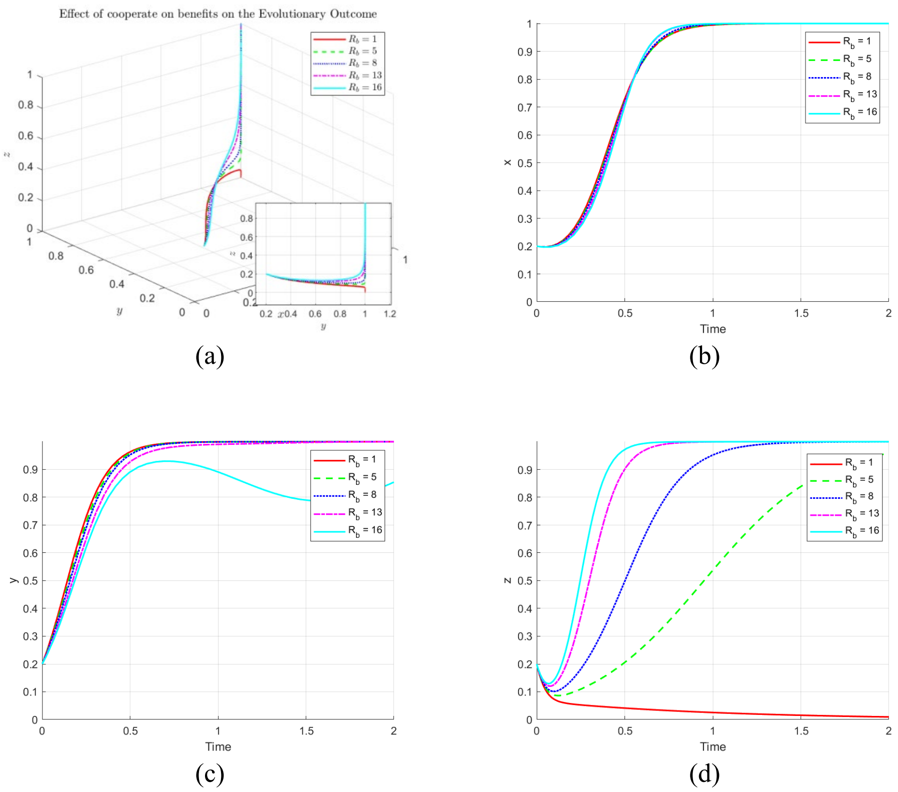

Fig. 5. Impact of Manufacturer Concessions on the Supply Chain

Fig. (a) illustrates that variations in the cooperative concession coefficient influence the system's steady-state trend, shifting convergence from (1, 1, 0) to (1, 1, 1). Figures (b)-(d) show that this coefficient significantly affects the evolution rate of each supply chain participant. Although its impact on suppliers' adoption of green production (x=1) relatively minor, an excessively high concession may lead to fluctuations in the manufacturer's implementation of traceability production (y=1), while a concession that is too low may impede the realization of brand-side active cooperation (z=1). A moderate increase in the concession coefficient can expedite brand engagement, as the manufacturer's concessionary behavior not only alleviates the brand's economic burden but also enhances the stability of long-term partnerships. Therefore, maintaining an optimal level of cooperative concessions is essential to ensuring that the manufacturer's traceability production strategy effectively promotes active cooperation from the brand side.

5.2 Impact of External Factors on the Evolutionary Dynamics of the System

5.2.1 Consumer Preferences μ

To examine the effect of the consumer traceability preference coefficient (μ) on the evolutionary outcomes of the three-party game, μ is assigned values of 0.1, 0.3, 0.5, 0.7, and 0.9. The corresponding simulation results are presented below.

