



Research article

Green innovation strategies for circular express packaging

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Abstract: Mitigating the environmental impact of used express packaging has become an urgent imperative for firms seeking to assume environmental responsibility. Here, we considered a closed-loop supply chain comprising a package manufacturer and a logistics firm and explored the optimal green innovation strategy (upstream-invest, downstream-invest, or collaboration). First, we observed that, contingent upon the specific entity undertaking green innovation and the associated investment efficiency, heightened consumer environmental awareness does not unilaterally increase recycling volume, nor does it invariably diminish the recycling incentives of logistics firms. Second, due to the high investment threshold, cooperative innovation is difficult to achieve. However, when the manufacturer considers environmental, social, and governance (ESG) dual-purpose, it prefers to achieve collaboration by shouldering a larger share of the innovation investment, thereby creating win-win scenarios. Third, when the logistics firm invests in green innovation independently or cooperatively, the manufacturer's green innovation level increases monotonically with its ESG concern in both scenarios. This strategic framework can optimize green innovation investments in circular packaging and meet consumer environmental expectations while maintaining a performance advantage.

Keywords: Circular express packaging; green innovation; ESG dual-purpose; manufacturing; sustainable supply chains

Mathematics Subject Classification: 90B06, 91A65

1. Introduction

The exponential growth of logistics services has intensified the environmental challenges posed by express packaging waste in sustainable logistics operations. Commodity express packaging produces more than 21 million tons of packaging waste annually. This waste of resources and environmental pollution create a serious social burden [1]; hence, reducing the adverse effects of packaging waste on the environment is urgent. Numerous countries worldwide are actively advocating the development of

new technologies related to packaging waste, including China [2], the United States [3], Germany [4], and Japan [5].

Green innovation represents a primary pathway for improving the recyclability and sustainable value of express packaging. Driven by the concept of sustainable development, both upstream and downstream firms in the logistics supply chain are increasingly engaging in green innovation practices for circular express packaging. This trend reshapes the conventional supply structure and opens new avenues for collaboration between packaging manufacturers and logistics firms. In practice, the logistics firm is an important central hub connecting upstream manufacturers and consumers, and primarily undertakes the innovation, transportation, and recycling of express packaging. For example, Amazon's Frustration Free Packaging (FFP) program requires packaging to be 100% recyclable and unbreakable [6]. SF Express developed the " π -box" packaging box independently, made of polypropylene honeycomb material, in which each package can be recycled more than 70 times [7]. JD Logistics' Qingliu package can be recycled more than 20 times [8]. Overall, enhancing express packaging through material and structural improvements driven by green innovation facilitates recycling and simultaneously strengthens the business competitiveness and environmental performance of logistics firms. At the same time, upstream packaging manufacturers encounter strategic dilemmas in balancing their response to green development initiatives with the need to maintain competitive advantage. Although investments in green innovation can help sustain market competitiveness, they also entail substantial costs. For example, Zhilu Technology [9] has developed recyclable packaging solutions for various logistics firms, while the American firm Limeloop [10] independently designed parcel bags that can be reused up to 2000 times. To mitigate innovation costs and risks, some upstream and downstream firms have adopted collaborative approaches. For example, BBKA Biotechnology Inc. partnered with China Post to establish a joint manufacturing laboratory that applies the biomaterial PLA to the production of recyclable express packaging [11]. Similarly, Finland's Repack Inc., in cooperation with the national postal system, developed collapsible recycling bags that can be returned through mailboxes for reuse [12]. Such upstream-downstream collaborative innovation models allow packaging manufacturers and logistics firms to leverage their respective strengths in design and manufacturing, thereby mitigating innovation risks and improving resource allocation efficiency. Nevertheless, the reuse of circular express packaging may reduce the demand for new packaging, potentially diminishing upstream manufacturers' sales and complicating cooperation between the two parties.

The above cases illustrate that, in practice, green innovation in circular express packaging can be initiated by upstream manufacturers, downstream logistics firms, or both parties collaboratively. Upstream-led innovation (e.g., Zhilu Technology) is driven by the manufacturers' need to balance environmental responsiveness with competitive advantage under cost pressure. Downstream-led innovation (e.g., Amazon, SF Express) is motivated by logistics firms' role as the central hub connecting manufacturers and consumers, enabling them to improve both operational efficiency and environmental performance through material and structural enhancements. Collaborative innovation (e.g., BBKA and China Post, Repack and Finland Post) is driven by the desire to share investment risks and leverage complementary strengths. However, the conditions under which these three scenarios can be implemented remain unclear, creating a practical challenge: firms find it difficult to pre-evaluate which innovation model will yield the optimal economic and environmental outcomes. Meanwhile, these three innovation strategies have a clear theoretical rationale. From the perspective of game theory, the reuse of circular packaging may reduce manufacturers' sales of new packaging, leading to conflicts of interest and a deadlock in cooperation between upstream and downstream partners. From the perspective of resource dependence theory, manufacturers possess material technology resources, while logistics firms control the recycling network and customer interface; the collaboration between the two parties

represents the flow and sharing of resource advantages. Therefore, it is necessary to compare their optimality within a unified closed-loop supply chain framework.

The strategic interaction of green innovation between upstream and downstream firms becomes complex when express packaging recycling is integrated into a closed-loop supply chain (CLSC). For upstream packaging manufacturers, greater product recyclability achieved through green innovation leads to more reuse cycles, which may in turn reduce logistics firms' demand for new packaging products. Conversely, if manufacturers refrain from engaging in green innovation, they risk losing orders from sustainability-oriented logistics firms. This dynamic creates a strategic tension wherein environmental benefits may conflict with short-term economic incentives. Consequently, packaging manufacturers are motivated to explore optimal green innovation strategies. From the downstream perspective, logistics firms' investment decisions in green innovation are influenced by multiple operational factors. As the direct beneficiaries of innovative recyclable packaging, logistics firms must weigh the costs of green innovation investment against the cost savings generated through recycling, while simultaneously considering how consumer environmental awareness affects their investment and operational strategies. This is because consumer environmental awareness not only shapes recycling efficiency but also influences market demand.

As consumer environmental awareness increases and logistics operations mature within a sustainable framework, the single purpose of profit maximization reveals inherent limitations. The classic agency theory reveals that technological input is constrained by the firm's profit-maximization objective in traditional corporate analysis [13]. Schneider and Murray [14] argued that continued economic growth and profit-driven practices perpetuate an unsustainable cycle, one that does little to advance environmentally responsible business conduct or ethical progress. To overcome these shortcomings, firms incorporate environmental, social, and governance (ESG) criteria into their strategic objectives, forming a growing trend toward ESG-oriented firms [15]. ESG serves as a governance framework aligning corporate objectives with stakeholder interests across environmental, social, and governance dimensions [16]. The transition toward dual-purpose firms, seeking both economic and sustainability goals, may fundamentally reshape operational decisions such as green innovation and collaborative behavior [17]. However, the financial implications of ESG practices remain debated: while some studies suggest that ESG investment does not yield direct economic benefits and may even negatively affect performance [18,19], others highlight positive correlations between ESG engagement and financial outcomes [20,21]. The uncertainty surrounding the economic impact of ESG practices motivates this study to examine how ESG governance influences green innovation decisions within sustainable logistics supply chains.

In light of these issues, this study aims to investigate the strategic interactions and optimal green innovation decisions between upstream packaging manufacturers and downstream logistics firms in the development of circular express packaging. It seeks to address the inherent tension between environmental sustainability and economic performance. Specifically, the study seeks to answer the following research questions: (1) What is the optimal green innovation strategy for circular express packaging for sustainable logistics supply chain firms? (2) How does consumer environmental awareness affect packaging recycling and the innovation level? (3) How do ESG manufacturers reshape the optimal green innovation strategy?

To answer the above research questions, we construct a Stackelberg game model consisting of a package manufacturer, a logistics firm, and consumers. Under this framework, the manufacturer produces express packaging, while the logistics firm purchases the packaging from the manufacturer, provides express delivery services to consumers, and then collects and recycles the packaging for reuse. We investigate the strategic choices of green innovation of circular express packaging under three scenarios:

(1) the packaging manufacturer independently invests in green innovation; (2) the logistics firm independently invests in green innovation of circular express packaging; and (3) the logistics firm and the manufacturer collaborate on green innovation through cost-sharing contracts. In addition, we extend the model to examine the optimal strategy shifts for manufacturers pursuing both profit maximization and ESG objectives.

