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Green Product R&D Strategies under Different Sales Modes

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Abstract: Manufacturers faced the dilemma of independently developing green products or collaborating with e-commerce platforms for joint development. To address this, a two-level green supply chain consisting of a single manufacturer and a single e-commerce platform was examined using game theory methods to explore the strategy selection for green product development under different sales models (distribution and consignment). The study found that under the distribution model, as the technology spillover effect of the e-commerce platform strengthens, the product wholesale price, retail price, manufacturer's R&D effort, e-commerce platform's R&D investment, market demand, and profits of both parties all increased monotonically. Collaborative R&D invariably represented the Pareto-optimal solution for both the manufacturer and the e-commerce platform. However, under the consignment model, although the product retail price, manufacturer's R&D effort, e-commerce platform's R&D investment, and market demand continued to grow in tandem with the strengthening of the technology spillover effect, the manufacturer's profit exhibited a non-monotonic trend of "first decreasing and then increasing". At the same time, the platform's profit initially increased, followed by a decrease, and then another increase. In this model, collaborative R&D was the optimal strategy for both parties only when the e-commerce platform's R&D cost coefficient was relatively high.

Keywords: Green product innovation; Independent R&D; Cooperative R&D; Sales modes

1. Introduction

As the concept of global sustainable development becomes increasingly ingrained, green consumption has emerged as a significant force driving economic transformation and upgrading. According to the International Energy Agency's (IEA) "World Energy Outlook 2025" report, the global green products market surpassed $2.3 trillion in 2024, representing a year-on-year increase of 14.7%, with China contributing nearly 30% of the growth, ranking first globally.[1] The "2024 China Green Consumption Annual Report" indicates that as consumer attention to green products continues to rise, over 78% of consumers prioritize environmental attributes when purchasing products such as home appliances and daily necessities. A majority of respondents (65%) expressed willingness to pay a price premium exceeding 10% for products with significant energy-saving and emission-reduction effects.[2] Despite the rapid growth in demand for green products, the IEA report notes that the overall failure rate of green product research and development (R&D) remains as high as 60%.[3] High R&D costs, immature technologies, and insufficient consumer trust continue to be key challenges for businesses.

Consequently, to address these challenges, a growing number of companies are ramping up investments in green products. According to McKinsey's 2023 Global Survey on Corporate Sustainability, over 65% of surveyed companies reported increased spending on green R&D, with leading enterprises seeing an average annual growth of 25% in green R&D expenditure.[4] For example, Gree Electric Appliances invested over 8 billion yuan in 2023 in green technology and product development. Its self-developed "zero-carbon source" air conditioning technology has been implemented in multiple countries, reducing carbon emissions by over 80%.[5] Unilever has invested 1 billion euros in its "Clean Future" initiative, dedicated to developing biodegradable and renewable material formulations. By early 2024, more than 20 new green products had entered the market.[6] Thus, investment in and R&D for green products have become a crucial pathway for enterprises to achieve both environmental goals and competitive advantage.

Currently, there are two main models for green product R&D. The first is independent R&D, where manufacturers autonomously conduct green product development using their own technology and capital. For example, Gree Electric Appliances adheres to a "core technology independently developed" strategy, investing 8.5 billion yuan of R&D funds in 2024 and successfully developing a photovoltaic direct-drive variable-frequency centrifugal machine system, enabling zero-carbon operation of air conditioning systems;[7] TCL has continuously invested in display technology, launching QLED televisions using eco-friendly quantum dot materials, reducing heavy metal usage by up to 90%.[8]

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1 https://www.iea.org

2 http://www.cnis.ac.cn

3 https://www.iea.org/reports/energy-technology-perspectives-2023

4 https://www.mckinsey.com/industries/sustainability/our-insights/sustainability-in-industry-2023

5 http://www.gree.com/cn/about-gree/social-responsibility

6 https://www.unilever.com/planet-and-society/clean-future/

7 https://www.gree.com.cn

8 https://www.tcl.com

However, since green innovation involves multidimensional knowledge, such as consumer behavior, some manufacturers also choose to collaborate with e-commerce platforms on green product R&D. E-commerce platforms can provide manufacturers with full-chain support—from demand definition to product iteration—by leveraging their massive user data, precise consumer insights, and rapid market feedback capabilities. For instance, in 2023, Procter & Gamble collaborated with JD to launch the “Eco-Pack” customization program, jointly developing several low-carbon laundry products tailored to Chinese consumer preferences based on JD’s consumer big data and user insights.[9]

Similarly, Panasonic partnered with JD to develop a “low-carbon, energy-saving refrigerator”. Based on user research, it is possible to identify consumers’ dual demand for “freshness preservation and low power consumption”. JD prompted Panasonic to optimize its compressor and temperature control systems, ultimately improving the product’s energy efficiency by 20%.[10] Notably, under both R&D models, manufacturers can choose either a reselling or agency selling model to market green products, meaning that different sales models may influence the choice of green product R&D strategies.

