

Research on Green Technology Investment Strategies in Biodegradable Materials Supply Chain under Information Asymmetry

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Abstract: Scientific design of patent licensing contract and sales channel selection are key to breaking the green technology promotion dilemma of biodegradable materials. Under market scale information asymmetry, we construct a three-echelon supply chain principal agent model including a patent technology supplier, a biodegradable material manufacturer and a terminal sales company. By comparing game equilibrium solutions when the terminal sales company chooses single channel or dual channel sales, we explore the optimal patent licensing contract design and channel selection strategy. We further compare the results with those under symmetric information, explore information value and discuss information disclosure strategy. The study shows that: Both the supplier and the company make strategic decisions on contract design and channel selection under information asymmetry. Reasonable matching of patent licensing contract and channel selection can effectively motivate the manufacturer to increase green technology investment and accelerate green technology diffusion in the supply chain. Information asymmetry deviates the supply chain from the optimal state. Internal information sharing negotiations can alleviate its negative impacts only when disclosure costs and benefits meet specific conditions. External government subsidies can significantly alleviate the negative impact and boost the manufacturer's green technology investment. Market scale and consumer green preference coefficient have a synergistic effect on improving supply chain profit, consumer surplus and social welfare, and this effect becomes more significant when government subsidies are introduced.

Keywords: Biodegradable Materials; Green Technology Promotion; Patent Licensing Contract Design; Channel Selection; Information Asymmetry.

1. Introduction

Against the background of advancing global green and low carbon strategy, the research and development (R&D) and application of biodegradable materials have become the core path to address plastic pollution and achieve a circular economy (Haq et al., 2025). At the policy level, many countries and international organizations have strengthened overall strategic planning. The European Union advances R&D and industrialization of biodegradable materials through policy planning and financial support, and China emphasizes the synergetic promotion of carbon reduction, pollution reduction, green development and economic growth. Both provide solid policy support for the technological innovation and large-scale application of biodegradable materials. In practice, the core supply chain enterprise, such as biodegradable material manufacturer, adopts green technologies, including the efficient strain directional breeding, microbial fermentation synthesis and blend modification. These technologies significantly improve product degradability, promote the application and transformation of environmental protection technologies, effectively reduce the negative environmental externality of plastic pollution, and support the control of "white pollution" (Calero et al., 2021; Akram et al., 2024).

However, promoting green technology in the biodegradable material supply chain still faces multiple constraints. On the one hand, the design of the patent licensing contract is inadequate. The incentive and restraint mechanism is unbalanced. This leads to low efficiency in

green technology transfer. Cases such as Biotec's "thermoplastic processable starch (TPS)" technology infringement (<https://case-law.vlex.com/vid/biotec-biologische-naturverpackungen-v-892790603>) and Occlutech GmbH's resorbable cardiac occluder patent dispute (https://www.toutiao.com/article/7566079380427751976/?upstream_biz=doubao&source=m_redirect.) expose structural defects in the profit distribution of current patent licensing contract. These defects restrict the vertical transfer of green technology in the supply chain. On the other hand, channel selection disconnects from green technology value conversion. Biodegradable materials have specific characteristics, such as sensitivity to degradation conditions and diverse certification requirements. These characteristics set higher demands for channel coordination. However, the current market follows a dual track pattern: online e-commerce traffic is scattered, and offline channels rely on traditional distributors. This pattern makes channel coordination highly difficult, so the value of green technology is hard to pass on to end consumers. Take Haizheng Biotech's PLA lunch boxes as an example. The product can degrade in marine environments through a high temperature extrusion process. But the traditional distributors focus on the "low cost" of traditional plastic lunch boxes. They cannot effectively pass on technical advantages like full biodegradability and industrial composting certification. As a result, the product fails to reach core customers such as chain restaurants and food delivery platforms, leading to the undervaluation of its technical value.

In addition, information asymmetry increases decision making complexity. The biodegradable material industry has

fast technology updates, inconsistent certification standards and large market fluctuations. These features create significant information barriers between supply chain entities. This asymmetry makes it hard to quantify the role of patent licensing contract design and channel selection in green technology promotion. It also makes it hard to accurately evaluate promotion effects. This further hinders sustainable promotion. Therefore, we study patent licensing contract design and channel selection strategy for biodegradable material green technology under market scale information asymmetry. This study is a key means to break current green technology promotion bottlenecks. It is also a theoretical necessity to drive industrial green and low carbon transformation.

Based on this, our study aims to answer the following questions:

(1) Under different market scales, how should the patent technology supplier design the licensing contract to encourage effective green technology adoption? How should the terminal sales company choose the channel to drive green technology market transformation?

(2) What is the linkage between patent licensing contract design and channel selection strategy? Under what conditions can the green technology investment level for biodegradable materials be maximized?

(3) How does market scale information asymmetry affect the profit of the supply chain participant and the overall supply chain profitability for biodegradable materials? How to ease profit distribution imbalance caused by information asymmetry and improve supply chain operation efficiency?

(4) How do different market scales and consumer green preference affect supply chain system performance?

To address the above questions, we draw on the biodegradable material industry's characteristics. Under market scale information asymmetry, we build a three-echelon supply chain decision model. The model includes a patent technology supplier, a biodegradable material manufacturer and a terminal sales company. We analyze patent licensing contract design and channel selection strategy in green technology promotion. We also analyze each entity's optimal strategy selection under asymmetric information. Furthermore, we explore information value and information disclosure strategy.

This study makes four key contributions. First, this study breaks the traditional "exogenously given contracts" assumption in patent licensing research. It treats the patent licensing contract as an endogenous decision variable and constructs a more realistic principal-agent model. It explores the green technology licensing contract design logic of the patent technology supplier under market scale information asymmetry, and reveals the core role of contract parameter design in identifying actual market scale and reducing technology promotion friction. Second, this study innovatively incorporates consumer channels and green preferences to investigate the optimal channel selection strategy, and analyzes the reverse driving effect of green technology investment by the biodegradable materials manufacturer on the operational decisions of the terminal sales company. It provides a theoretical reference for improving channel efficiency and facilitating green technology popularization. Third, this research integrates upstream patent licensing contract design and downstream sales channel selection to construct a unified decision-making framework. It clarifies the promotion mechanism of contract

design and channel selection on green technology investment, and explores the joint influence path of the two strategies on technology investment, which provides a theoretical basis for solving practical industrial problems regarding the mode and scale of enterprise green investment. Finally, targeting the profit distribution imbalance caused by severe information barriers in the biodegradable materials industry, this study introduces government subsidy as a moderating variable. It further explores how government subsidy facilitates green technology investment and mitigates the profit distribution imbalance within the supply chain, providing a scientific decision-making basis for realizing transparent industrial operation and promoting the high-quality development of the environmental protection materials industry.