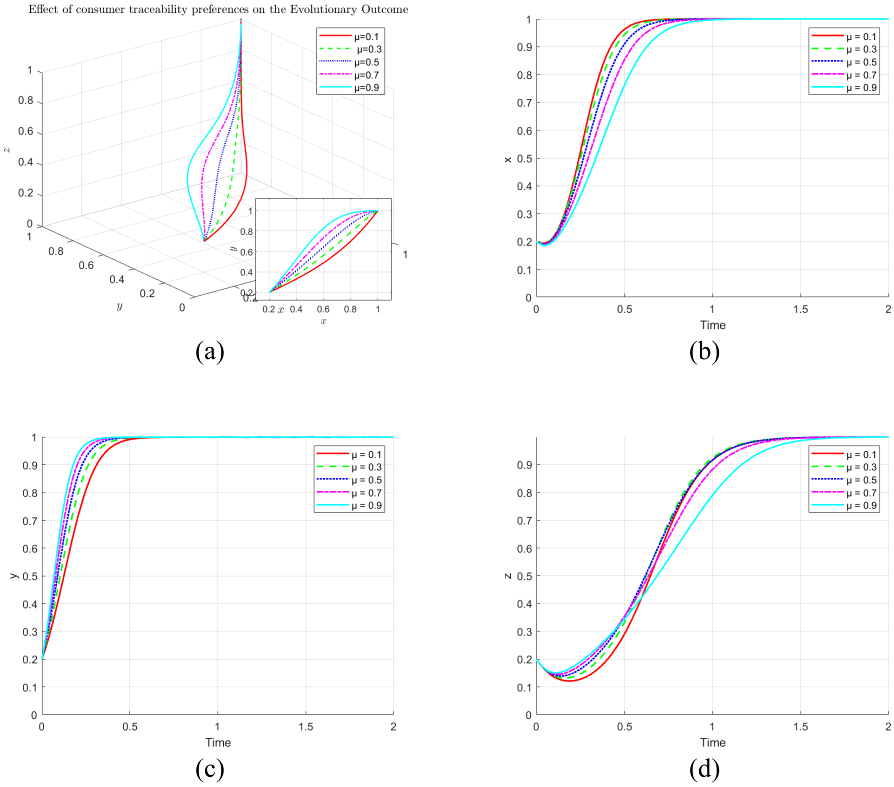

Fig. 6. Impact of Consumer Traceability Preferences on the Supply Chain

Fig. (a) shows that variations in μ do not affect the system's eventual convergence to the stable equilibrium point (1,1,1). However, figures (b)-(d) reveal that μ substantially affects the evolutionary trajectories of each supply chain member. Specifically, a higher consumer preference for traceability accelerates the adoption of traceability production (y=1) by manufacturers but delays the transition of suppliers to green production (x=1). Regarding brand active cooperation (z=1), μ demonstrates a phase-dependent effect: in the early stages of evolution, higher values of μ increase the willingness of brands to cooperate actively, whereas excessively high values in later stages tend to slow down the pace of cooperation. As brands possess direct access to consumer insights, their active engagement is crucial for the establishment of a robust traceability system within the supply chain. Therefore, it is advisable to maintain μ within a reasonable range (μ<0.9) and to strategically initiate traceability production by manufacturers to promote the active participation of all supply chain actors.

5.2.2 Influence of Greenness on System Evolutionary Outcomes

To assess the effect of the greenness level (g) on the outcomes of the three-party evolutionary game, the parameter g is assigned values of 0.1, 0.3, 0.5, 0.7, and 0.9. The corresponding simulation results are presented below.

Fig. (a) shows that changes in the greenness parameter do not affect the system's convergence to the stable equilibrium point (1,1,1). However, figures (b)-(d) reveal that greenness substantially influences the evolutionary pace of each supply chain entity. Higher greenness levels accelerate both the transition of suppliers to green production (x=1) and the adoption of traceability technology by manufacturers (y=1), whereas very low greenness levels impede brand-side willingness to engage in active cooperation (z=1). Therefore, increasing greenness serves as a crucial lever for promoting collaborative production across the supply chain. Brands, given their direct access to consumer preferences, are fully aware of the market value associated with greenness and are likely to participate actively only when the greenness level exceeds a critical threshold (g=0.1). Moreover, suppliers exhibit adaptability to market dynamics, adjusting their green production strategies in response to both economic feasibility and corporate social responsibility.