Therefore, implementing green product R&D activities according to different sales models becomes a highly worthwhile research topic. Based on this, this paper primarily investigates the following two questions: (1) Under reselling and agency selling models, should manufacturers choose to independently develop green products or collaborate with e-commerce platforms on R&D? (2) How does the e-commerce platform’s technology spillover effect influence product wholesale prices, retail prices, the manufacturer’s R&D capability, the platform’s R&D effort, market demand, and the profits of both parties?

2. Literature Review

Existing research on green products primarily focuses on optimal pricing strategies (Raza & Govindaluri, 2019; Pal et al., 2023; Li et al., 2024), channel selection (Yang et al., 2019; Tao et al., 2023; Tao et al., 2024; Yan et al., 2018), green investment strategies (Yan et al., 2018; Hosseini-Motlagh et al., 2021; Zhang et al., 2023), and green supply chains (Dou et al., 2024; Cai et al., 2023; Ma et al., 2022; Feng et al., 2022; Jin et al., 2021).Most of these studies do not consider collaboration among firms. However, the green product industry chain involves numerous interconnected enterprises, both upstream and downstream. Relying solely on a single firm's internal resources is inadequate to meet the demands of sustainable industry development. Therefore, inter-firm collaboration has become an inevitable trend for advancing the green industry.

Furthermore, some literature has begun to explore cooperation in green product development. For example, Chen et al. (2019) assess the effects of manufacturer-retailer green R&D collaboration on supply chain performance across economic, environmental, and social dimensions, while also considering technology spillover effects and power structures within the supply chain. They identify a key determinant for economic improvement through green R&D

[9] https://corporate.jd.com/newsDetail/19412

[10] https://www.panasonic.cn

collaboration: the extent of a firm's green contribution. The interplay of green R&D efficiency, technology spillover, and inter-firm power relations is shaped by this variable.

Moreover, Yu et al. (2021) analyzed four payment-based R&D cooperation mechanisms structured through different contracts (i.e., vertical R&D cooperation contracts with revenue sharing, vertical R&D cooperation contracts with fixed payments, joint R&D contracts with the marketing party responsible for sales, and joint R&D contracts with the innovator responsible for sales) within a green technology R&D partnership formed between an automaker and a battery manufacturer. They conclude that, from the marketing party's perspective, no single contract form is consistently optimal. The specific choice depends on the trade-off between the marketing party and the innovator in terms of R&D efficiency and sales efficiency.

Additionally, Wu et al. (2021) center their investigation on green R&D collaboration within a supply chain involving one supplier and two competing manufacturers, analyzing how technology spillover, R&D efficiency, and competition intensity affect equilibrium outcomes. They observe that higher technology spillover rates lead to increased R&D investment by the supplier. In contrast, manufacturers' investment is determined by their individual R&D efficiency and the degree of market competition.

Besides, Yang et al. (2022) explore cooperation between a manufacturer and a retailer in green product operations under decentralized and cartelized models. Their results show that, compared to the decentralized model, the cartelized model can improve the profitability of the entire supply chain and the manufacturer, but does not enhance the retailer's profitability. Moreover, unless the manufacturer can effectively incentivize the retailer to participate in cooperation, a Pareto improvement cannot be achieved in the green supply chain under the cartelized model.

On one hand, Wan et al. (2024) consider a scenario in which a manufacturer and a supplier collaborate to improve green product quality, finding that when the manufacturer's innovation efficiency-to-cost ratio is low, collaboration can reverse a declining trajectory into an upward one, and conversely. However, these studies are limited to the green investment activities of conventional supply chain participants (e.g., suppliers, manufacturers, and retailers), neglecting the green investment strategies of e-commerce platforms.

On the other hand, Wang et al. (2022) investigate the interaction between an e-commerce platform's green investment and a supplier's online channel selection. They demonstrate that suppliers do not invariably profit from the platform's green initiatives. Under the reselling model, for suppliers with higher investment efficiency, the platform's green investment leads to higher retail prices, thereby worsening their position.

Similarly, Yang et al. (2023) investigate the e-commerce platform's green investment strategy and its interaction with supply chain members' choices of e-commerce sales models, finding that manufacturers prefer the platform sales model only when they are in a weak position or possess a cost advantage. Otherwise, they tend to favor the reselling model. However, the aforementioned literature overlooks the issue of collaboration among supply chain members.