The review of relevant literature is in Section 2. Section 3 defines research questions, explains symbol definitions and clarifies basic assumptions. Section 4 builds a mathematical model under market scale information asymmetry and conducts analysis. Section 5 explores information value and disclosure strategies. We use numerical examples to illustrate the questions and further extract management implications. Section 6 conducts extended discussion to draw new conclusions. Section 7 presents research conclusions, analyzes management implications and puts forward future research prospects.

2. Literature Review

This study relates to three aspects: green technology investment decisions for biodegradable products, green technology patent contract design, and channel selection in the biodegradable materials supply chain.

2.1. Green Technology Investment Decisions for Biodegradable Products

As consumers' green preferences grow and their demands for sustainable development rise, green technology has become a core driver of competitiveness in the biodegradable materials supply chain (Zhang et al., 2019; Zhu et al., 2023). Existing studies focus on the implementation benefits and influencing factors of green technology investment. Currently, the worsening plastic waste pollution is one of the major global environmental threats. Biodegradable plastics produced with green technology can effectively reduce environmental pollution and energy consumption (Gioia et al., 2021; Li et al., 2024). Guo et al. (2023) found that the green technology of biodegradable film mulching can increase crop yields and farmers' incomes in agricultural production. Li and He (2024) confirmed that consumers' green preferences have a positive impact on the profit of green building material manufacturer and retailer. Xia and Chen (2025) found that more green investment by manufacturer makes it easier to achieve Pareto improvement in the supply chain. However, green technology investment in biobased, biodegradable and compostable plastics can reduce carbon footprints and alleviate environmental pollution, but it still faces multiple constraints including price competition, unstable raw material supply, immature technology, and lack of relevant legal protection (Moshood et al., 2021; Nizamuddin and Chen, 2024). Some scholars have analyzed the factors that influence green technology investment. Sui and Gao. (2023) pointed out that a company's resource endowment positively affects its green investment behavior, and technical cognition can strengthen this effect. Jijue et al. (2024) revealed that market

participation can influence green investment behavior through economic income, market information and green cognition. Wang et al. (2024) confirmed that industrial collaboration models effectively promote green technology diffusion. Most existing studies assume that the manufacturer directly owns the right to use green technologies, but they rarely focus on how the manufacturer obtains legal authorization for green technologies through patent licensing. They also fail to explore how patent licensing can increase the value of green technology investment. Only by clarifying the mechanism of the patent licensing contract in green technology investment can we solve the problems of insufficient green technology investment and low efficiency value conversion, and drive the efficient and large scale diffusion of green technology.

2.2. Green Technology Patent Contract Design

As green technology patent infringement disputes frequently occur in the biodegradable materials field, the patent licensing contract have gradually become a focus of academic research. It is a core factor to ensure the compliant promotion and accelerate the diffusion of green technology. (Jiang et al., 2024; Block et al. 2025). Kulatilaka et al. (2006) confirmed that dynamic royalty contracts have more significant efficiency advantages than fixed fee contracts in green technology transfer when no capital constraints exist. Ye and He (2018) focused on the pollution control field and found that fixed fee licensing is more helpful for the promotion of pollution control technologies. Sarmah et al. (2020) emphasized that fixed fee models may reduce the enthusiasm of foreign enterprises for R&D investment. Wu (2019) found that compared with static patent fees, dynamic patent fee mechanisms can effectively ease the intensity of price competition in the green materials market and help technology owning enterprises maintain higher sales profit margins. Jin et al. (2024) confirmed that asymmetric information on market size drives supplier to strategically select terms of license contracts. Lin and Zhang (2024) found that the two part tariff contracts promote the licensing of carbon emission reduction technologies. Pal and Guin (2025) found that supply chain participants can achieve optimal profits only if they choose option contract technologies and set fixed option prices and exercise prices. Zheng et al. (2025) further revealed that under asymmetric cost information, the wholesale price and one time transfer payment in the optimal contract. These contracts come from supplier of biodegradable film technology. Both factors are closely related to the supplier's cost type. Despite important progress in green technology patent license contract design, existing studies still have some limitations. First, most existing studies base on the assumption of symmetric information. This assumption differs greatly from the real situation of the biodegradable materials industry, which has high technical barriers and complex certification systems. Second, most existing studies focus on traditional manufacturing scenarios. Specialized research on the emerging field of biodegradable materials is relatively scarce. Although Zheng et al.'s (2025) study involved technology promotion, it only considered traditional offline sales channels. It failed to fully reflect the demand for multi-channel integration innovation models of biodegradable materials enterprises in practice. Therefore, based on existing studies, we will focus on breaking the symmetric information assumption. It will combine the characteristics of the biodegradable materials industry. It will

also explore the coordinated optimization mechanism of patent license contracts and channel selection under asymmetric information environments.

2.3. Channel Selection in the Biodegradable Materials Supply Chain

Channel selection is a key link in the value conversion of green technologies for biodegradable materials. Sound channel selection not only drives enterprises to actively develop green technologies, but also accelerates their efficient promotion (Yang et al., 2019; Pal et al., 2023). Existing literature mainly starts from the supply side to study the channel selection strategies of manufacturer and retailer. Li et al. (2016) confirmed that manufacturer will choose dual channel sales for green products only when consumers' loyalty to retail channels and greening costs meet specific conditions. Wu et al. (2023) proved that in optimistic markets, manufacturer can gain higher profit through the resale model if online channel promotion prices are higher than those of traditional channels. In pessimistic markets, however, the reverse pricing order can bring higher returns to manufacturer. Lin et al. (2023) found that green product manufacturer prefers direct sales channels when significant differences exist in the cost of marketing efforts, as this selection prevents traditional retailers from switching to non-green products due to the high effort costs of promoting green products. Wang et al. (2024) showed that green technology investment helps both platform and manufacturer achieve Pareto-level profit and drives platforms to choose the resale model. Tao et al. (2024) further pointed out that higher consumer green awareness positively affects green technology levels and the profit of all supply chain parties, and as this awareness grows, manufacturer shifts from a single resale channel to dual channel sales of green products. Wang et al. (2024) found that manufacturer will introduce online channels for dual channel sales of green products when retailers share demand information. Gao et al. (2025) noted that as consumers' preference for the green economy increases, consumers prefer to buy green products through platform channels. Zhang et al. (2025) found that manufacturer prefers a dual channel model with both online direct sales and online resale when the government provides R&D cost subsidies. However, manufacturer will choose dual channel sales of green products only if specific conditions are met when the government provides per-unit output subsidies. Existing studies generally ignore the key role of heterogeneous consumer preferences. In fact, the complex certification and delayed benefits of biodegradable materials significantly increase consumers' demand for channel professionalism and information credibility. For example, environmentally conscious consumers often prefer professional retail channels or brand owned direct channels that can provide professional certification explanations and traceability information. Therefore, it is urgent to explore the optimal channel selection strategy from the dual perspectives of consumer channel preferences and green preferences, combined with the product characteristics of biodegradable materials. This strategy can effectively promote the efficient transmission of green technology value to end consumers and support the healthy development of the biodegradable materials market.