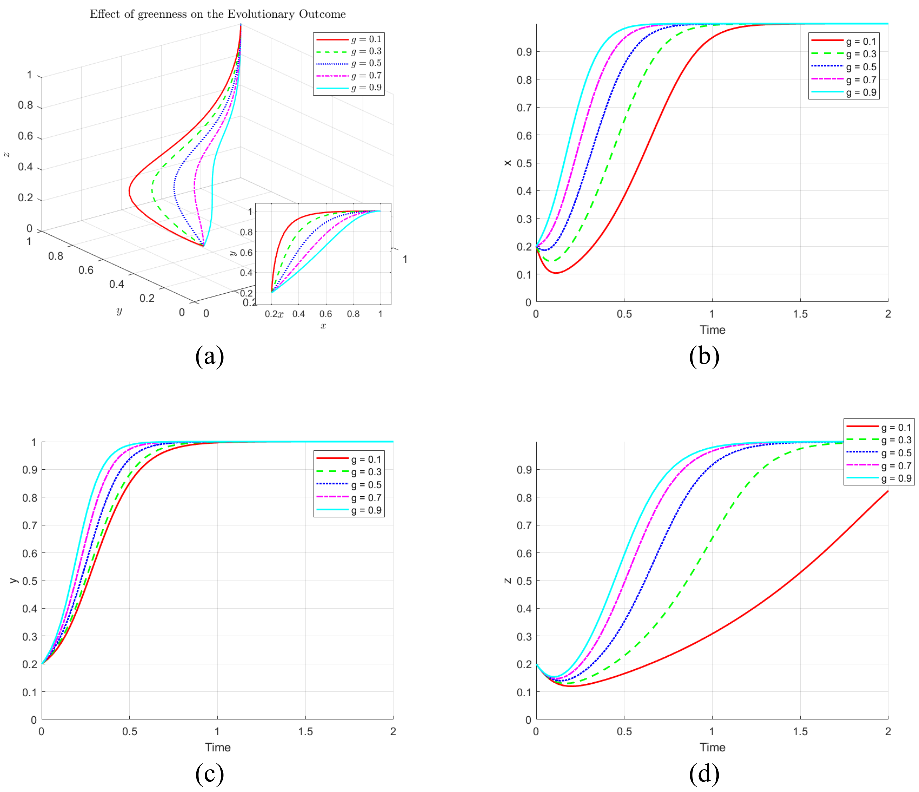

Fig. 7. Impact of Greenness on the Supply Chain

6. Discussion

Given the critical role of collaborative development in the sustainability of green packaging supply chains, a comprehensive investigation of traceability-integrated supply chain management is essential. This paper also explores the impact of brand-side cooperation on supply chain dynamics and examines the influence of various factors on the system's evolutionary outcomes.

First, the behavioral choices of suppliers, manufacturers, and brands are interdependent, with manufacturers serving as a crucial bridge among participants. As the supply chain matures, production-side actors initially depend on each other's initiatives but gradually transition toward a joint development approach. During this process, the system may converge to intermediate equilibrium states, such as (1, 1, 0) or (0, 1, 1). At this stage, suppliers respond to consumer demand through traceability linkages facilitated by manufacturers, which in turn promote the adoption of green production and enhance supply chain sustainability. In the short term, brands may benefit from "free-rider" advantages, consistent with the findings of Liu et al. (2022). However, this study demonstrates that brands become increasingly motivated to engage in active cooperation over time. Ultimately, the system stabilizes at the equilibrium point (1, 1, 1), where suppliers adopt green production, manufacturers implement traceability measures, and brands participate in full cooperation. This outcome reflects the synergistic interaction among supply chain stakeholders and highlights the manufacturer's pivotal role in linking and coordinating the green transformation.