Our research contributes to the literature and offers managerial implications in four key ways. First, in terms of model construction, we tailor a closed-loop supply chain framework to the unique characteristics of circular express packaging. Unlike prior studies that focus on product remanufacturing [22], our setting assumes that reused packaging does not require costly refurbishment; consumers are indifferent to the number of uses as long as it provides adequate protection during transit. As green innovation improves packaging recyclability, more reusable packages re-enter the market. Because consumers prefer more environmentally friendly products, this increased availability of reusable packaging may consequently reduce the logistics firm's demand for new packaging from the manufacturer. Traditional research on green innovation has predominantly focused on how it enhances environmental performance, brand image, or market share [23,24], while paying limited attention to the potential adverse effect whereby green innovation may suppress demand for new products by increasing the supply of reusable products. This trade-off is frequently observed in practice but receives limited analytical attention. By aligning the model with this practical feature, this assumption directly mirrors real logistics operations and enhances the applicability of our findings to sustainable logistics supply chains.

Second, we explicitly incorporate two observable factors into the recycling function: the logistics firm's recycling incentive measures and consumers' environmental awareness. Usually, the recycling incentive always decreases as environmental awareness increases, while the recycling rate increases with environmental awareness. This is because higher environmental awareness implies that consumers are more willing to participate in recycling [25], which motivates the logistics firm to reduce its recycling incentive. However, we identify two novel findings: (i) When the logistics firm participates in green innovation (downstream-innovation or cooperation innovation), and the investment efficiency is high, the logistics firm increases its recycling incentive as consumer environmental awareness increases. This is because the logistics firm's involvement in green innovation gives it a better understanding of the package's recyclability, leading it to believe that the product is worth a higher recycling incentive. (ii) When the logistics firm does not participate in green innovation (upstream-innovation) and the investment efficiency is high, the recycling quantity decreases as consumer environmental awareness increases. This occurs because the manufacturer significantly improves packaging recyclability and raises the corresponding wholesale price. Consequently, the logistics firm reduces its recycling incentive. However, the negative effect of this reduced incentive outweighs the positive effect of environmental awareness, resulting in the counterintuitive phenomenon of an overall decline in the recycling quantity as consumer environmental awareness increases. For practice, logistics firms should adjust their recycling incentive strategies based on whether they participate in green innovation and the level of investment efficiency, urging firms to carefully balance incentive design. Our framework also offers a tool for packaging manufacturers to evaluate innovation investments under the risk of recycled products cannibalizing sales of new products.

Third, our analysis demonstrates the superiority of collaborative green innovation investment and identifies its boundary conditions, which directly responds to the practical question of which innovation mode works best. Traditional closed-loop supply chain research typically treats logistics firms as passive recycling executors [26]. Even when it is explicitly recognized that collaborative innovation outperforms independent innovation [27], the conditions under which it does so remain unidentified. In contrast, this

study proposes that logistics firms should extend their activities upstream to the packaging design stage and identifies the boundary conditions under which collaborative innovation outperforms independent innovation. We find that joint investment in recyclable packaging technology can achieve a win-win outcome for both manufacturer and logistics firm, with green innovation level and recycling volume always higher than under independent investment. In practice applications, this implies that logistics firms should extend their operational expertise upstream, participating in packaging design to improve recyclability while preserving protection performance. This finding provides a cooperative roadmap for logistics firms to transition from a pure “use” model to a circular “design–use–recycle” system, thereby enabling them to act as both recyclers and innovators, establishing a more effective collaborative innovation closed-loop recycling mechanism.

Fourth, collaborative innovation, though efficient, is often difficult to sustain in practice. Thus, we explore the role of the manufacturer’s ESG dual-purpose in promoting collaborative innovation. We show that an ESG dual-purpose manufacturer is willing to take on a larger share of innovation costs, thereby significantly expanding the Pareto improvement region for collaboration. Contrary to earlier studies [18,19] that find limited or negative economic effects of ESG concerns, our results reveal that under a collaborative innovation strategy, ESG concerns can create strategic value, even expanding the optimal region compared to pure profit maximization. This finding contributes to stakeholder theory and the literature on sustainable business models by clarifying how ESG governance generates economic benefits beyond compliance. It also offers a practical guideline for managers: when collaborative innovation is desirable yet blocked by cost-sharing barriers, emphasizing ESG objectives can break the deadlock and unlock mutually beneficial cooperation.

The remainder of this paper is organized as follows: We review the related literature in Section 2. In Section 3, we describe the model settings and obtain the equilibrium results. In Section 4, we analyze the equilibrium results. In Section 5, we extend the model to consider ESG dual-purpose. We conclude the main findings and discuss the managerial insights in Section 6.

2. Literature review

Our paper is primarily associated with two research streams. The first concerns green innovation in sustainable supply chains; the second focuses on recycling and reuse in express packaging supply chain operations, integrating the product characteristics of the circular express packaging into the discussion.

2.1. Green innovation in sustainable supply chains

Green innovation is an efficient green management activity to improve the environmental attributes of products [28]. In the context of low-carbon targets, how to alleviate environmental pressure through green innovation is an important practical issue. Many studies have focused on the issue of green supply chain management and found that firms investing in green innovation can bring both economic and ecological benefits [29,30]. Li et al. [31] examined the dynamics of a firm’s green process innovation under green-based price regulation and network externality and found that the monopolist’s innovation efforts and green performance were below the socially optimal level. In contrast, our study extends the analysis from a single monopoly to green innovation strategies led respectively by a green packaging manufacturer and a logistics firm, as well as collaborative strategies, thereby broadening the context for analyzing innovation efforts and green performance.

Green innovation includes product green innovation and process green innovation. Product innovation activity is mainly concerned with improving product quality and increasing sales, while process innovation activity focuses on reducing production cost (Bonanno and Haworth, 1988). Since

demand depends on price and quality, many studies suggest that design or quality improvement through green innovation plays a crucial role in increasing demand [32,33]. In the practice of adopting green innovative products, firms' decisions not only depend on their own performance but are also influenced by competitors. Yue et al. [34] explored the optimal reusable packaging adoption strategies of two competing e-commerce platforms in the presence of green consumers, where the equilibrium outcomes depend on reusability and innovation costs. Deng et al. [35] examined a closed-loop supply chain that includes a risk-averse retailer and a third-party remanufacturer, showing that risk aversion affects remanufacturing model selection. In contrast, our study considers circular express packaging that can be directly recycled and reused by logistics firms, without involving remanufacturing or third-party remanufacturers.

Many studies have investigated the impact of a cooperative green innovation strategy on supply chain profits. Different innovation costs shared by supply chain members in a collaboration affect the level of greening, price, and profitability of the product [36]. However, collaborative innovation is not always accepted, and the contract preferred by the upstream and downstream firms depends on a trade-off between costs and benefits [28]. Different power structures and investment periods in the supply chain also affect a firm's choice of collaborative innovation strategy [37]. Cantu and Tunisini [38] focused on supply chain networks composed of non-commercial participants and adopted a case study approach to reveal how social embeddedness mechanisms facilitate collaborative circular innovation. In contrast, this study complements research on supply chains composed of commercial participants, identifies when cost-sharing-based collaborative innovation outperforms independent innovation, and introduces the manufacturer's ESG dual-purpose objective as a key variable for resolving the "difficulty of collaboration".

Current literature has extensively examined economic benefits and strategic choices of green innovation within supply chains. However, research on how to optimize green innovation strategies to balance environmental and economic benefits within a low-carbon sustainability framework remains relatively limited. In particular, studies examining the interaction between supply chain firms and consumer behavior factors remain underdeveloped. This study constructs a theoretically innovative model of the interaction between environmental drivers and technological factors, providing the first quantitative analysis of how consumer environmental awareness, green innovation efficiency, and ESG dual-purpose systematically influence supply chain innovation decisions. Thus, we fill a gap in existing literature by integrating consumer behavior and offering a theoretical analysis of multi-factor interaction mechanisms within the sustainable governance framework.