3. Problem Description and Model Assumptions

3.1. Problem Description

Under market scale information asymmetry, we construct a three-echelon supply chain principal agent model including a patent technology supplier (e.g., NatureWorks, Zhongna Biotech), a biodegradable material manufacturer (e.g., Braskem, Hengli Biotech) and a terminal sales company (e.g., PLA lunch box brand, eco-friendly materials supply chain platform). The decision sequence is as follows: first, the patent supplier designs a green technology license contract $\{r, f\}$ for biodegradable materials (e.g., high efficiency strain breeding, blend modification process) by setting royalty rate and one time fixed fee (hereafter fixed fee). Second, after accepting the contract, the manufacturer decides its green technology investment level t and the wholesale price of biodegradable materials w . Third, the terminal sales company decides the sales price p for a single channel and offline and online sales prices (p_r, p_d) for a dual channel.

3.2. Model Assumptions

To investigate the promotion of green technology in biodegradable materials and conform to industrial operational characteristics, this paper proposes model assumptions based on classical demand theory and existing studies on green consumption behavior, which underpin the subsequent theoretical analysis and model solution. The specific assumptions are presented below.

(1) Referring to Li et al. (2014) and Cao et al. (2024), product prices are negatively correlated with market demand, while green technology investments can effectively boost consumers' purchase intention by incorporating processes for improving degradation performance and meeting industrial certification standards. Correspondingly, we establish the demand functions: for the single-channel mode, $q = a - p + kt$; for the dual-channel mode, the offline and online channels are expressed as $q_r = \theta a - p_r + bp_d + kt$ and $q_d = (1 - \theta)a - p_d + bp_r + kt$, respectively. In these functions, a denotes market size, θ ($0 < \theta < 1$) represents consumers' preference for offline channels, b ($0 < b < 1$) denotes the cross-price sensitivity coefficient between channels, and k ($0 < k < 1$) represents the consumer green preference coefficient.

(2) Following Roy et al. (2019) and Lin et al. (2026), green technology investment exhibits increasing marginal costs. A quadratic cost function $\frac{1}{2}t^2$ is adopted to depict this feature, where t stands for the green technology investment level, which can be measured by practical indicators such as the growth rate of product degradation efficiency.

(3) The technology supplier is excluded from sales and thus cannot acquire accurate market scale information. In contrast, both the manufacturer and sales company engage in product distribution and can accurately grasp real market scale through sales data and demand fluctuations. Based on Jin et al. (2023) and Levi et al. (2022), market scale is divided into two types: high a_H and low a_L ($a_H > a_L$), with probability distributions of $Pr(a_H) = \rho$ and $Pr(a_L) = 1 - \rho$ ($0 < \rho < 1$).

(4) The biodegradable materials industry features

fragmented production, and the commercialization of green technologies faces high uncertainty and risks. The diffusion and application of such technologies carry prominent externalities and rely heavily on patent licensing contracts. Accordingly, the technology supplier designs differentiated patent licensing contracts $\{(r_H, f_H), (r_L, f_L)\}$ according to the prior probability of market scale, so as to balance technological R&D risks and economic returns.

(5) Contract design must satisfy the participation constraint IR and the incentive-compatibility constraint IC for the manufacturer, where IR represents the minimum expected return R (reservation profit) on green technology investment for the manufacturer, as determined by industry research, specifically, $\Pi_{FH} \geq R$ and $\Pi_{FL} \geq R$. The incentive-compatibility constraint, via $\Pi_{FH} \geq \Pi_{FHL}$ and $\Pi_{FL} \geq \Pi_{FLH}$, ensures that the manufacturer selects contracts based on actual market scale, thereby preventing misreporting of information.

(6) To guarantee model validity and the existence of equilibrium solutions, the probability of low market scale is set at a relatively high level ($a_L/a_H > \rho$), which reflects the uncertainty of industrial policy implementation. Referring to Huang et al. (2025), the demand influence of consumer green preference is weaker than the cross-price sensitivity between channels ($k < \sqrt{2(1-b)}$), which is consistent with the price-sensitive dominant characteristic of the current biodegradable materials market.

4. Model Construction and Analysis

Based on the above problem descriptions and model assumptions, this section denotes the game models as Model S and Model D respectively. These models apply when terminal sales company chooses single channel or dual channel sales under asymmetric market size information.

1) Model S

When the sales company operates a single-channel sales mode, the game model is

$$\text{Max}_{r_H, f_H, r_L, f_L} \Pi_T^S = \rho(r_H q_H + f_H) + (1 - \rho)(r_L q_L + f_L)$$

$$\text{s.t. Max}_{t_i, w_i} \Pi_{Fi}^S = (w_i - r_i)q_i - \frac{1}{2}t_i^2 - f_i$$

$$\text{s.t. Max}_{p_i} \Pi_{Mi}^S = (p_i - w_i)q_i$$

2) Model D

When the sales company operates a dual-channel sales mode, the game model is

$$\text{Max}_{r_H, f_H, r_L, f_L} \Pi_T^D = \rho(r_H(q_{dH} + q_{rH}) + f_H) + (1 - \rho)(r_L(q_{dL} + q_{rL}) + f_L)$$

$$\text{s.t. Max}_{t_i, w_i} \Pi_{Fi}^D = (w_i - r_i)(q_{ri} + q_{di}) - \frac{1}{2}t_i^2 - f_i$$

$$\text{s.t. Max}_{p_{ri}, p_{di}} \Pi_{Mi}^D = (p_{ri} - w_i)q_{ri} + (p_{di} - w_i)q_{di}$$

Taking Model S as an example, where $\Pi_{TH}^S = r_H q_H + f_H$ and $\Pi_{TL}^S = r_L q_L + f_L$. The problem is solved by backward induction. At the first game stage, the patented technology supplier cannot observe the true market scale and therefore provides the manufacturer with a menu of alternative patent licensing contracts $\{(r_H, f_H), (r_L, f_L)\}$. By observing the manufacturer's contract choice, the supplier can infer the actual market scale.