In summary, although some existing literature on green products has addressed cooperation issues (Chen et al., 2019; Yu et al., 2021), it has not considered the green investment behaviors of e-commerce platforms. In the rapidly evolving e-commerce landscape, the role of platforms in enhancing the green performance of products is equally important. While a few studies have examined the green investment strategies of e-commerce platforms (Wang et al., 2022; Yang et al., 2023), they have not taken into account cooperation among supply chain members. Therefore, this study centers on the issue of collaborative green product R&D under conditions where the e-commerce platform provides technological support.

Based on this, this paper investigates a two-echelon green supply chain consisting of a manufacturer and an e-commerce platform, where the manufacturer is primarily responsible for green product R&D. The manufacturer can choose between independent R&D and collaborative R&D with the e-commerce platform. Additionally, reflecting real-world practices, this paper considers two sales models available to the manufacturer: reselling and agency selling. The study aims to explore green product R&D strategies under these sales models, providing decision-making references for manufacturers to select appropriate green R&D strategies depending on the sales model adopted.

3. Model description

The researcher considers a green supply chain consisting of a manufacturer and an e-commerce platform (hereinafter referred to as "platform"), where the manufacturer produces a green product with a unit cost c and sells it to consumers through the platform under either a reselling or an agency selling model. In the reselling model, the manufacturer is responsible for supplying the product to the platform at wholesale price w, which the platform then retails to consumers at a price p. In contrast, the agency model involves the manufacturer selling directly to consumers via the platform at price p, with the platform receiving a proportionate service fee γ $(0 < \gamma < 1)$ (Wang et al., 2022). Given the critical role of green R&D in enhancing product environmental performance and market competitiveness, the manufacturer can improve the product's green level through two R&D modes: (1) independent R&D mode (Mode N), where the manufacturer engages in green product R&D autonomously; (2) collaborative R&D mode (Mode C), where the manufacturer collaborates with the platform on green product development.

Considering the combined impact of market potential, product price, and R&D capability on market demand, we assume the demand for the green product is given by $D^i = a - p + \theta K^i$ $(i = N, C)$, where a denotes the potential market size of the green product, p denotes the product's selling price, θ indicates consumers' preference for the product's green performance, and K^i denotes the R&D capability under R&D mode i.

When the manufacturer chooses independent R&D (i=N), it conducts R&D autonomously based on its own capabilities. Its R&D capability is denoted as $K^N = k$. The corresponding R&D cost is $\frac{1}{2}\lambda_m k^2$, where λ_m represents the manufacturer's R&D cost coefficient (Wan et al., 2024). When the manufacturer collaborates with the platform on R&D ($i = C$), the platform can provide support to the manufacturer by leveraging its advantages in user data, understanding of consumption scenarios, and product application, generating a technology spillover effect that enhances the manufacturer's R&D capability.

For example, Haier and JD.com jointly developed green smart home appliances, with JD.com providing Haier with precise recommendations for optimizing energy efficiency and designing low-carbon features based on its vast consumer data and usage feedback. This collaboration enables Haier to enhance the green performance of its products and achieve more efficient green innovation. In this case, the R&D capability is expressed as $K^C = k + \eta e$, where

η $(0<\eta<1)$ represents the technology spillover effect provided by the platform, e denotes the R&D effort exerted by the platform, and the platform incurs an R&D cost of $\frac{1}{2}\lambda_p e^2$, where λ_p is the platform's R&D cost coefficient (Yang et al., 2023). Without loss of generality, we assume $\lambda_m=1$, $\lambda_p=\lambda$. When $\lambda>1$, it indicates that the platform has a higher R&D cost coefficient than the manufacturer. When $0<\lambda<1$, it indicates that the manufacturer has a lower R&D cost coefficient than the platform.

In practice, two different sales models exist between manufacturers and platforms. On one hand, the reselling model (Model R). For example, Xiaomi delivers its green smart home appliances to JD.com at a wholesale price, and JD.com independently sets the retail price and handles after-sales services. On the other hand, the agency selling model (Model A). For instance, numerous small and medium-sized green appliance manufacturers (such as Smartmi, Shuleishi, and Airmate) list their products on the JD.com platform, where the manufacturers set the retail prices autonomously, and JD.com charges a certain percentage (e.g., 5%–15%) of the actual sales revenue as a platform service fee.

Therefore, based on the two R&D modes available to the manufacturer (independent R&D vs. collaborative R&D) and the two sales models in the supply chain (reselling vs. agency selling), the researcher primarily investigate four scenarios: (1) independent R&D by the manufacturer under the reselling model (Model RN), (2) collaborative R&D under the reselling model (Model RC), (3) independent R&D by the manufacturer under the agency selling model (Model AN), and (4) collaborative R&D under the agency selling model (Model AC).

4. Equilibrium analysis

This section constructs the objective functions for both the manufacturer and the platform under the reselling model with independent versus collaborative R&D (RN vs. RC) and under the agency selling model with independent versus collaborative R&D (AN vs. AC). It then employs game-theoretic methods to analyze the equilibrium outcomes in each scenario.