2.2. Recycling in express packaging supply chain operations

Many core factors influencing recycling efficiency have been examined in the literature, including recycling incentives and government subsidies [39], corporate social responsibility and consumers' environmental awareness [40], and recycling channels and perceived convenience [41]. Some studies highlighted the critical role of green consumers. Environmentally conscious consumers notably drive recycling effectiveness [25] and influence firms' recycling policies and incentive decisions [42]. As retailers raise incentives, consumers participate more, while a low proportion of green consumers inevitably hinders the large-scale application of reusable packaging [34]. Resnitzky et al. [24] treated external pressures (e.g., policies, regulations, public environmental awareness) as exogenous drivers and employed qualitative research methods to analyze their important role in facilitating innovation projects of packaging recycling cooperatives. In contrast, this study focuses on how for-profit firms (manufacturers and logistics firms) form collaborative innovation through game theoretic interactions in the absence of third-party social organizations and captures the dual role of consumer environmental

awareness in both promoting recycling and reducing logistics firms' incentives for innovation, thereby providing a more nuanced mechanism analysis for the literature.

Many studies have focused on the impact of green innovation on product recycling. In the recycling stage, green innovation helps increase product performance and recyclable value [43], reduces environmental impacts by raising recycling frequency [44], and improves recyclability [45]. In the post-recycling stage, green innovation facilitates the reuse or remanufacturing of recycled products [46]. Moreover, the product reuse rate is positively correlated with the level of green innovation [47], while product reuse also incurs refurbishment costs [48]. Kao et al. [49] identified barriers to developing green express packaging (e.g., insufficient R&D in green innovation, difficulties in recycling) through empirical research. In contrast, this study quantifies the optimal levels of green innovation investment and strategic choices through a game-theoretic model, thereby providing directly applicable decision support for firms.

Existing literature has predominantly investigated stakeholder decision-making in supply chain recycling, determinants of recycling efficiency, and the contribution of green innovation to product recyclability and remanufacturing. However, it lacks systematic analytical models linking green innovation strategies with green consumer recycling behavior, failing to examine the comparative advantages of collaborative over independent innovation in recycling outcomes of circular express packaging. This study fills these gaps by developing a model grounded in the operational characteristics of circular express packaging. Based on the practical characteristics of circular express packaging, we construct a parameter framework in which recycled packaging can be directly reused without incurring refurbishment costs or price discounts. The findings offer valuable insights and managerial implications for designing effective green innovation and recycling strategies in sustainable logistics systems.

3. Problem and model

3.1. Model formulation

We consider a CLSC consisting of a packaging manufacturer and a logistics firm, incorporating different green innovation strategies into the model. The model structures for the green innovation strategies are shown in Figure 1. We assume that supply chain firms make decisions based on the pursuit of profit maximization, i.e., a single profit-maximization objective. Then, we relax this assumption in Section 5, where the manufacturer pursues an ESG dual-purpose objective, which is a linear combination of optimizing profits, environmental impact, and consumer surplus.

The forward channel. The manufacturer produces new circular express packaging at unit cost c and supplies them to the logistics firm at unit wholesale price w . For simplicity, we normalize manufacturing cost c to 0. The logistics firm incorporates express packaging as part of its logistics services, with the sales price of each express packaging denoted as p . Additionally, owing to the characteristics of circular express packaging, the logistics firm can directly reuse the recycled express packaging without incurring any refurbishment costs [50].

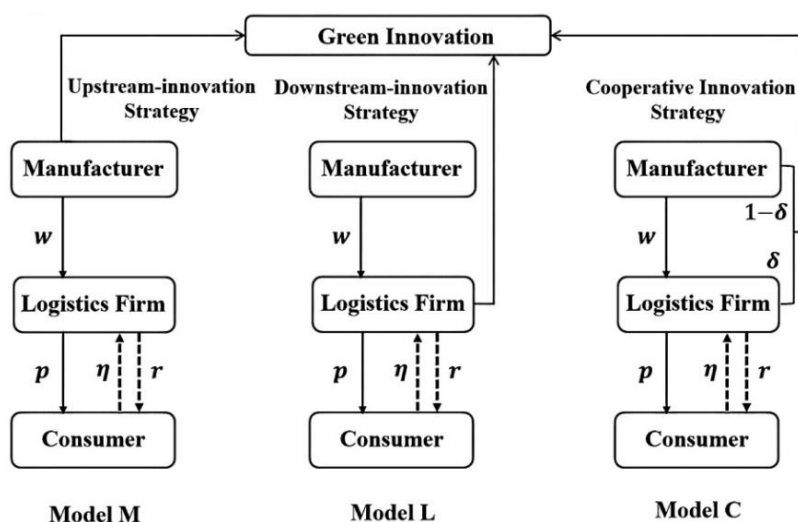


Figure 1. The green innovation strategies model structures.

The reverse channel. Consumers' recycling behavior is influenced by their environmental attitudes and responsiveness to external incentives. We consider that both consumers' environmental awareness e and product green innovation level x affect the recycled circular express packaging quantity η , i.e., $\eta = (1 + x)e$, where $(1 + x)$ captures the positive effect of green innovation on the proportion of packaging that is returned, because more eco-friendly packaging encourages consumers to return it. Furthermore, the recycling incentive or subsidy is recognized as an effective stimulus for promoting recycling behavior; thus, we assume that the logistics firm provides an incentive r to consumers who participate in recycling. With this incentive, the recycling quantity is expressed as $\eta = (1 + x)e + br$ [22,26,51], where b is the sensitivity coefficient of consumers to the provided incentive, and br represents the positive effect of recycling incentives on the recycling quantity. In practice, many logistics firms adopt incentive measures to guide consumers to actively participate in express packaging recycling. For example, Amazon offers cash rewards to incentivize merchants and consumers to use recycled packaging. Cai Niao Express has offered gifts such as eggs, tissues, and express coupons in exchange for used packaging [52].

Green innovation strategies. This study considers three innovation strategies: (1) We define that the express packaging manufacturer (denoted as m) independently invests in green innovation of circular express packaging as the upstream-innovation strategy (Model M). (2) The logistics firm (denoted as l) independently invests in green innovation of circular express packaging as the downstream-innovation strategy (Model L). (3) The logistics firm and the manufacturer collaboratively invest in green innovation of circular express packaging as the collaborative innovation strategy (Model C), in which the logistics firm's share of the investment cost is δ , and the manufacturer's share is $(1 - \delta)$.

Green innovation. The green innovation of circular express packaging focuses on utilizing eco-friendly materials or designs to improve the recyclability of express packaging. For example, SF Express's "π-box" uses polypropylene (PP) environmentally friendly honeycomb materials, in which each box can be recycled more than 70 times. As such, enhancing recyclability can significantly reduce the generation rate of packaging waste. Let x_i denote the firm i 's green innovation level, where $x_i \in (0,1)$, $i \in \{m, l\}$. The investment cost of green innovation is a quadratic function $I(x_i) = \frac{\lambda x_i^2}{2}$, where λ denotes the cost coefficient; a higher cost coefficient indicates lower investment efficiency [22], and the investment cost increases monotonically with the cost coefficient and the convexity of green innovation level [53].

Consumer utility. Consistent with the traditional model of consumer preference, the consumer's willingness-to-pay θ for the new package is heterogeneity uniformly distributed in $[0,1]$. Previous studies

have shown that consumers with environmental awareness tend to prefer green products [54]; thus, we model the consumer's net utility as $U = \theta - p + x$, which means that a higher green innovation level increases consumers' utility. Consumers will purchase only when $U > 0$.

The demand. We assume that the potential market size is A , and the recycling quantity of used express packaging affects the logistics firm's purchase quantity of new express packaging; thus, the demand function of new packaging is expressed as $q = A - p - \eta + x$, and the inverse demand function can be obtained as $p = A - q - \eta + x$. For simplicity, we normalize A to 1 [55].

The sequence of events. We model the interactions between the manufacturer and the logistics firm in three stages. In stage 1, the green innovation level is decided by different entities under different strategies. In stage 2, the manufacturer sets the wholesale price of new packaging based on the green innovation level. In stage 3, the sales price and recycling reward are decided by the logistics firm. The sequence of events is shown in Figure 2, and all notations are shown in Table 1.