The optimal decision problem is formulated as follows:

$$\begin{aligned} \text{Max}_{r_H, r_L, f_H, f_L} \quad & \Pi_T^S = \rho(r_H q_H + f_H) + (1-\rho)(r_L q_L + f_L) \\ \text{s.t.} \quad & \begin{cases} IR(H) : \Pi_{FH}^S(w_H^{S*}, t_H^{S*} | r_H, f_H) \geq R \\ IR(L) : \Pi_{FL}^S(w_L^{S*}, t_L^{S*} | r_L, f_L) \geq R \\ IC(H) : \Pi_{FH}^S(w_H^{S*}, t_H^{S*} | r_H, f_H) \geq \Pi_{FHL}^S(w_{HL}^{S*}, t_{HL}^{S*} | r_L, f_L) \\ IC(L) : \Pi_{FL}^S(w_L^{S*}, t_L^{S*} | r_L, f_L) \geq \Pi_{FLH}^S(w_{LH}^{S*}, t_{LH}^{S*} | r_H, f_H) \end{cases} \end{aligned}$$

It is straightforward to verify the condition $\Pi_{FHL}^S(w_{HL}^{S*}, t_{HL}^{S*} | r_L, f_L) - \Pi_{FL}^S(w_L^{S*}, t_L^{S*} | r_L, f_L) > 0$. Meanwhile, under the constraints IR and IC , we obtain $\Pi_{FH}^S(w_H^{S*}, t_H^{S*} | r_H, f_H) \geq \Pi_{FHL}^S(w_{HL}^{S*}, t_{HL}^{S*} | r_L, f_L) > \Pi_{FL}^S(w_L^{S*}, t_L^{S*} | r_L, f_L) \geq R$. Consequently, $IR(H)$ holds

permanently. We then construct the Lagrangian function based on the K-T conditions: $Y(r_H, r_L, f_H, f_L, \lambda_1, \lambda_2, \lambda_3) = \rho \Pi_{TH}^S + (1-\rho) \Pi_{TL}^S + \lambda_1 (\Pi_{FL}^S - R) + \lambda_2 (\Pi_{FH}^S - \Pi_{FHL}^S) + \lambda_3 (\Pi_{FL}^S - \Pi_{FLH}^S)$.

From the K-T conditions, namely $\frac{\partial Y}{\partial r_i} = 0, \frac{\partial Y}{\partial f_i} = 0$ ($i = H, L$), $\lambda_m \geq 0$ and $\lambda_m \frac{\partial Y}{\partial \lambda_m} = 0$, it follows that $m = 1, 2, 3$. Thus, we can solve for $r_H^{S*}, r_L^{S*}, f_H^{S*}$, and f_L^{S*} .

Theorem 1 Under asymmetric market size information, the patent technology supplier designs the optimal contract. This applies when the terminal sales company chooses single channel or dual channel sales. Details are shown in Table 1.

Table 1. Optimal patent licensing contract design under market scale information asymmetry

i	r_i^{S*}	f_i^{S*}	r_i^{D*}	f_i^{D*}
H	0	$\frac{2(a_H - a_L)r_L + a_L^2}{2(4 - k^2)} - R$	0	$\frac{4(1-b)(a_H - a_L)r_L + a_L^2}{8(2 - 2b - k^2)} - R$
L	$\frac{\rho(a_H - a_L)}{1 - \rho}$	$\frac{(a_L - r_L)^2}{2(4 - k^2)} - R$	$\frac{\rho(a_H - a_L)}{2(1-b)(1-\rho)}$	$\frac{4(1-b)r_L((1+b)r_L - a_L) + a_L^2}{8(2 - 2b - k^2)} - R$

Based on Theorem 1, under asymmetric market size information, the patent technology supplier strategically designs patent licensing contracts. It aims to identify the actual market size and avoid profit losses. Specifically, the supplier in a high market scale designs a contract with only a fixed fee. The supplier in a low market scale designs the two part tariff contract with both royalty and fixed fee. The channel selection of the terminal sales company does not affect the contract form. But it affects the actual sales volume and profit margin of biodegradable materials. This prompts the supplier to adjust the contract parameters.

Proposition 1 1) When $k_1 < k < 1$, $\Pi_{TH}^{S*} < \Pi_{TH}^{D*}$, $\Pi_{TL}^{S*} < \Pi_{TL}^{D*}$; otherwise, $\Pi_{TH}^{S*} > \Pi_{TH}^{D*}$, $\Pi_{TL}^{S*} > \Pi_{TL}^{D*}$. 2) When $k_1 < k < 1$, $\Pi_{FH}^{S*} < \Pi_{FH}^{D*}$; otherwise, $\Pi_{FH}^{S*} > \Pi_{FH}^{D*}$. $\Pi_{FL}^S = \Pi_{FL}^{D*}$. 3) When $0 < \theta < \theta_1$ or $\theta_2 < \theta < 1$, $\Pi_{MH}^{D*} > \Pi_{MH}^{S*}$; otherwise, $\Pi_{MH}^{D*} < \Pi_{MH}^{S*}$. When $0 < \theta < \theta_3$ or $\theta_4 < \theta < 1$, $\Pi_{ML}^{D*} < \Pi_{ML}^{S*}$; otherwise, $\Pi_{ML}^{D*} > \Pi_{ML}^{S*}$. Where $k_1 = \sqrt{\frac{4(1-2b)}{3}}$, $\theta_1 = \Lambda_1 - \Lambda_2$, $\theta_2 = \Lambda_1 + \Lambda_2$, $\theta_3 = \Lambda_1 - \Lambda_3$, $\theta_4 = \Lambda_1 + \Lambda_3$; and $\theta_1 < \theta_2$, $\theta_3 < \theta_4$. $\Lambda_1 = \frac{8(1-b) - (2(3-b) - k^2)k^2}{2(2-2b-k^2)(4-k^2)}$, $\Lambda_2 = \frac{\sqrt{(7+b^2+8b)k^4 + 8(2-4b-3k^2)(1-b^2)}}{2(2-2b-k^2)(4-k^2)}$, $\Lambda_3 = \frac{\sqrt{(1+b)(a_L - 2(1-b)r_L)^2(8(2-4b-3k^2)(1-b^2) + (7+b^2+8b)k^4)}}{2(2-2b-k^2)(4-k^2)a_L}$.

From Proposition 11) and 2), when consumers exhibit a high green preference coefficient ($k_1 < k < 1$), both the technology supplier and the manufacturer with high-scale market achieve higher profits under the dual-channel mode. In markets with low scale and subject to the constraint IR , the manufacturer's profit is always equal to the retained revenue

R , regardless of channel selection or consumer green preference. This is because strong green preferences effectively boost market demand. In the dual-channel mode, the supplier tends to raise fixed licensing fees to maximize profit (when $k_1 < k < 1$, $f_i^{S*} < f_i^{D*}$). Given the high upfront costs and uncertain returns of green technology investment, the combination of large market scale and strong green preferences helps the manufacturer accelerate cost recovery and revenue growth through sales expansion.