4.1. Reselling scenario

4.1.1 Mode RN

Under the reselling model, the manufacturer employs a wholesale contract, and the platform distributes the product. If the manufacturer chooses to independently develop the green product, it first determines the R&D capability, k to maximize its own profit, then sets the wholesale price, w. Finally, the platform determines the retail price, p. In this case, the profit functions of the manufacturer and the platform are given by:

$$\pi_m^{RN}=(w-c)D^N-\frac{1}{2}k^2 \#(1)$$

$$\pi_p^{RN}=(p-w)D^N \#(2)$$

The equilibrium pricing under mode RN can be obtained by using backward induction, as shown in Table 1. Proofs for all propositions in this paper are provided in the Appendix.

4.1.2 Mode RC

Under the reselling model, if the manufacturer collaborates with the platform on green product development, both parties first decide their respective R&D investment levels k and e. Then, the manufacturer sets the wholesale price w, and finally, the platform determines the retail price p. In this case, the profit functions of the manufacturer and the platform are given by:

$$\pi_m^{RC} = (w-c)D^C - \frac{1}{2}k^2 \quad (3)$$

$$\pi_p^{RC} = (p-w)D^C - \frac{\lambda}{2}e^2 \quad (4)$$

Unlike the independent R&D mode, in this scenario, the platform also needs to bear the corresponding R&D cost of $\frac{\lambda}{2}e^2$. By solving mode RC, the corresponding equilibrium results are summarized in Table 1.

Table 1. The equilibrium outcomes under the reselling mode

Equilibrium outcomes	Mode RN	Mode RC
w^*	$c+\frac{2(a-c)}{4-\theta^2}$	$\frac{(4a+4c-2c\theta^2)\lambda-\eta^2\theta^2 c}{8\lambda-(\eta^2+2\lambda)\theta^2}$
p^*	$c+\frac{3(a-c)}{4-\theta^2}$	$\frac{(6a+2c-2c\theta^2)\lambda-\eta^2\theta^2 c}{8\lambda-(\eta^2+2\lambda)\theta^2}$
k^*	$\frac{\theta(a-c)}{4-\theta^2}$	$\frac{2\lambda\theta(a-c)}{8\lambda-(\eta^2+2\lambda)\theta^2}$
e^*	−	$\frac{\theta\eta(a-c)}{8\lambda-(\eta^2+2\lambda)\theta^2}$
D^*	$\frac{a-c}{4-\theta^2}$	$\frac{2\lambda(a-c)}{8\lambda-(\eta^2+2\lambda)\theta^2}$
π_m^*	$\frac{(a-c)^2}{8-2\theta^2}$	$\frac{2\lambda^2(a-c)^2(4-\theta^2)}{(8\lambda-(\eta^2+2\lambda)\theta^2)^2}$
π_p^*	$\frac{(a-c)^2}{(4-\theta^2)^2}$	$\frac{\lambda\ (a-c)^2\ (8\ \lambda-\eta^2\ \theta^2\ )}{2\ (8\lambda-(\eta^2+2\lambda)\theta^2)^2}$

Lemma 1 Under mode RN, customers will always purchase the green product, whereas under mode RC, customers will purchase the green product only when $\lambda > \lambda_1$, where $\lambda_1=\frac{\eta^2\theta^2}{8-2\theta^2}$.

Lemma 1 indicates that, under the reselling model, if the manufacturer chooses independent green product development, customers will always purchase the green product. However, when the manufacturer collaborates with the platform on R&D, the situation differs. Notably, under the collaborative arrangement, as the R&D cost coefficient λ decreases, the product price increases accordingly. Thus, a condition of $\lambda < \lambda_1$ leads to a relatively high price level, thereby suppressing consumer demand and ultimately resulting in no customers purchasing the green product. Conversely, when λ is high ($\lambda > \lambda_1$), the lower price makes the product more attractive to consumers, ensuring positive market demand.

Lemma 2 $\frac{\partial w^{RC*}}{\partial \eta} > 0$, $\frac{\partial p^{RC*}}{\partial \eta} > 0$, $\frac{\partial k^{RC*}}{\partial \eta} > 0$, $\frac{\partial e^{RC*}}{\partial \eta} > 0$, $\frac{\partial D^{RC*}}{\partial \eta} > 0$, $\frac{\partial \pi_m^{RC*}}{\partial \eta} > 0$, $\frac{\partial \pi_p^{RC*}}{\partial \eta} > 0$

Lemma 2 shows that, as the platform's technology spillover effect, η increases, the product wholesale price, retail price, the manufacturer's R&D capability, the platform's R&D investment, market demand, and the profits of both parties are all positively affected. This is because a higher η means that each unit of the platform's R&D effort contributes more significantly to the enhancement of the product's overall green performance, thereby increasing the platform's return on investment and motivating it to raise R&D investment. In response, the manufacturer also increases its own R&D investment. A rise in η further enhances the competitiveness of the green product, supporting higher wholesale and retail prices, attracting more consumers, and driving an increase in market demand. This series of positive changes ultimately leads to a dual increase in the profits of both the manufacturer and the platform. Since the profits of both parties rise with η, this indicates that the willingness of supply chain members to engage in collaborative R&D increases as the platform's technology spillover effect strengthens.