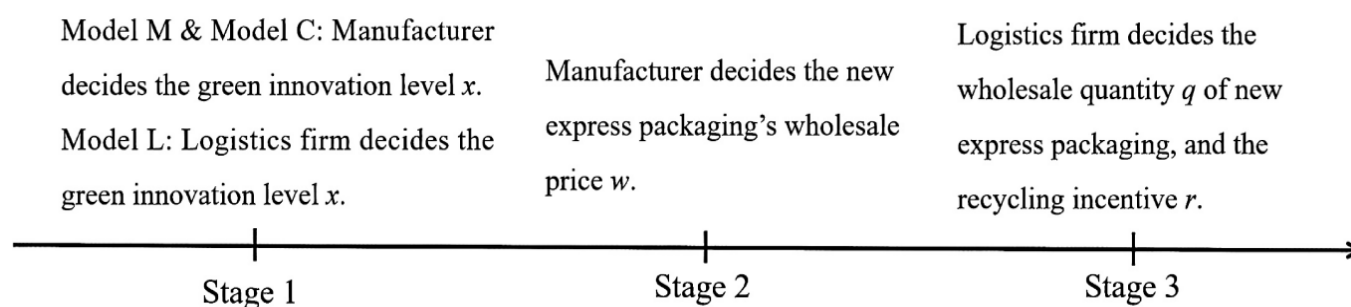


Figure 2. Sequence of events.

Table 1. Notations.

Decision variables	Definition
w	Wholesale price of a unit new circular express packaging
p	Retail price of a unit circular express packaging
q	Sales quantity of new circular express packaging
x	Green innovation level of circular express packaging
r	Recycling incentive for consumer provided by the logistics firm
δ	Proportion of investment cost shared by logistics firm
Exogenous parameters	Definition
η	Recycling quantity of used circular express packaging
e	Consumer's environmental awareness
b	Sensitivity coefficient of consumer's recycling incentive
λ	Investment cost coefficient for green innovation
$I(x_i)$	Green innovation investment cost of circular express packaging
π_m^j	Profit of the manufacturer in Model j , $j \in \{M, L, C\}$
π_l^j	Profit of the logistics firm in Model j
a	ESG concern degree of the manufacturer
u	Carbon emissions of unit new express packaging

3.2. The models

3.2.1. Model M: Green innovation by the manufacturer

In model M, the express packaging manufacturer independently invests in green innovation of circular express packaging, i.e., upstream-innovation strategy. The optimization problem of the logistics firm is:

$$\max_{q^M, r^M} \pi_l^M = (p^M - w^M)q^M + (p^M - r^M)\eta^M, \quad (1)$$

The first term in Equation (1) denotes the profit from selling new express packaging, while the second term denotes the profit from selling recycled express packaging.

The optimization problem of the manufacturer is:

$$\max_{w^M, x_m^M} \pi_m^M = w^M q^M - \frac{\lambda x_m^{M^2}}{2}. \quad (2)$$

The first term in Equation (2) denotes the profit from wholesaling new express packaging, and the second term denotes the green innovation investment cost.

We derive the equilibrium results by backward deduction. The boundary conditions for satisfying the nonnegative equilibrium results are $0 < e < \bar{e}$, $\underline{b} < b < 1$, $\lambda_1 < \lambda < 1$. The upper limit $\bar{e}$ means that consumer environmental awareness is not too high, which is consistent with the reality that there is a relative lack of consumer education on environmental awareness. The lower limit $\underline{b}$ means that the consumer's sensitivity coefficient for recycling incentives is not too low; this makes sense for logistics firms to offer recycling incentives. The lower limit of green innovation cost coefficient λ_1 represents the upper bound of investment efficiency, which is consistent with the reality that green innovation is associated with technological thresholds and risks.

3.2.2. Model L: Green innovation by the logistics firm

In Model L, the logistics firm (denoted as l) independently invests in green innovation of circular express packaging, i.e., downstream-innovation strategy. The optimization problem of the logistics firm is:

$$\max_{x_l^L, q^L, r^L} \pi_l^L = (p^L - w^L)q^L + (p^L - r^L)\eta^L - \frac{\lambda x_l^{L^2}}{2}, \quad (3)$$

The optimization problem of the manufacturer is:

$$\max_{w^L} \pi_m^L = w^L q^L. \quad (4)$$

Similarly, the boundary conditions for satisfying the nonnegative equilibrium results are $0 < e < \bar{e}$, $\underline{b} < b < 1$, $\lambda_2 < \lambda < 1$.

3.2.3. Model C: Green innovation by cooperation

In Model C, the logistics firm and the manufacturer collaboratively invest in green innovation of circular express packaging, and the logistics firm shares a proportion δ of the green innovation cost, i.e., collaborative innovation strategy. The logistics firm's optimization problem is:

$$\max_{q^C, r^C, \delta} \pi_l^C = (p^C - w^C)q^C + (p^C - r^C)\eta^C - \frac{\delta \lambda x_m^{C^2}}{2}, \quad (5)$$

The manufacturer's optimization problem is:

$$\max_{w^C, x_m^C} \pi_m^C = w^C q^C - \frac{(1-\delta)\lambda x_m^{C^2}}{2}. \quad (6)$$

Similarly, the boundary conditions for satisfying the nonnegative equilibrium results are $0 < e < \bar{e}$, $\underline{b} < b < 1$ and $\lambda_3 < \lambda < 1$.

4. Analysis

In this section, we analyze the optimal green innovation strategy of the supply chain through a comparison of equilibrium results and explore the impacts of different green innovation strategies on operational decisions.

4.1. Analysis of the green innovation decisions

Lemma 1. The impact of environmental awareness e on the green innovation level x :

- (1) In Model M, x decreases in e , i.e., $\frac{\partial x}{\partial e} < 0$.
- (2) In Model L and Model C, x increases in e , i.e., $\frac{\partial x}{\partial e} > 0$.

Lemma 1 reveals that environmental awareness exhibits significant heterogeneous effects on green innovation level across different models. In Model L and Model C, environmental awareness demonstrates a positive correlation with green innovation levels, consistent with conventional expectations. Conversely, in Model M, increased environmental awareness paradoxically leads to reduced green innovation levels, which defies conventional intuition.

Conventional intuition suggests that an increase in consumer environmental awareness should drive firms to increase their green innovation investment in order to cater to market demand, capture green premiums, or establish differentiated competitive advantages. However, when packaging manufacturers invest independently in green innovation, the opposite result emerges. The underlying economic logic can be comprehensively explained by the following propositions and lemmas. First, manufacturers have a relatively low investment threshold; this production advantage enables them to achieve a higher innovation level ($x^M > x^L$), yet the diminishing marginal returns lead manufacturers to rationally reduce their investment. Second, anticipating that increased environmental awareness may boost the volume of recycling, retailers reduce their recycling incentives ($\frac{\partial r}{\partial e} < 0$) in an attempt to “free ride”, which implies that manufacturers’ green innovation investments are not fully visible to or recognized by consumers. This further diminishes manufacturers’ willingness to invest in green innovation.

Proposition 1. The optimal green innovation decisions:

- (1) The green innovation level is the highest in Model C, i.e., $x^C > \max\{x^M, x^L\}$.
- (2) If the collaborative cannot be achieved ($\lambda_1 < \lambda < \lambda_3$), there are two scenarios:
 - 1) when $0 < e < \frac{1}{21}$, $\underline{b} < b < b_1$, then $x^M > x^L$.
 - 2) when $0 < e < \frac{1}{21}$, $b_1 < b < 1$, $\lambda_2 < \lambda < \lambda_3$, or $\frac{1}{21} < e < \frac{1}{5}$, $\bar{\lambda}_2 < \lambda < \bar{\lambda}_3$. $x^L > x^M$

The results of Proposition 1 demonstrate that the collaborative model (Model C) possesses distinct advantages in promoting green innovation, with its optimal green innovation level consistently exceeding those of the other two models. This finding supports cooperative innovation theory [56], indicating that inter-firm collaboration can effectively enhance green technology innovation investment through cost-sharing mechanisms.

When the cooperative investment cannot be achieved, the green innovation activity will be conducted by either the manufacturer or the logistics firm exclusively. Specifically, when consumer environmental awareness and the consumer’s lower incentive sensitivity coefficient are lower, the manufacturer tends to invest a higher green innovation level ($x^M > x^L$). In this scenario, logistics firms recycle less used packaging, so they will procure more new packaging from manufacturers, which

benefits the manufacturers. On the contrary, when the situation is conducive to the logistics firm recycling more used packaging, the logistics firm tends to invest a higher green innovation level in order to save purchasing costs ($x^L > x^M$).