Proposition 13) indicates that, regardless of market scale, the sales company adopts the dual-channel mode only when consumers' offline channel preferences fall within specific intervals (i.e., relatively $0 < \theta < \theta_1$, $0 < \theta < \theta_3$ or relatively high $\theta_2 < \theta < 1$, $\theta_4 < \theta < 1$). This is because, when offline preference is weak, dual-channel operation enables precise targeting of online consumers to stimulate sales; when offline preference is strong, the online channel functions as a complementary tool to explore latent market demand and optimize overall sales configuration.

According to Theorem 1 and Proposition 1, under market-scale information asymmetry, the patent technology supplier dynamically designs the patent licensing contract according to market scale. It formulates a pure fixed-fee contract for a high market scale and a two-part tariff contract for a low market scale. Meanwhile, the terminal sales company flexibly selects its sales channel by considering factors including consumer channel preference, consumer green preference and market scale. Thus, we obtain Conclusion 1.

Conclusion 1 Under market-scale information asymmetry, both the patent technology supplier and the terminal sales company will strategically design the patent licensing contract and select the sales-channel mode.

5. Value of Information and Information Disclosure Strategy

To study the impact of asymmetric market size information on decisions in the biodegradable material supply chain, we take the symmetric market size information case as a benchmark. Specifically, the patent technology supplier can accurately obtain market size information a_i ($i=H$ or L). It only needs to design corresponding patent licensing contracts (r_i, f_i) for different market size types. It maximizes its own profit on the premise of meeting the constraints of the biodegradable material manufacturer IR , without considering other constraints IC . We denote the models as Model SN and Model DN respectively, when the terminal sales company chooses single channel or dual channel sales under symmetric market size information.

5.1. Value of Information

Proposition 2 1) $t_H^{SN*} = t_H^{S*}$, $t_L^{SN*} > t_L^{S*}$; 2) $t_H^{DN*} = t_H^{D*}$, $t_L^{DN*} > t_L^{D*}$.

Proposition 2 indicates that under information asymmetry, regardless of the channel selected by the terminal sales company, the green-technology investment of the biodegradable materials manufacturer can reach the optimal level under information symmetry when the market scale is high, and the channel mode exerts no influence on it. When the market scale is low, affected by high upfront investment cost and uncertain returns of green technology, the biodegradable materials manufacturer will reduce its green-technology investment to hedge against risks from demand fluctuation.

Proposition 3 1) $E(\Pi_T^{SN*}) > E(\Pi_T^{S*})$, $E(\Pi_T^{DN*}) > E(\Pi_T^{D*})$; 2) $E(\Pi_F^{SN*}) < E(\Pi_F^{S*})$, $E(\Pi_F^{DN*}) < E(\Pi_F^{D*})$; 3) $E(\Pi_M^{SN*}) > E(\Pi_M^{S*})$, $E(\Pi_M^{DN*}) > E(\Pi_M^{D*})$; 4) $E(\Pi_{SC}^{SN*}) > E(\Pi_{SC}^{S*})$, $E(\Pi_{SC}^{DN*}) > E(\Pi_{SC}^{D*})$.

Proposition 3 illustrates that under information asymmetry, to guarantee smooth cooperation, the patent licensing contract designed by the patent technology supplier needs to satisfy both constraint IR and constraint IC of the biodegradable materials manufacturer. Such constraints squeeze its expected profit margin. The biodegradable materials manufacturer can obtain extra benefit ($\Pi_{FH}^{S*} > \Pi_{FH}^{SN*}$) by concealing private information under a high market scale, while it only gains reservation profit ($\Pi_{FL}^{S*} = \Pi_{FL}^{SN*} = R$) under a low market scale. The pricing decision of the terminal sales company is affected by the biodegradable materials manufacturer's choices, and its expected profit also decreases.

Proposition 4 1) $CS_H^{SN*} = CS_H^{S*}$, $CS_L^{SN*} > CS_L^{S*}$; $CS_H^{DN*} = CS_H^{D*}$, $CS_L^{DN*} > CS_L^{D*}$; 2) $SW_H^{SN*} = SW_H^{S*}$, $SW_L^{SN*} > SW_L^{S*}$; $SW_H^{DN*} = SW_H^{D*}$, $SW_L^{DN*} > SW_L^{D*}$.

Proposition 4 illustrates that regardless of the selected channel, information asymmetry exerts no influence on consumer surplus and social welfare under a high market scale, yet it weakens their improvement under a low market scale.

According to Propositions 2-4, information asymmetry drives supply-chain decisions away from optimality. The supply chain can achieve optimal decision-making efficiency under a high market scale. Under a low market scale, however, the green-technology investment level, the profit of the patent technology supplier, the profit of the terminal sales company and the overall supply-chain profit, consumer surplus as well as social welfare all decline. Meanwhile, the biodegradable materials manufacturer can obtain information rent by taking advantage of its private information to raise its own expected profit. For instance, research institutes hold green technologies such as PHA synthesis and PLA modification, while the biodegradable materials manufacturer is better informed about production adaptability and end-user demand. The party with information advantage is reluctant to share information voluntarily, making it difficult for the supply chain to reach optimal decisions.

5.2. Information Disclosure Strategy

To explore the motives and conditions under which the biodegradable materials manufacturer voluntarily discloses private information to achieve a “win-win” outcome, this study assumes that the bargaining power of the patent technology supplier and the biodegradable materials manufacturer are τ ($0 < \tau < 1$) and $1-\tau$, respectively. A larger value of τ indicates stronger bargaining power for the patent technology supplier. Under the single-channel and dual-channel modes of the terminal sales company, the conditions for both parties to reach an information-sharing negotiation are $\tau_1(\Pi_{Ti}^{SN*} + \Pi_{Fi}^{SN*}) > \Pi_{Ti}^{S*}$, $(1-\tau_1)(\Pi_{Ti}^{SN*} + \Pi_{Fi}^{SN*}) > \Pi_{Fi}^{S*}$, $\tau_2(\Pi_{Ti}^{DN*} + \Pi_{Fi}^{DN*}) > \Pi_{Ti}^{D*}$ and $(1-\tau_2)(\Pi_{Ti}^{DN*} + \Pi_{Fi}^{DN*}) > \Pi_{Fi}^{D*}$, respectively. That is, the profit of each party after negotiation is no lower than that under information asymmetry.