Proposition 1 $k^{RC*} > k^{RN*}$, $w^{RC*} > w^{RN*}$, $p^{RC*} > p^{RN*}$, $D^{RC*} > D^{RN*}$.

Proposition 1 analyzes, under the reselling model, the impact of collaborative green product R&D between the manufacturer and the platform on the product's wholesale price, retail price, the manufacturer's R&D capability, and market demand. Collaborative R&D serves to elevate the manufacturer's R&D capabilities, thereby driving up both wholesale and retail prices. The pooling of resources from both parties through collaborative R&D enables a superior enhancement of the product's green performance over independent manufacturer efforts. As the product's green performance improves to a greater extent, it creates room for the manufacturer to raise the wholesale price, which in turn drives up the retail price. Although collaborative R&D leads to a higher retail price, consumers are still willing to pay more due to the significant improvement in the product's green attributes, thereby further expanding market demand.

Proposition 2 $\pi_m^{RC*} > \pi_m^{RN*}$, $\pi_p^{RC*} > \pi_p^{RN*}$

Proposition 2 confirms that a win-win outcome is achievable under the reselling model through collaborative R&D (as shown in Figures 1 (a) and (b), where $\theta = 0.8$, $\lambda = 0.5$). This is because collaborative green product development between the manufacturer and the platform serves as a driver for higher wholesale and retail prices, while market demand also grows accordingly. As stated in Proposition 1, collaborative R&D raises the R&D costs of both parties. However, the positive effects of price increases and demand expansion outweigh the negative impact of higher R&D costs, ultimately making collaboration more beneficial for both parties. This finding sheds light on the trend of increasing cooperative alliances between manufacturers and e-commerce platforms. For example, in 2024, Haier Smart Home and Tmall jointly announced the establishment of a "Green Smart Appliance Joint Innovation Center", focusing on developing water- and energy-saving smart home ecosystems. Through this collaboration, they launched the first batch of refrigerators and washing machines equipped with intelligent energy management systems.

(a) the manufacturer's profit) (b) the E-commerce platform's profit

Figure 1. Profit comparison under the reselling mode

Proposition 2 attests that, under the reselling model, collaboration in green product R&D between the manufacturer and the platform yields mutual benefits. However, do both parties still prefer collaborative R&D under the agency selling model? The following section will address this question.

4.2. Agency selling scenario

4.2.1 Mode AN

Under the agency selling model, the manufacturer sells directly to consumers, paying the platform a proportionate service fee γ. If the manufacturer chooses to undertake independent development of the green product, it first determines the R&D capability, k to maximize its own profit, and then sets the retail price, p. In this case, the manufacturer and the platform have the following profit functions:

$$\pi_m^{AN} = ((1-\gamma)p - c)D^N - \frac{1}{2}k^2 \#(5)$$

$$\pi_p^{AN} = \gamma p D^N \#(6)$$

Using backward induction, the equilibrium pricing under mode AN can be obtained, as shown in Table 2.

4.2.2 Mode AC

Under the agency selling model, if the manufacturer collaborates with the platform on green product development, both parties first determine their respective R&D investment levels, k and e. Then the manufacturer sets the retail price, p. In this case, the manufacturer and the platform have the following profit functions:

$$\pi_m^{AC} = ((1-\gamma)p - c)D^C - \frac{1}{2}k^2 \#(7)$$

$$\pi_p^{AC} = \gamma p D^C - \frac{\lambda}{2} e^2 \#(8)$$

Unlike the independent R&D mode, in this scenario, the platform also needs to bear the corresponding R&D cost, $\frac{\lambda}{2}e^2$. By solving mode AC, the corresponding equilibrium results are summarized in Table 2.