Proposition 1 offers clear practical guidance: when collaboration is feasible, firms should adopt cooperative innovation; otherwise, they must decide the innovation leader based on market conditions. Manufacturer-led innovation is preferable when consumer environmental awareness and incentive sensitivity are low, whereas logistics firm-led innovation is better when consumer environmental awareness is high.

4.2. The optimal recycling decisions

Lemma 2. The effect of environmental awareness e on recycling incentive r and recycling quantity η :

In Model M, (1) r decreases in e , i.e., $\frac{\partial r}{\partial e} < 0$.

(2) If the investment efficiency is relatively low (λ is higher), η increases in e , i.e., $\frac{\partial \eta}{\partial e} > 0$; if the investment efficiency is relatively high (λ is lower), η decreases in e , i.e., $\frac{\partial \eta}{\partial e} < 0$.

In Model L and Model C, (1) if the investment efficiency is relatively low (λ is higher), r decreases in e , i.e., $\frac{\partial r}{\partial e} < 0$; if the investment efficiency is relatively high (λ is lower), r increases in e , i.e., $\frac{\partial r}{\partial e} > 0$.

(2) η increases in e , i.e., $\frac{\partial \eta}{\partial e} > 0$.

Lemma 2 reveals the impact of consumer environmental awareness on the logistics firm's recycling incentive and recycling quantity. Under upstream-innovation strategy, the recycling incentive always decreases with environmental awareness. This is because higher environmental awareness means consumers are more willing to participate in recycling [25], which motivates logistics firms to reduce recycling incentives. However, we find that when the logistics firm participates in green innovation, as in Model L and Model C, higher consumers' environmental awareness also prompts the logistics firm to offer a higher recycling incentive when the investment efficiency is relatively high. This is because the logistics firm, being involved in green innovation, is better informed about the package's recyclability and therefore believes that the product is worth a higher recycling incentive.

The correlation between recycling quantity and consumer environmental awareness depends on the efficiency of green innovation investment in circular express packaging. Generally, higher consumer environmental awareness leads to a higher recycling quantity. However, under the upstream-innovation strategy, when investment efficiency is relatively high, the recycling quantity decreases as consumer environmental awareness increases. This is because, at high levels of investment efficiency, the manufacturer substantially improves packaging recyclability ($x^M > x^L$) and wholesale price ($w^M > w^L$). In response, the logistics firm reduces its recycling incentive, anticipating that environmentally conscious consumers will voluntarily return the packaging. However, the negative effect of reduced incentives outweighs the positive effect of heightened environmental awareness, resulting in an overall decline in the recycling quantity as consumer environmental awareness rises.

Proposition 2. Optimal express packaging recycling decisions:

(1) The recycling incentive and recycling quantity are the highest in Model C, i.e., $r^C > \max\{r^M, r^L\}$ and $\eta^C > \max\{\eta^M, \eta^L\}$.

(2) If the collaborative contract cannot be achieved, there are two cases:

1) when $0 < e < \frac{1}{21}$, $\underline{b} < b < b_1$, and $\lambda_1 < \lambda < \lambda_2$, the recycling incentive and recycling quantity are higher in Model M, i.e., $r^M > r^L$ and $\eta^M > \eta^L$.

2) When $0 < e < \frac{1}{21}$, $b_1 < b < 1$, $\lambda_2 < \lambda < \lambda_3$, or $\frac{1}{21} < e < \frac{1}{5}$, the recycling incentive and recycling quantity are higher in Model L, i.e., $r^L > r^M$ and $\eta^L > \eta^M$.

Proposition 2 reveals that Model C is the most conducive to maximizing the recycling quantity of circular express packaging. Additionally, when the investment efficiency is relatively high, higher consumer environmental awareness prompts the logistics firm to lower the recycling incentive under upstream-innovation strategy, and manufacturers set a lower green innovation level ($x^M > x^L$, $\eta^M > \eta^L$, $r^M > r^L$). This allows manufacturers to avoid the consequence of the new package purchase quantity being greatly squeezed by the recycling quantity. When investment efficiency is relatively low, the downstream-innovation strategy is more conducive to recycling green innovation ($x^L > x^M$, $\eta^L > \eta^M$).

Proposition 2 provides practical implications for recycling decisions in logistics supply chains. When investment efficiency is high, manufacturers should strategically limit their green innovation levels to avoid excessive substitution of new packaging sales, while logistics firms can lower recycling incentives without harming recovery performance. In contrast, when investment efficiency is low, logistics firms should take the lead in green innovation to enhance recycling outcomes.

4.3. Analysis of production and pricing decisions

Proposition 3. Analysis of production and pricing decisions:

(1) When $0 < e < \frac{1}{21}$, $\underline{b} < b < b_1$, $\lambda_1 < \lambda < \lambda_3$, the sales quantity and wholesale price are higher in Model M, i.e., $q^M > q^L$ and $w^M > w^L$.

(2) When 1) $0 < e < \frac{1}{21}$, $b_1 < b < 1$, $\lambda_2 < \lambda < \lambda_3$; 2) $\frac{1}{21} < e < \frac{1}{5}$, the sales quantity and wholesale price are higher in Model L, i.e., $q^L > q^M$ and $w^L > w^M$.

(3) When $\lambda_3 < \lambda < 1$, the sales quantity of new product and wholesale price are the highest under Model C, i.e., $q^C > \max\{q^M, q^L\}$ and $w^C > \max\{w^M, w^L\}$.

Proposition 3 shows that the logistics firm always tends to purchase more new products at higher wholesale prices and achieves maximum sales under the cooperation innovation. Therefore, the demand-stimulating effect of green innovation level on product demand for logistics firms outweighs the demand-suppressing effect of wholesale prices, which is driven by the joint influence of green innovation level and recycling decisions. The logistics firm is willing to pay more to purchase more new products with a higher green innovation level to quickly capture the market and attain a green image. It follows that the green innovation level has a greater impact on the logistics firm's purchasing decisions than the wholesale price. Proposition 3 offers a clear practical insight for logistics managers: they should not hesitate to accept increased procurement costs if the innovation level is sufficiently high, as the resulting market expansion and green image enhancement will more than compensate. This challenges the conventional cost-first logic and encourages managers to prioritize green innovation performance in partner selection and contract design.

In addition, the green innovation investment efficiency moderates the effect of consumer environmental awareness on wholesale prices and sales quantity. With the increase in consumers' environmental awareness and the improvement of investment efficiency, the manufacturer's motivation shifts from "high price for a novelty" (i.e., setting higher wholesale prices, $\frac{\partial w}{\partial e} > 0$, $\frac{\partial q}{\partial e} < 0$) to "small profit but rapid turnover" (i.e., setting lower wholesale prices, $\frac{\partial w}{\partial e} < 0$, $\frac{\partial q}{\partial e} > 0$).

4.4. Analysis of the optimal green innovation strategies for circular express packaging

Proposition 4. The optimal green innovation strategy for the manufacturer:

- (1) When $0 < e < \frac{1}{21}$, $\underline{b} < b < b_1$, and $\lambda_1 < \lambda < \lambda_{i1}$, the manufacturer prefers the upstream-innovation strategy, i.e., $\pi_m^M > \pi_m^L$.
- (2) When 1) $\lambda > \lambda'$; 2) $0 < e < \frac{1}{21}$, $\underline{b} < b < b_1$, $\lambda_{i1} < \lambda < \lambda_3$, and $b_1 < b < 1$, $\lambda_2 < \lambda < \lambda_3$; 3) $\frac{1}{21} < e < \frac{1}{5}$, $\lambda_2 < \lambda < \lambda_3$, the manufacturer prefers the downstream-innovation strategy, i.e., $\pi_m^L > \pi_m^M$.
- (3) When $\lambda_3 < \lambda < \lambda'$, the manufacturer prefers the collaborative innovation strategy, i.e., $\pi_m^C > \max\{\pi_m^M, \pi_m^L\}$.

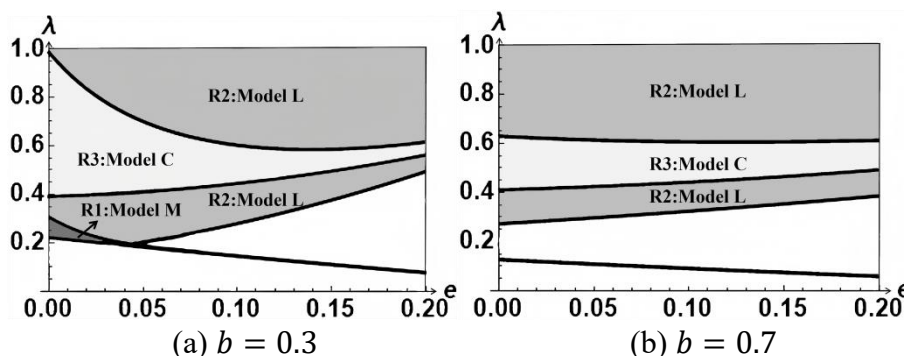


Figure 3. The optimal green innovation strategy for the manufacturer.