Proposition 5 Regardless of the channel mode, both parties cannot reach an information-sharing negotiation under a high market scale. Under a low market scale, the two sides can achieve information-sharing negotiation if condition $\tau_1 \in (\bar{\tau}_1, \underline{\tau}_1)$ holds for the single-channel mode and condition $\tau_2 \in (\bar{\tau}_2, \underline{\tau}_2)$ holds for the dual-channel mode. Here,

$$\underline{\tau}_1 = \frac{a_L^2 - r_L^2 - 2(4-k^2)R}{a_L^2}, \quad \bar{\tau}_1 = \frac{a_L^2 - 2(4-k^2)R}{a_L^2},$$

$$\underline{\tau}_2 = \frac{a_L^2 - 4(1-b)^2 r_L^2 - 8(2-2b-k^2)R}{a_L^2} \quad \text{and} \quad \bar{\tau}_2 = \frac{a_L^2 - 8(2-2b-k^2)R}{a_L^2}.$$

Proposition 5 reveals that under a high market scale, the biodegradable materials manufacturer cannot obtain higher profit after negotiation than under information asymmetry regardless of bargaining results, so negotiation cannot be realized. Under a low market scale, when the bargaining power of the patent technology supplier reaches a specific threshold, both parties can realize Pareto improvement in profit through negotiation. In other words, two prerequisites including “low market scale” and “qualified bargaining power of the supplier” should be satisfied to realize a “win-win” result via information disclosure. Otherwise, information barriers will hinder the diffusion of green technology.

Since the effect of internal information-sharing negotiation is constrained by thresholds, and the promotion of green technology for biodegradable materials faces difficulties such as high R&D costs and uncertain returns, market mechanisms alone cannot eliminate information barriers. As a vital policy instrument, government subsidy can effectively resolve the prisoner's dilemma of information through cost-sharing and incentive guidance (Chen and Li, 2021; Yan Z S et al., 2025). Therefore, government subsidy is introduced. The single-channel model and dual-channel model with government subsidy are denoted as ST and DT , respectively.

It is worth noting that as the core participant in the biodegradable material supply chain, the manufacturer plays a vital role in investing in green technology for production and manufacturing. This process is the starting point for the green operation of the supply chain (Feng Hongqi et al., 2019). This section considers that the government provides subsidies g for each unit of green technology investment made by the biodegradable material manufacturer. Thus, when the manufacturer's green technology investment level reaches t , the government subsidies amount is gt . Based on the difference in the optimal green technology investment level between symmetric and asymmetric information scenarios (i.e., $t_i^{SN*} - t_i^{S*}$, where t_i^{SN*} and t_i^{S*} represent the optimal investment levels under symmetric and asymmetric information respectively), the government sets an additional reservation profit $g(t_i^{SN*} - t_i^{S*})$ for the manufacturer. In this case, the reservation profit of the manufacturer is $R + g(t_i^{SN*} - t_i^{S*})$.

Proposition 6 $t_i^{ST*} > t_i^{S*}$; $t_i^{DT*} > t_i^{D*}$.

Proposition 6 shows that regardless of market size or the sales channel chosen by the terminal sales company, introducing government subsidies can directly incentivize the biodegradable material manufacturer to increase its green technology investment level by reducing the investment cost of green technology for biodegradable materials. This conclusion has also received real-world verification. The EU provided a €7.6 million subsidies for the Greco Project through the "Horizon Europe" program. The subsidies support the research and development of high performance, recyclable and biodegradable food packaging. It not only directly incentivizes enterprises to increase investment in green technology, but also improves the biodegradability, production efficiency and quality of PLA in the field of food packaging. It further promotes the circular application and biodegradability optimization of PLA materials.

Proposition 7 1) $\Pi_{Ti}^{ST*} > \Pi_{Ti}^{S*}$, $\Pi_{Ti}^{DT*} > \Pi_{Ti}^{D*}$; 2) $\Pi_{Fi}^{ST*} > \Pi_{Fi}^{S*}$, $\Pi_{Fi}^{DT*} > \Pi_{Fi}^{D*}$; 3) $\Pi_{Mi}^{ST*} > \Pi_{Mi}^{S*}$, $\Pi_{Mi}^{DT*} > \Pi_{Mi}^{D*}$.

Proposition 7 shows that introducing government subsidies can directly expand the profit margin of each link in the biodegradable material supply chain by reducing green technology costs: the patent technology supplier will increase the fixed fee to expand its own profit ($f_i^{JT*} > f_i^{j*}$, $j = S, D$); for the biodegradable material manufacturer, combined with Proposition 6, it can promote the increase of green technology investment through government subsidies on the one hand, and raise the wholesale price through the differentiation of biodegradable materials on the other hand ($w_i^{JT*} > w_i^{jS*}$), thus increasing its own profit; the terminal sales company will

raise the sales price to expand its own profit ($p_i^{ST*} > p_i^{S*}$; $p_{ri}^{DT*} > p_{ri}^{D*}$, $p_{di}^{DT*} > p_{di}^{D*}$).

Proposition 8 1) $CS_i^{ST*} > CS_i^{S*}$, $CS_i^{DT*} > CS_i^{D*}$; 2) $SW_i^{ST*} > SW_i^{S*}$, $SW_i^{DT*} > SW_i^{D*}$.

According to Proposition 8, government subsidy can further improve consumer surplus and social welfare. Combined with Proposition 6, government subsidy can incentivize the biodegradable materials manufacturer to increase green-technology investment and improve the quality of biodegradable materials, to optimize consumer experience and enhance consumer surplus as well as social welfare.

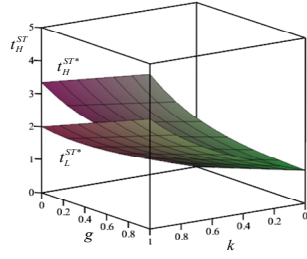
It can be found from Propositions 5-8 that information negotiation within the biodegradable material supply chain can alleviate the negative impact of information asymmetry on the supply chain system to a certain extent. However, its effect is subject to certain threshold conditions. Introducing government subsidies from outside can enhance the manufacturer's willingness to increase investment in green technology. It can also incentivize profit margin growth in all links of the supply chain, improve more consumer surplus and social welfare, and thus alleviate the negative impact of information asymmetry on the biodegradable material supply chain. For example, the UK government invested 62 million pounds in Pulpex Limited, a sustainable packaging company, to build a fiber based biodegradable bottle factory. It helped the company share risks in early technology R&D and production capacity construction, helped the company break through technical bottlenecks, and drove order growth for upstream wood pulp supplier. This practice not only helped the UK reduce plastic packaging pollution and achieve the goal of "eliminating avoidable plastic waste", but also let consumers get better environmental protection experiences. To sum up, we can draw Conclusion 2.

Conclusion 2 Information asymmetry causes supply-chain decisions to deviate from optimality, and information-sharing negotiation can take effect only under specific conditions. Government subsidy can effectively mitigate information asymmetry, incentivize the biodegradable materials manufacturer to increase green-technology investment, raise the profit of each supply-chain participant, and improve consumer surplus as well as social welfare.