Table 2. The equilibrium solution under the agency mode

Equilibrium outcomes	Mode AN	Mode AC
p^*	$\frac{Z_1}{(2-(1-\gamma)\theta^2)(1-\gamma)}$	$\frac{c\eta^2\gamma\theta^2 - 2\lambda Z_1}{2(1-\gamma)((\theta^2(1-\gamma)-2)\lambda + \eta^2\gamma\theta^2)}$
k^*	$\frac{\theta((1-\gamma)a-c)}{2-(1-\gamma)\theta^2}$	$\frac{(2c\lambda - c\eta^2\gamma\theta^2 - 2a\lambda(1-\gamma))\theta}{2(\eta^2\gamma\theta^2 - \lambda(2-(1-\gamma)\theta^2))}$
e^*	–	$\frac{(2a - c\theta^2)\eta\gamma}{2(\eta^2\gamma\theta^2 - \lambda(2-(1-\gamma)\theta^2))}$
D^*	$\frac{(1-\gamma)a-c}{(2-(1-\gamma)\theta^2)(1-\gamma)}$	$\frac{Z_2}{2(1-\gamma)Z_3}$
π_m^*	$\frac{((\gamma-1)a+c)^2}{2(2-(1-\gamma)\theta^2)(1-\gamma)}$	$\frac{(2-(1-\gamma)\theta^2)Z_2^2}{8(1-\gamma)Z_3^2}$
π_p^*	$\frac{\gamma(a(1-\gamma)-c)Z_1}{(2-(1-\gamma)\theta^2)^2(1-\gamma)^2}$	$\frac{Z_4}{2(1-\gamma)^2 Z_3^2}$

Note. $Z_1 = c - (c\theta^2 - a)(1-\gamma)$, $Z_2 = 2\lambda(a(1-\gamma)-c) + c\eta^2\gamma\theta^2$, $Z_3 = (2-\theta^2(1-\gamma))\lambda - \eta^2\gamma\theta^2$, $Z_4 = 2Z_1(a(1-\gamma)-c)\lambda^2 - \gamma\eta^2\theta^2\left(\left(-\frac{c\theta^2}{2}+a\right)^2\gamma^2 + \left(-\frac{c^2\theta^4}{2} + (2ac - c^2)\theta^2 - 2a^2\right)\gamma + \frac{c^2\theta^4}{4} - c(a-c)\theta^2 + a^2 - 2c^2\right)\lambda - \frac{c^2\eta^4\gamma^2\theta^4}{2}$.

Lemma 3 Under mode AN, customers will purchase the green product if and only if $c < a(1-\gamma)$. Meanwhile, under mode AC, customers will purchase the green product if and only if $c > a(1-\gamma)$ and $0 < \lambda < \lambda_2$, where $\lambda_2 = \frac{c\gamma\theta^2\eta^2}{2(c-a(1-\gamma))}$.

Lemma 3 shows that, under the agency selling model, when the manufacturer chooses independent green product development, whether consumers purchase the green product is influenced by its production cost, because the cost of the green product directly affects the retail price. The lower the cost of the green product, the more attractive it is for consumers to purchase it. However, even in the face of high production costs, the manufacturer's R&D collaboration with the platform can still prove beneficial. The demand for the green product maintains a positive value, $(D^{AC*} > 0)$, provided that the platform's R&D cost coefficient remains below a certain threshold. This shows that collaborative R&D has the potential to unlock market demand for high-cost green innovation.

Lemma 4 ① $\frac{\partial p^{AC*}}{\partial \eta} > 0$, $\frac{\partial k^{AC*}}{\partial \eta} > 0$, $\frac{\partial e^{AC*}}{\partial \eta} > 0$, $\frac{\partial D^{AC*}}{\partial \eta} > 0$; ② Let $\lambda_3 = \frac{\eta^2 \gamma \theta^2}{2-(1-\gamma)\theta^2}$. When $0 < \lambda \le \lambda_3$, $\frac{\partial \pi_m^{AC*}}{\partial \eta} \le 0$; $\frac{\partial \pi_m^{AC*}}{\partial \eta} > 0$, when $\lambda_3 < \lambda < \lambda_2$. ③ Let $\lambda_4 = \frac{\eta^2 \gamma \theta^2}{2+(1-\gamma)\theta^2}$. When $0 < \lambda \le \lambda_4$ or $\lambda_4 \le \lambda < \lambda_2$, $\frac{\partial \pi_p^{AC*}}{\partial \eta} \ge 0$; $\frac{\partial \pi_p^{AC*}}{\partial \eta} < 0$, when $\lambda_4 < \lambda < \lambda_3$.

Under the agency selling model, as the technology spillover effect, η increases, the product's retail price, the manufacturer's R&D capability, the platform's R&D effort, and market demand all increase, which is consistent with Lemma 2. This suggests that regardless of whether the reselling or agency model is adopted, a stronger technology spillover effect contributes to the enhancement of the manufacturer's green product development capabilities and the expansion of green product market demand. However, unlike the reselling model's monotonic increase in profits for both firms with technology spillover, the agency model reveals a more complex relationship. Under the agency selling model, the impact of the spillover effect on the profits of both parties is non-monotonic.