Proposition 4 shows that the region where upstream manufacturers are willing to undertake green innovation independently is extremely limited (see R1 in Figure 3). Specifically, the manufacturer prefers the upstream-innovation strategy only when consumer environmental awareness and the recycling incentive are relatively low, and investment efficiency is relatively high. Otherwise, the manufacturer prefers the collaborative innovation strategy when investment efficiency is at an intermediate level (see R3 in Figure 3), and prefers the downstream-innovation strategy when the investment efficiency is relatively low (see R2 in Figure 3). The economic reason behind non-cooperation is that although the manufacturer may gain a higher order quantity in a cooperative model, lower investment efficiency prompts the logistics firm to reduce its cost-sharing proportions ($\frac{\partial \delta}{\partial \lambda} < 0$). Consequently, the manufacturer bears higher investment costs associated with the higher green innovation level.

Proposition 4 provides clear practical guidance for manufacturers regarding green innovation strategy selection. Manufacturers must evaluate two key practical parameters: consumer environmental awareness and investment efficiency. When both awareness and efficiency are low, downstream innovation is preferable; when efficiency is at an intermediate level, collaborative innovation yields the best outcome; only when efficiency is very high, and both awareness and recycling incentives are low, should manufacturers consider independent innovation. This quantitative framework helps manufacturers achieve optimal resource allocation and risk control in green innovation.

Proposition 5. The optimal green innovation strategy for the logistics firm:

- (1) When 1) $0 < e < \frac{1}{93}(6\sqrt{5} - 5)$, $0 < b < \underline{b}$, $\lambda_{i2} < \lambda < \lambda_3$; 2) $\frac{1}{93}(6\sqrt{5} - 5) < e < \frac{1}{5}$, $\underline{b} < b < 1$, $\lambda_1 < \lambda < \lambda_2$, the logistics firm prefers the upstream-innovation strategy, i.e., $\pi_l^M > \pi_l^L$.
- (2) When 1) $0 < e < \frac{1}{93}(6\sqrt{5} - 5)$, $0 < b < \underline{b}$, $\lambda_2 < \lambda < \lambda_3$; 2) $\frac{1}{93}(6\sqrt{5} - 5) < e < \frac{1}{5}$, $\underline{b} < b < 1$, $\lambda_2 < \lambda < \lambda_3$, the logistics firm prefers the downstream-innovation strategy, i.e., $\pi_l^L > \pi_l^M$.
- (3) When $\lambda > \lambda_3$, the logistics firm prefers the collaborative innovation strategy, i.e., $\pi_l^C > \max\{\pi_l^L, \pi_l^M\}$.

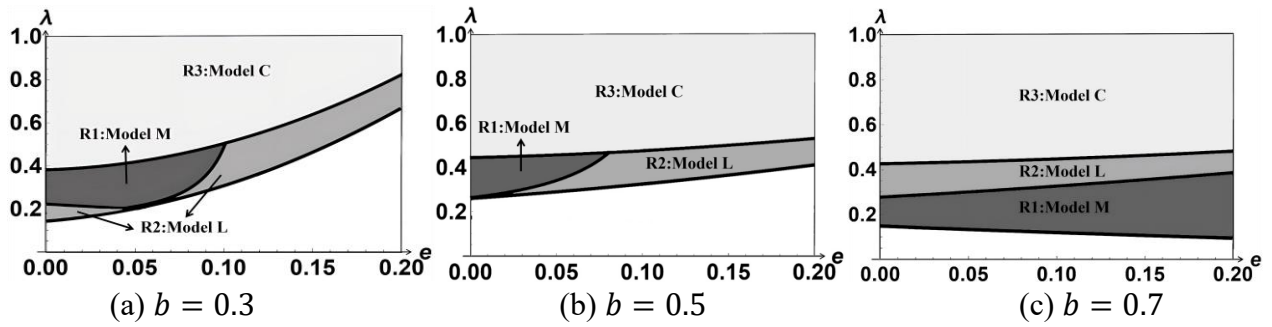


Figure 4. The optimal green innovation strategy for the logistics firm.

Proposition 5 shows that the region where downstream logistics firms are willing to undertake green innovation independently is also extremely limited (see R2 in Figure 3). When green innovation investment efficiency for circular express packaging is excessively high, logistics firms tend not to innovate themselves due to high costs. When investment efficiency is too low, innovation is less effective than procurement. Specifically, when the investment efficiency is relatively low, the logistics firm prefers the collaborative innovation strategy (see R3 in Figure 4). When investment efficiency is relatively high, the logistics firm prefers the upstream-innovation strategy (see R1 in Figure 4). Proposition 5 provides a strategic insight: logistics firms should focus on their core operations, such as logistics and packaging recycling, while leaving packaging production and innovation to upstream partners. This suggests that logistics managers should treat packaging innovation as a service to be procured or co-developed, rather than an in-house capability to be over-pursued.

Proposition 6. The Pareto improvement areas:

- (1) When $0 < e < \frac{1}{21}$, if $\underline{b} < b < b_1$ and $\lambda_1 < \lambda < \lambda_{i1}$, both the manufacturer and the logistics firm prefer the upstream-innovation strategy, i.e., $\pi_m^M > \max\{\pi_m^C, \pi_m^L\}$, $\pi_l^M > \max\{\pi_l^L, \pi_l^C\}$.
- (2) When 1) $0 < e < \frac{1}{21}$, $b_1 < b < b_2$, $\lambda_2 < \lambda < \lambda_{i2}$, and $b_2 < b < 1$, $\lambda_2 < \lambda < \lambda_3$; 2) $\frac{1}{21} < e < \frac{1}{93}(6\sqrt{5} - 5)$, $\underline{b} < b < b_2$, $\lambda_2 < \lambda < \lambda_{i2}$, and $b_2 < b < 1$, $\lambda_2 < \lambda < \lambda_3$; 3) $\frac{1}{93}(6\sqrt{5} - 5) < e < \frac{1}{5}$, both the manufacturer and the logistics firm prefer the downstream-innovation strategy, i.e., $\pi_m^L > \max\{\pi_m^M, \pi_m^C\}$, $\pi_l^L > \max\{\pi_l^M, \pi_l^C\}$.
- (3) When $\lambda_3 < \lambda < \lambda'$, both the manufacturer and the logistics firm prefer the collaborative innovation strategy, i.e., $\pi_m^C > \max\{\pi_m^M, \pi_m^L\}$, $\pi_l^C > \max\{\pi_l^L, \pi_l^M\}$.

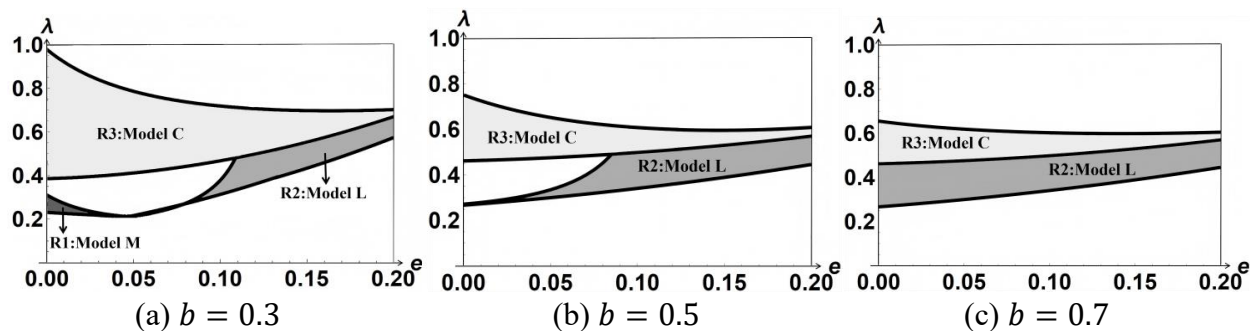


Figure 5. The Pareto improvement areas.