Second, multiple factors influence suppliers' production strategies, including consumer traceability preference, product greenness, the internal penalty mechanism, and the carbon trading allocation ratio. Among these factors, the internal penalty mechanism exerts the most significant influence, consistent with the findings of Zhu et al. (2023). The results indicate that an increase in consumer traceability preference delays suppliers' adoption of green production. In contrast, higher levels of greenness and a greater allocation of carbon trading quotas substantially accelerate the transition to green production. Additionally, a low internal penalty coefficient discourages suppliers from adopting green practices. However, once the penalty coefficient exceeds a critical threshold, its capacity to promote green production increases significantly. Therefore, strengthening the internal penalty mechanism is essential to ensure that the coefficient surpasses this threshold. This imposes sufficient cost pressure on suppliers to discourage traditional production methods and incentivize a shift toward sustainable practices. Simultaneously, the rational allocation of carbon trading quotas, in collaboration with manufacturers, is vital to achieving mutually beneficial outcomes within the supply chain.

Third, manufacturers' production strategies are influenced by multiple factors, including consumer traceability preference, product greenness, the internal penalty mechanism, the carbon trading allocation ratio, and cooperative concessions. Under the internal penalty mechanism, manufacturers consistently adopt traceability production regardless of the magnitude of the penalty coefficient, indicating that this mechanism exerts a relatively minor influence on their behavior. Furthermore, increases in consumer traceability preference, product greenness, and the carbon trading allocation ratio accelerate the adoption of traceability production by manufacturers. However, cooperative concessions introduce variability in manufacturers' decision-making, with larger concession coefficients resulting in greater instability in their traceability strategies. As manufacturers serve as a central node in the supply chain—linking upstream suppliers and downstream brands—their traceability practices are essential for ensuring effective coordination. Therefore, manufacturers must strategically manage cooperative concessions to maintain stable collaboration with brands while avoiding excessive concessions that could undermine the stability of their traceability strategies. Establishing a reasonable concession range through negotiation is thus essential for balancing the interests of manufacturers and brands. Additionally, since consumer traceability preference plays a major role in shaping traceability production, effectively leveraging traceability technology can enhance transparency in green packaging, thereby strengthening consumer trust and facilitating the sustainable development of the supply chain.

Finally, the brand's decisions regarding active cooperation are influenced by consumer traceability preferences, product greenness, and cooperative concessions. First, excessively high consumer traceability preferences decelerate the brand's active cooperation process during the later stages of system evolution. Second, lower levels of product greenness hinder brand engagement, and when greenness falls below a critical threshold, brands may exhibit hesitation in participating in collaborative efforts. Third, the manufacturer's concessions play a pivotal role in shaping brand cooperation; brands are more likely to engage in cooperation when concessions exceed a critical threshold, and the extent of willingness increases with the size of the concession. In practice, brands are directly connected to consumers and possess valuable market-specific insights. Consumer traceability preferences and willingness to pay for green products significantly influence brand strategy. However, excessive consumer expectations for traceability may impose a greater financial burden on brands, thereby slowing their active participation. To mitigate these challenges, it is essential to enhance the overall level of greenness and simultaneously guide consumers toward traceability-driven purchasing behavior. Additionally, reaching an optimal level of negotiated concessions with manufacturers is critical. Such collaborative measures not only strengthen brand value but also foster a stable and resilient supply chain, ultimately contributing to a mutually beneficial outcome for all parties involved.

7. Conclusions and Recommendations

7.1 Conclusions

This study develops a green packaging supply chain model based on evolutionary game theory that includes suppliers, manufacturers, and brands. The model incorporates key factors such as consumer traceability preference, greenness, internal penalties, cooperative concessions, and carbon trading allocation to assess their influence on the strategic behaviors of the three parties and the evolutionary dynamics of the system. The study further analyzes system stability and evaluates the effects of parameter variations on equilibrium outcomes through MATLAB-based simulations.