Specifically, the manufacturer's profit increases with η only if the platform's R&D cost coefficient exceeds a certain threshold. For the platform, the enhancement of the technology spillover effect positively impacts its profit only if the platform's R&D cost coefficient is either low or high. Therefore, in the agency selling model, manufacturers and platforms engaging in collaborative R&D should rationally assess the actual value of the technology spillover effect, avoid blindly pursuing excessively high spillover levels, and make comprehensive decisions based on the platform's R&D cost structure.

Proposition 3 When $0 < \lambda \le \lambda_3$, $p^{AN*} \ge p^{AC*}$, $k^{AN*} \ge k^{AC*}$, $D^{AN*} \ge D^{AC*}$; when $\lambda_3 < \lambda < \lambda_2$, $p^{AC*} > p^{AN*}$, $k^{AC*} > k^{AN*}$, $D^{AC*} > D^{AN*}$

Proposition 3 shows that, under the agency selling model, whether the manufacturer's R&D capability, product retail price, and market demand are superior under collaborative R&D compared to independent R&D depends on the platform's R&D cost coefficient. Specifically, only when the platform's R&D cost coefficient is relatively high do these metrics become higher under collaborative R&D than under independent R&D (as shown in Figure 2, where $\theta = 0.7$, $\lambda = 0.4$). The reason is that a higher R&D cost coefficient implies higher costs for the platform to conduct R&D, leading the platform to reduce its own R&D effort. In response, the manufacturer increases its own R&D capabilities to compensate for this shortfall, thereby significantly improving product performance and stimulating market demand. Meanwhile, to offset the increased R&D costs, the manufacturer also raises the retail price. Then, from a profit perspective, is collaborative R&D beneficial for both parties? Proposition 4 provides the answer.

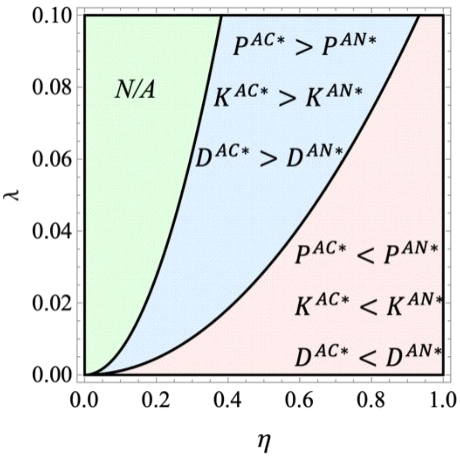
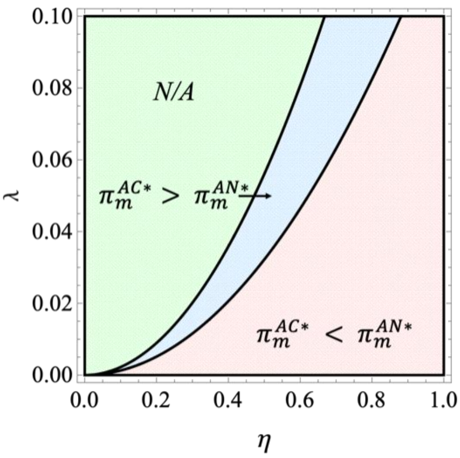


Figure 2. Comparison of equilibrium outcomes under the agency selling mode

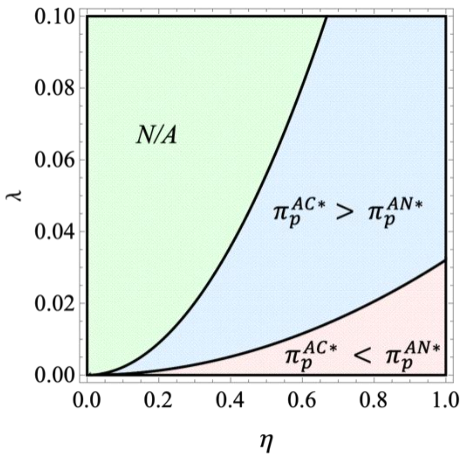
Proposition 4 ①Let $\lambda_5 = \frac{(2c-(a+c\theta^2)(1-\gamma))\theta^2\eta^2\gamma}{4(2-\theta^2(1-\gamma))(c-a(1-\gamma))}$. When $0 < \lambda \leq \lambda_4$, $\pi_m^{AN*} > \pi_m^{AC*}$; when $\lambda_4 < \lambda < \lambda_2$, $\pi_m^{AC*} > \pi_m^{AN*}$.②Let $\lambda_6 = \frac{2\theta^2\eta^2\gamma}{4-\theta^4(1-\gamma)^2}$. When $0 < \lambda \leq \lambda_6$, $\pi_p^{AN*} > \pi_p^{AC*}$; when $\lambda_6 < \lambda < \lambda_2$, $\pi_p^{AC*} > \pi_p^{AN*}$.