Proposition 6 demonstrates the win-win region where manufacturers and logistics firms can achieve a Pareto improvement. It provides a quantitative foundation for evaluating collaborative green innovation strategy in sustainable logistics by establishing clear threshold conditions. The Pareto improvement

framework provides valuable insights into collaborative strategies across different levels of innovation investment efficiency and consumer environmental awareness scenarios. Proposition 6 offers practitioners a practical threshold-based tool for identifying win-win collaborative green innovation. Managers can apply the Pareto improvement framework to evaluate whether a given investment efficiency and consumer awareness level falls inside the cooperation region, thus preventing fruitless negotiations. More importantly, the proposition exposes a real-world “business vacuum”, i.e., situations where no firm innovates.

This framework fails to address the business vacuum that arises when neither manufacturers nor logistics firms engage in green innovation; it overlooks the institutional and regulatory constraints within sustainable logistics practices, such as the European Green Deal [57] and China’s 14th Five-Year Plan for Modern Logistics Development [58]. Furthermore, this study only examines the innovation strategies of firms operating under a single profit-maximization purpose, yet the single-purpose model is no longer fully applicable in the increasingly complex sustainable market context. To optimize sustainable innovation strategies for logistics firms, manufacturers must rethink their position within the supply chain and transition toward an ESG dual-purpose objective. The next section presents a detailed discussion.

5. Extension model: ESG dual-purpose of the manufacturer

5.1. Extended models

ESG dual-purpose represents a paradigmatic shift in business strategy, transitioning from traditional profit-maximization models to dual-value creation frameworks that integrate economic and social objectives. Under this ESG-driven approach, firms are better positioned to reconcile the competing interests of diverse stakeholders, including internal stakeholders, supply chain partners, consumers, and society. Therefore, in this section, we consider that the manufacturer’s ESG dual-purpose is achieved by incorporating two parts into the profit function: (1) the concern for consumer surplus, $CS = \frac{q^2}{2}$; (2) the concern for environmental impact, $E = u(1 - x)q$, where u denotes the carbon emissions per unit of new circular express packaging, and $u(1 - x)$ denotes that green innovation can reduce carbon emissions. Thus, the change in total manufacturer’s profit structure under ESG dual-purpose is expressed as $a(CS - E)$, and a denotes the manufacturer’s ESG concern degree. For simplicity, we normalize both b and u to 1; relaxing this assumption will not change the main results.

There are also three strategy models here. Under the scenario of a manufacturer with ESG dual-purpose, we denote the scenario where the packaging manufacturer and the logistics firm independently invest in green innovation as Model DM and Model DL, respectively, and the scenario where the logistics firm collaborates with the manufacturer as Model DC.

5.2. The impact of the manufacturer’s ESG dual-purpose on operation decisions

Lemma 3. Analysis of the changes in firms’ willingness to invest in green innovation: $\lambda_1^D > \lambda_1$; $\lambda_2^D > \lambda_2$, $\lambda_3^D > \lambda_3$.

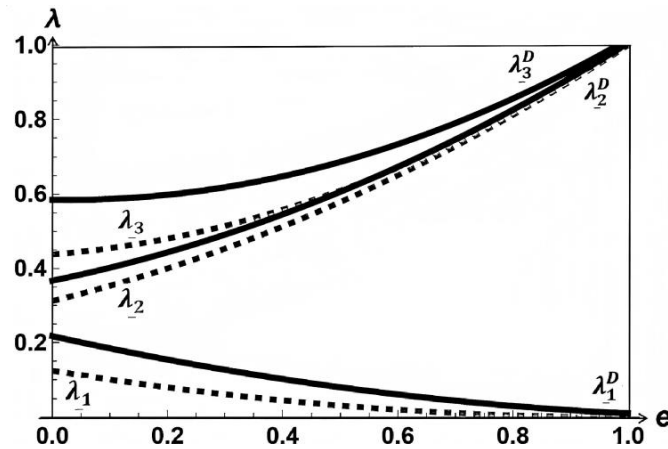


Figure 6. Changes in willingness to invest in green innovation.

Notes: $\lambda > \lambda_1^D$ is the region where the manufacturer is willing to invest in green innovation; $\lambda > \lambda_2^D$ is the region where the logistics firm is willing to invest in green innovation; $\lambda > \lambda_3^D$ is the region where both the manufacturer and the logistics firm are willing to cooperatively invest in green innovation.

By comparing the boundary conditions of Model j and Model h , $j \in \{M, L, C\}$ and $h \in \{DM, DL, DC\}$, we can intuitively find that when the manufacturer considers ESG dual-purpose, the investment cost coefficients under all three strategies increase, indicating that both the manufacturer and the logistics firm are willing to invest more than the scenario considering single profit-maximization purpose. This is due to the fact that the manufacturer incorporates consumer surplus and environmental benefits into its business performance; thus, the manufacturer and the logistics firm are willing to accept a higher investment threshold. Based on these findings, this study further examines the effectiveness and rationality of the mechanism by which ESG dual-purpose promotes sustainable innovation in the logistics industry.

Lemma 4. Analysis of the impact of manufacturer's ESG concern a on the green innovation level x , wholesale price w , recycling quantity η , recycling incentive r , and logistics firm's sharing proportion of investment cost δ .

Table 2. The impact of ESG concerns.

Variables	$\frac{\partial x}{\partial a}$		$\frac{\partial w}{\partial a}$		$\frac{\partial \eta}{\partial a}$		$\frac{\partial r}{\partial a}$		$1 - \delta$
	low a	high a	low a	high a	low a	high a	low a	high a	
Model DM	↗	↘	↗	↘	↗	↘	↗	↘	-
Model DL	↗	↗	↗	↘	↗	↘	↗	↘	-
Model DC	↗	↗	↗	↘	↗	↘	↗	↘	↗

*Notes: “↗” denotes that the variable increases with a ; “↘” denotes that the variable decreases with a ; “Low a ” denotes $0 < a < a'$; “high a ” denotes $a' < a < \bar{a}$.

Lemma 4 indicates that the manufacturer's ESG concern exhibits a convex relationship with the relevant parameters under Model DM. Specifically, when the manufacturer's ESG concern a is relatively low, the green innovation level and wholesale price increase with the manufacturer's ESG concern, and the green innovation level improves compared to Model M ($x^{DM} > x^M$). Consequently, the logistics firm also prefers to increase recycling incentives and collect more used products. When a is relatively high, the marginal benefits of green innovation tend to diminish. In other words, manufacturers' ESG concern

is effective but limited in increasing green innovation levels. This is because the initial investment in green innovation is relatively small, yielding significant technological improvements. However, achieving a higher green innovation level later requires breakthrough innovations and substantial investments. When weighing economic considerations, manufacturers will not make excessive investments. Moreover, while a higher green innovation level enhances the environmental friendliness of the unit product, it simultaneously stimulates overall sales growth, potentially leading to the “Jevons Paradox” phenomenon, where technological advancement instead increases total resource consumption and environmental impact [59]. Under Model DL and Model DC, sustainable logistics supply chains benefit from manufacturers’ higher ESG concerns; the manufacturer not only supports the logistics firm’s green innovation level by offering a lower wholesale price but is also willing to share a larger proportion of green innovation costs in cooperation ($\frac{\partial \delta}{\partial a} < 0$), which reduces the financial pressure on the logistics firm.

As upstream supply chain players, manufacturers strategically invest in green innovation to capture market opportunities and enhance competitive positioning. This upstream investment enables logistics partners to optimize operational efficiency across transportation, packaging, and recovery processes, creating shared value throughout the supply chain ecosystem. This upstream-innovation strategy represents a viable business model for sustainable logistics development, where early-stage innovation investments generate long-term cost advantages and market differentiation opportunities.

5.3. The optimal green innovation strategy under the manufacturer’s ESG dual-purpose

Proposition 7. The optimal green innovation strategy under the manufacturer’s ESG dual-purpose:

For the manufacturer:

(1) When $\lambda''' < \lambda < 1$, the manufacturer prefers the collaborative innovation strategy, i.e., $\pi_m^{DC} > \max\{\pi_m^{DL}, \pi_m^{DM}\}$.

(2) When $\bar{\lambda}_3^D < \lambda \leq \lambda'''$, the manufacturer prefers the downstream-innovation strategy, i.e., $\pi_m^{DL} > \pi_m^{DM}$.