This study presents the following key findings: (1) The evolution of the green packaging supply chain unfolds across four distinct stages. In the initial stage, supply chain members operate independently without collaboration. In the initiation stage, a single stakeholder drives early attempts at green production and cooperation. During the development stage, a bilateral alliance forms, led by the manufacturer, gradually deepening collaborative efforts. Finally, in the maturity stage, all members coordinate their efforts, collectively fostering the sustainable advancement of the supply chain and maximizing overall benefits. (2) Decisions related to traceability cooperation among supply chain members are shaped by a combination of internal and external influences. Internal mechanisms include penalty systems, carbon trading allocation, and cooperative concessions, while external influences encompass consumer preferences for traceability and product greenness. Suppliers are primarily influenced by internal mechanisms, with moderate penalties effectively incentivizing green production. Manufacturers are more responsive to external factors, such as consumer traceability preferences, which drive the implementation of traceability systems and engagement with market feedback. Brands, by contrast, are influenced by both internal and external factors: consumer demand for traceability and greenness shapes their cooperation strategies, while concession mechanisms encourage alignment with production-side stakeholders. (3) As the central node in the supply chain, manufacturers link upstream and downstream participants through traceability production. By optimizing cooperative concession mechanisms, they facilitate a benefit-sharing model with brands, reinforcing collaborative intentions. Simultaneously, they leverage market signals—such as consumer preferences for traceability and green products—to encourage suppliers' green transformation, while also utilizing internal mechanisms to promote coordinated emissions reduction with upstream partners.

7.2 Recommendations

Based on the research findings, this paper proposes the following recommendations:

(1) Enhancing the tripartite cooperation mechanism is essential for the effective operation of the green packaging supply chain.

Manufacturers, suppliers, and brands should establish stable, long-term strategic partnerships to jointly formulate green packaging standards and production plans, share information and resources, and capitalize on complementary advantages. Regular communication and performance evaluation are essential for the continuous optimization of cooperative processes and mechanisms, thereby enhancing the supply chain's adaptability and resilience. Additionally, all three parties should collaborate to respond proactively to market changes and challenges, proactively fulfill social responsibilities, and enhance the collective social image and brand value of the supply chain.

(2) As the origin of the green packaging supply chain, suppliers play a pivotal role in providing environmentally friendly raw materials. They should increase investments in green production, actively align with the supply chain's green transformation, and enhance the sustainability of packaging materials through advancements in green technology to better meet evolving consumer demands. Additionally, internal incentives—such as penalty mechanisms and carbon trading allocation schemes—should be effectively utilized to enhance suppliers' intrinsic motivation for sustainable practices. Strengthening cooperation with manufacturers and leveraging consumer traceability feedback can help optimize production strategies, ensuring both sustainability and market adaptability. Furthermore, suppliers must remain highly attuned to market signals, adjusting their production strategies accordingly to facilitate their own green transition and lay a solid foundation for the collaborative development of the entire supply chain.

(3) Manufacturers serve as the central hub of the green packaging supply chain, connecting upstream raw material suppliers with downstream brands. They should prioritize strengthening the traceability production system to build a transparent and efficient supply chain. By ensuring precise traceability and streamlining logistics and distribution, manufacturers can improve the quality and stability of the green packaging supply. Additionally, refining the cooperative concession mechanism and ensuring equitable profit distribution can reinforce brand partnerships and promote long-term collaboration. Moreover, manufacturers play a vital role in interpreting market signals, providing timely feedback to suppliers, and steering them toward green transformation—ultimately facilitating collaborative production and advancing the sustainable development of the entire supply chain.

(4) As a key driver of the green packaging supply chain, brands play a crucial role in increasing overall efficiency and promoting sustainable development. Brands should actively respond to consumer demand, gain in-depth insights into consumer preferences regarding traceability and sustainability, and adjust their collaborative strategies to enhance market competitiveness. By leveraging brand promotion and consumer education, brands can influence consumer awareness and demand for green packaging, thereby fostering a supportive market environment conducive to supply chain transformation. Furthermore, brands should deepen their understanding of supply chain collaboration, recognizing the strategic benefits of active participation in enhancing overall supply chain efficiency. Through proactive partnerships with manufacturers and suppliers, jointly developing green packaging standards and marketing strategies, and sharing market insights and consumer feedback, brands can cultivate a synergistic and competitive supply chain ecosystem.

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