Recalling Proposition 2, under the reselling model, a collaborative R&D strategy consistently yields a mutually superior outcome for both the manufacturer and the platform. One might assume that collaborative R&D remains advantageous for both parties under the agency selling model as well. However, Proposition 4 shows that this is not the case. Specifically, under the agency selling model, collaboration is beneficial for both parties only if the platform's R&D cost coefficient reaches an elevated level. Figure 3 visually illustrates this result (where $\theta = 0.7$, $\gamma = 0.4$). This stems from the manufacturer's retention of pricing authority within the agency model, which allows it to set the retail price directly. At the same time, the platform earns only a fixed proportion, γ, of sales revenue as a service fee. When the platform's R&D cost coefficient is high, its incentive to invest in R&D diminishes. In this situation, the dominant manufacturer tends to increase its own R&D investment, significantly improving product performance, which supports a higher retail price and effectively expands market demand (see Proposition 3). As a result, even though the platform contributes less, its revenue increases due to the growth in both product price and demand.

Meanwhile, the manufacturer achieves higher profits by leading the development of green products. This means that when the platform's R&D cost coefficient exceeds a certain threshold, collaborative R&D establishes a mutually beneficial outcome for both parties, thereby clarifying the underlying driver behind the divergent R&D collaboration strategies observed among different manufacturers and platforms in practice. For example, manufacturers with strong in-house R&D capabilities, such as Dyson and Siemens Home Appliances, typically do not collaborate with platforms on product development. In contrast, small appliance manufacturers like Ecovacs tend to engage in collaborative development with platforms. For instance, Ecovacs previously partnered with Tmall to launch energy-efficient air circulators. For e-commerce platforms, NetEase YANXUAN actively collaborates with manufacturers such as MUJI, Zwilling, and Samsonite to co-develop products. For example, in developing a series of energy-saving kitchen appliances with Zwilling, Zwilling handles core technology and production, while NetEase YANXUAN provides consumer trend analysis and design suggestions. In contrast, traditional platforms like Taobao and Pinduoduo do not directly participate in product definition or R&D collaboration, focusing instead on marketing and sales services.



(a) the manufacturer's profit



(b) the E-commerce platform's profit

Figure 3. Profit comparison under the agency selling mode

5. Conclusion

Against the backdrop of increasingly prominent green consumption trends, green R&D has become a key factor in enhancing product competitiveness. For green product development, manufacturers can choose either independent R&D or collaborative R&D with an e-commerce platform. Therefore, this study examines a green supply chain system comprising a manufacturer and an e-commerce platform, investigating whether the manufacturer should choose independent or collaborative R&D under different sales models. By constructing corresponding game-theoretic models, the main findings are as follows:

(1) Under the reselling model, as the platform's technology spillover effect, η, increases, the product's wholesale price, retail price, the manufacturer's R&D capability, the platform's R&D investment, market demand, and the profits of both parties are all positively affected. However, under the agency selling model, although the retail price, the manufacturer's R&D capability, the platform's R&D effort, and market demand still increase with η, the profit changes for both the manufacturer and the platform exhibit a more complex, non-monotonic pattern. The manufacturer's profit initially decreases and then increases with η, while the platform's profit first increases, then decreases, and finally increases again as η rises.

(2) Under the reselling model, compared to independent R&D by the manufacturer, collaborative R&D enhances the manufacturer's R&D capability, as well as the wholesale price, retail price, and market demand. Under the agency selling model, only when the platform's R&D cost coefficient is relatively high do the manufacturer's R&D capability, product retail price, and market demand under collaborative R&D exceed those under independent R&D.

(3) Under the reselling model, the manufacturer's independent R&D cannot match the performance of a collaborative R&D approach with the e-commerce platform. In contrast, under

the agency selling model, collaborative R&D becomes the optimal strategy for both parties only if the platform's R&D cost coefficient exceeds a certain threshold.

In conclusion, this study has several aspects that warrant further exploration. First, this paper primarily examines a vertical collaborative R&D model, whereas in practice, multiple manufacturers may also engage in horizontal cooperative R&D. The impacts of horizontal collaboration on manufacturers and e-commerce platforms require further investigation. Second, the paper assumes complete information symmetry among supply chain members, without considering scenarios of information asymmetry. Future research could explore manufacturers' choices of green product R&D modes under conditions of asymmetric information, such as asymmetric cost or R&D capability information.

AUTHOR CONTRIBUTIONS

Mengdi Qin: Conceptualization; investigation; data collection; methodology; formal analysis; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The data generated and analyzed in this study are available from the corresponding author upon reasonable request. All data will be provided without undue restriction.

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