For the logistics firm:

(1) When $\bar{\lambda}_3^D < \lambda < 1$, the logistics firm prefers the collaborative innovation strategy, i.e., $\pi_l^{DC} > \max\{\pi_l^{DL}, \pi_l^{DM}\}$.

(2) When $\bar{\lambda}_2^D < \lambda < \bar{\lambda}_3^D$, the logistics firm prefers the downstream-innovation strategy, i.e., $\pi_l^{DL} > \pi_l^{DM}$.

The Pareto improvement areas:

(1) When $\lambda''' < \lambda < 1$, both the manufacturer and the logistics firm prefer the collaborative innovation strategy, achieving a win-win result, i.e., $\pi_m^{DC} > \max\{\pi_m^{DL}, \pi_m^{DM}\}$, $\pi_l^{DC} > \max\{\pi_l^{DL}, \pi_l^{DM}\}$.

(2) When $\bar{\lambda}_2^D < \lambda < \bar{\lambda}_3^D$, both the manufacturer and the logistics firm prefer the downstream-innovation strategy, achieving a win-win result, i.e., $\pi_m^{DL} > \pi_m^{DM}$, $\pi_l^{DL} > \pi_l^{DM}$.

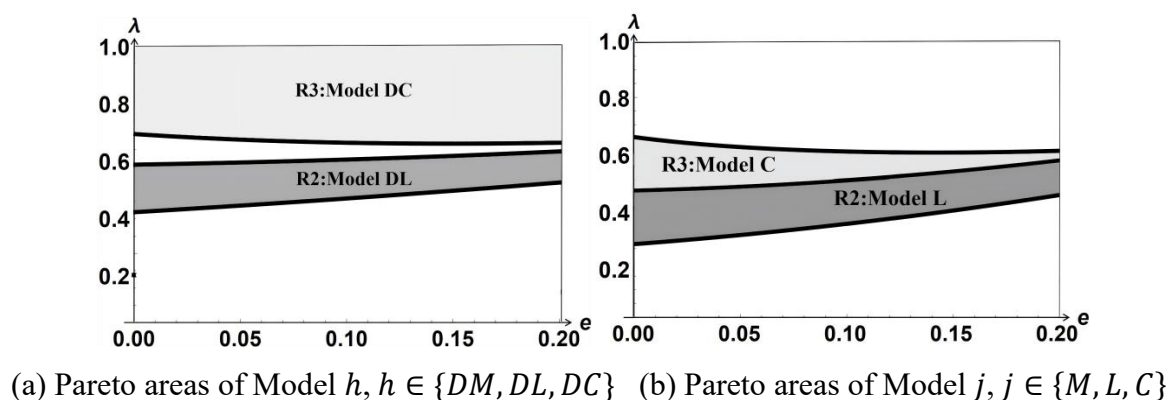


Figure 7. Pareto improvement areas under the manufacturer's ESG dual-purpose.

Under the ESG dual-purpose framework, the manufacturer's performance includes not only profits but also consumer surplus and environmental impact. When the green innovation investment efficiency is extremely low ($\lambda''' < \lambda < 1$), the high green innovation investment costs can only be balanced through collaboration between the manufacturers and the logistics firms. Therefore, the collaborative innovation strategy achieves Pareto improvement. When the investment efficiency is at a medium level ($\bar{\lambda}_3^D < \lambda < \lambda'''$), the green innovation effect of the upstream-innovation strategy is limited, cooperation involves coordinating cost-sharing proportion issues, and the marginal benefits of cooperation diminish. At this point, the downstream-innovation strategy achieves Pareto improvement. Furthermore, by comparing the sizes of the Pareto improvement regions [see Figure 7 (a) vs. (b)], we can intuitively find that the collaborative innovation strategy under the manufacturer's ESG dual-purpose has a larger optimal area than that under the manufacturer's single profit-maximization purpose.

These theoretical results have several important practical implications. First, for logistics firms, the ESG performance of upstream firms should be considered as a non-economic yet core criterion when selecting cooperation partners. Especially in collaborative green innovation, ESG is not merely a compliance or reputational practice; it directly expands the feasible space for mutually beneficial green innovation collaboration by coordinating cost-sharing mechanisms. Second, the comparison of Pareto regions provides practitioners with an intuitive decision-making reference. Practitioners should first evaluate the green innovation investment threshold required to achieve their operational management objectives. Based on where this threshold lies within the industry, they can then choose between advancing collaborative innovation efforts or pursuing independent innovation led by each party. Third, these findings guide the logistics industry in recognizing and adopting ESG practices. By promoting ESG standards throughout the logistics supply chain (e.g., carbon disclosure requirements or green procurement guidelines), relevant firms can optimize their cost structures and accelerate green technology diffusion without relying on heavy subsidies.

6. Conclusions

This study examines green innovation strategies for circular express packaging in a closed-loop supply chain comprising a manufacturer, a logistics firm, and consumers. Our key findings are summarized as follows:

First, consumer environmental awareness and innovation investment efficiency jointly determine the optimal green innovation strategy. Collaborative innovation consistently achieves higher green innovation levels than independent approaches, and the effect of consumer awareness on green innovation level and recycling quantity is non-monotonic. These findings highlight that environmental

and technological factors interact rather than operate independently. Second, due to the high investment threshold, cooperative innovation is inherently difficult to achieve. Nevertheless, when the manufacturer pursues an ESG dual-purpose objective, it prefers to enable collaboration by shouldering a larger share of innovation investment, thereby creating win-win scenarios. This provides theoretical proof that ESG-driven cost-sharing mechanisms can overcome barriers to cooperation, allowing logistics firms to extend their core expertise into upstream value creation and facilitating the establishment of circular systems. Third, when the logistics firm invests in green innovation independently or cooperatively, the manufacturer's green innovation level increases monotonically with its ESG concern in both scenarios. This reveals a cross-member transmission mechanism through which ESG concerns facilitate supply chain innovation.

This research provides significant practical guidance for different stakeholders navigating sustainable innovation strategies in circular express packaging. For packaging manufacturers, when investment efficiency is high, they should exercise caution regarding independent green innovation, as higher consumer environmental awareness may reduce profits. Under an ESG dual-purpose objective, manufacturers are advised to proactively shoulder a larger share of innovation costs to enable collaboration. For logistics firms, recycling incentive strategies should be adjusted based on whether the firm participates in green innovation: when a logistics firm invests in green innovation (downstream or collaboratively), it can afford to increase recycling incentives as consumer awareness rises. This is a counterintuitive operational recommendation, but it can amplify recycling benefits. Managers of logistics firms should adopt a systematic approach integrating consumer awareness, innovation efficiency, and upstream-downstream capabilities rather than relying on single-factor decisions. As the optimal driver of circular packaging, logistics firms should extend their operational expertise upstream, leverage their operational advantages (e.g., packaging design, transportation, and recycling) to amplify the value of supply chain collaboration, and establish a sustainable logistics system of “design–use–recycle”. For policymakers, collaborative innovation is desirable yet blocked by cost-sharing barriers; policies that encourage manufacturers to adopt ESG objectives can break the deadlock and unlock mutually beneficial cooperation. Additionally, our boundary conditions can identify when each innovation strategy is socially optimal, which can inform subsidy or regulatory design. Overall, these insights help enterprises develop precise management strategies that enhance long-term competitiveness and social value. We demonstrate that the ESG framework promotes collaboration among sustainability-oriented firms and enables multi-stakeholder value creation.

There are some avenues for future research. First, in terms of modeling, our model could be extended to multi-tier supply chain networks to examine the scalability of our findings. The linear demand and cost assumptions could be relaxed to test robustness under more complex market dynamics. Second, empirical validation using real-world data would enhance practical applicability as the circular packaging industry matures. Third, future research could explore how technological uncertainty, remanufacturing, and regulatory policies affect the identified strategic dynamics.

Author contributions

Shuli Yang: Writing-original draft, software, methodology, visualization, formal analysis, conceptualization; Junwu Chai: Supervision, funding acquisition, conceptualization; Zhifeng Qian: Writing-review & editing, funding acquisition, formal analysis, conceptualization.

Use of Generative-AI tools declaration

In the preparation of this work, the authors used ChatGPT to assist in improving the clarity of the language. All AI-assisted content was critically reviewed and verified by the authors.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that may have influenced the work reported in this study.

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