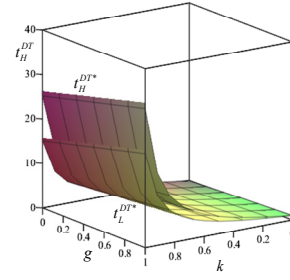
Drawing on the studies of Li and He (2024) and Guo et al. (2025), consumers' green preferences act as an endogenous driving force for industry development and a key driver that guides company' decisions on green production and sales. For example, since the implementation of China's plastic ban policies, consumers' awareness of "biodegradable bags" has increased by more than 50 percent, and their willingness to pay for such bags has also risen. This shift in preference has stimulated industrial growth, pushing the annual compound growth rate of China's biodegradable plastic shopping bag capacity to exceed 20 percent for consecutive years, with the total output value surpassing 10 billion yuan. (https://www.sac.gov.cn/xw/bzhdt/art/2025/art_1113ef079baf469dbc1f76b5448f70a5.html) According to Zhang and Xie (2025), government subsidies serves as an important policy tool that helps the biodegradable materials supply chain overcome the bottlenecks of high initial investment cost and uncertain return. For example, Spain has introduced subsidies that focuses on the use of compostable and biodegradable plastics and other alternative materials. These subsidies effectively

reduce the cost premium of alternative materials compared with traditional plastics, lowers farmers' actual expenses, helps reduce the use of traditional plastics, and supports the sustainable management of plastic waste and the

implementation of a circular economy in greenhouse agriculture in the province of Almería, Spain (Castillo-Díaz et al., 2021).

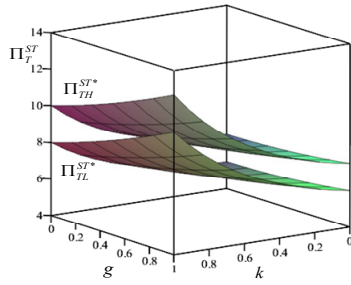


(a) single channel mode

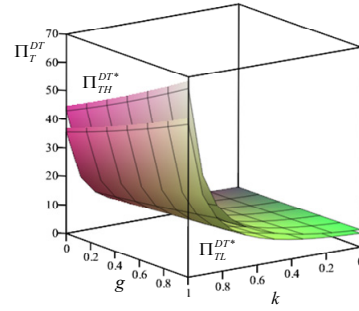


(b) dual channel mode

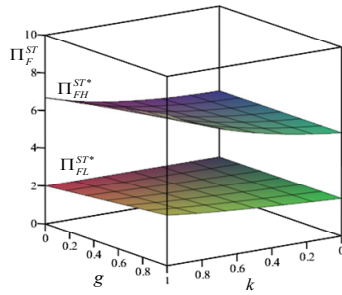
Figure 1. green technology investment level



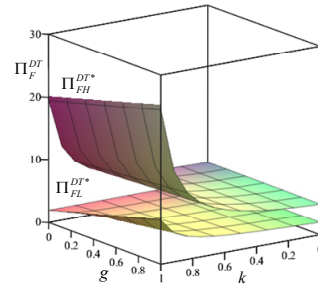
(a) Profit of the supplier under single-channel mode



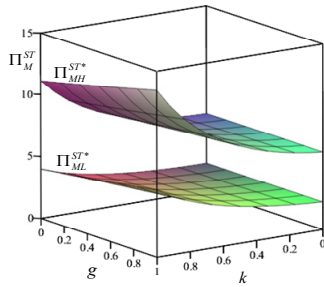
(b) Profit of the supplier under dual-channel mode



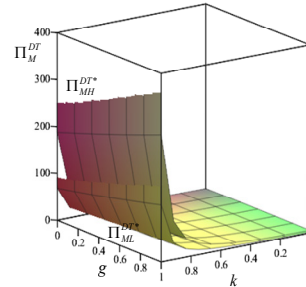
(c) Profit of the manufacturer under single-channel mode



(d) Profit of the manufacturer under dual-channel mode

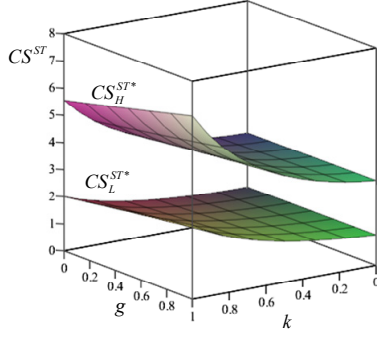


(e) Profit of the sales company under single-channel mode

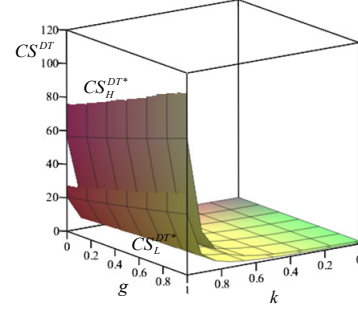


(f) Profits of the sales company under dual-channel mode

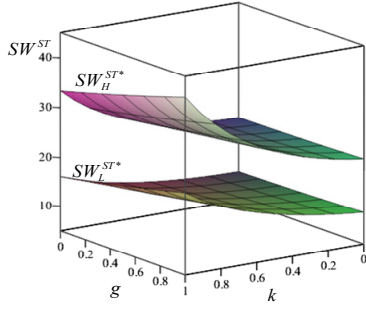
Figure 2. Profit of each member in the biodegradable materials supply chain



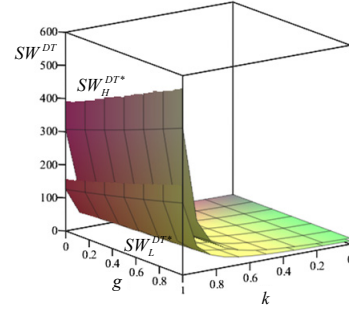
(a) Consumer surplus under single-channel mode



(b) Consumer surplus under dual-channel mode



(c) Social welfare under single-channel mode



(d) Social welfare under single-channel mode

Figure 3. Consumer surplus and social welfare

Based on the above theoretical analysis, this section uses numerical simulation to examine how the consumer green preference coefficient k and the government subsidies level g affect the biodegradable materials supply chain. Following Jin et al. (2023) and considering the constraints on the parameters in the model, we set the parameters as follows: $a_H=10, a_L=8, b=0.4, \theta=0.6, \rho=0.5, R=2$.

Figures 1-3 show that, regardless of the channel chosen by the terminal sales company, the green-technology investment of the biodegradable materials manufacturer, the profit of every member in the biodegradable-material supply chain, consumer surplus and social welfare all rise with increases in the consumer green-preference coefficient and the per-unit green-technology subsidy. This growth is more obvious when the market size is larger. Further comparison shows that consumer green preference has a stronger incentive effect than government subsidies.

The simulation results in Figure 1 come from the basic features of biodegradable materials. These materials offer the core value of being environmentally friendly, but they also have high costs, fast iteration and uncertain returns. When consumer green preference is stronger, consumers are more willing to pay a premium for the green attributes of products. This directly drives the biodegradable materials manufacturer to increase green-technology investment. Government subsidies can lower the cost of such investment. However, if consumer green preference is weak and market acceptance is low, the biodegradable materials manufacturer cannot easily recover costs, and its willingness to invest in technology will decline. Therefore, every member of the biodegradable-material supply chain should make the green performance of products more visible and increase promotion

efforts, so as to stimulate consumers' willingness to pay for green products.

The profit pattern shown in Figure 2 can be clearly confirmed by real industry cases. PLA materials developed by NatureWorks in the United States fit consumers' "plastic reduction" preference, and cooperation with retailers such as Walmart helps achieve a sales premium. In China, Kingfa Science and Technology benefits from rising consumer green preference under the "plastic restriction order," which drives sales of biodegradable plastics and profit growth across the whole supply chain. Both cases confirm that consumer green preference directly drives profit growth. Government subsidies, by contrast, mainly act as a risk buffer in the early stage of industry development. They can only relieve the short-term cost pressure on the biodegradable materials manufacturer for green-technology investment. They cannot create sustained pull from the demand side, so it is hard for them to drive sustained and large profit growth in the supply chain.

The changes in consumer surplus and social welfare in Figure 3 root in the core attribute of biodegradable materials: positive environmental externality. The value of these materials lies not only in their use function, but also in social benefits such as reduced plastic pollution and lower treatment costs. Higher consumer green preference increases consumers' willingness to pay a premium for green product attributes, and raises the market value of products from the demand side. Government subsidies, from the supply side, encourage the biodegradable materials manufacturer to increase technology investment and improve the green quality of products. Consumer green preference and government subsidies form a synergy. Consumers can obtain products that

better meet their green needs, which in turn improves consumer surplus and social welfare.

6. Discussion

(1) discussion I: the effects of market scale and consumer green preferences

First, under market scale information asymmetry, the following relationships hold: $t_H^{j*} > t_L^{j*}$, $\Pi_{IH}^{j*} > \Pi_{IL}^{j*}$, $\Pi_{FH}^{j*} > \Pi_{FL}^{j*}$, $\Pi_{MH}^{j*} > \Pi_{ML}^{j*}$, $CS_H^{j*} > CS_L^{j*}$ and $SW_H^{j*} > SW_L^{j*}$. After the introduction of government subsidies, these relationships evolve into: $t_H^{jT*} > t_L^{jT*}$, $\Pi_{IH}^{jT*} > \Pi_{IL}^{jT*}$, $\Pi_{FH}^{jT*} > \Pi_{FL}^{jT*}$, $\Pi_{MH}^{jT*} > \Pi_{ML}^{jT*}$, $CS_H^{jT*} > CS_L^{jT*}$, $SW_H^{jT*} > SW_L^{jT*}$ ($j = S, D$). Combined with Propositions 6-8, subsidies further amplify the growth of green technology investment, individual profits, consumer surplus and social welfare. It is evident that market scale expansion promotes green investment, supply chain profits and social welfare, and government subsidies further strengthen such positive effects.

Second, as illustrated in $\frac{\partial t_i^{jT*}}{\partial k} > \frac{\partial t_i^{j*}}{\partial k} > 0$, $\frac{\partial \Pi_{iH}^{jT*}}{\partial k} > \frac{\partial \Pi_{iH}^{j*}}{\partial k} > 0$, $\frac{\partial \Pi_{iL}^{jT*}}{\partial k} > \frac{\partial \Pi_{iL}^{j*}}{\partial k} > 0$, $\frac{\partial \Pi_{iF}^{jT*}}{\partial k} > \frac{\partial \Pi_{iF}^{j*}}{\partial k} > 0$, $\frac{\partial \Pi_{iM}^{jT*}}{\partial k} > \frac{\partial \Pi_{iM}^{j*}}{\partial k} > 0$, $\frac{\partial CS_i^{jT*}}{\partial k} > \frac{\partial CS_i^{j*}}{\partial k} > 0$, $\frac{\partial SW_i^{jT*}}{\partial k} > \frac{\partial SW_i^{j*}}{\partial k} > 0$, under market scale information asymmetry, the manufacturer's green technology investment, the profits of the patent technology supplier and the sales company, the manufacturer's profits in high-scale market overall supply chain profits, consumer surplus and social welfare all increase with the consumer green preference coefficient. Government subsidies reinforce this trend. By contrast, the manufacturer's profits in low-scale market are not affected by consumer green preferences. Accordingly, Conclusion 3 is proposed.

Conclusion 3. Market size and consumer green preferences exert synergistic effects in promoting green technology investment, supply chain profits, consumer surplus, and social welfare, and government subsidies can further strengthen these synergistic effects.

(2) discussion II: the effects of contract design and channel model selection

First, as shown in $\frac{\partial t_i^{D*}(r_i, f_i)}{\partial r_i^{D*}} < \frac{\partial t_i^{S*}(r_i, f_i)}{\partial r_i^{S*}} < 0$ and $\frac{\partial t_i^{DT*}(r_i, f_i)}{\partial r_i^{DT*}} < \frac{\partial t_i^{ST*}(r_i, f_i)}{\partial r_i^{ST*}} < 0$ ($i = H, L$), whether government subsidies are implemented or not, a higher royalty rate suppresses the manufacturer's green technology investment, and this inhibitory effect is more pronounced under the dual-channel model. Combined with Theorem 1, the royalty rate equals 0 in high-scale market. According to $t_H^{j*} > t_L^{j*}$ and $t_H^{jT*} > t_L^{jT*}$ ($j = S, D$), the manufacturer's green investment reaches the maximum level in this case; in the low market scale, the royalty rate is negatively correlated with green investment. This indicates that the royalty rate exerts a significant inhibitory effect on green investment in both subsidized and unsubsidized contexts. Only when the royalty rate is set to 0 under high-scale market can green technology investment be maximized.

Second, as indicated by $t_i^{S*} < t_i^{D*}$ and $t_i^{ST*} < t_i^{DT*}$, the dual-channel mode encourages the manufacturer to increase green technology investment, regardless of market scale and government subsidies. Calculations of the subsidized models show that when $0 < \theta < \theta_s$ or $\theta_6 < \theta < 1$, $\Pi_{MH}^{DT*} > \Pi_{MH}^{ST*}$, the sales company chooses the dual-channel mode; when $0 < \theta < \theta_s$ or $\theta_6 < \theta < 1$, $\Pi_{ML}^{DT*} < \Pi_{ML}^{ST*}$, the company still selects the dual-channel mode. Combined with Proposition 13), although the dual-channel mode can stimulate the manufacturer's green investment, the sales company will only adopt this channel when consumer channel preferences meet specific threshold conditions.

In summary, the rational matching of patent licensing contracts and channel modes can substantially promote green technology investment. Reducing the royalty rate and adopting the dual-channel model can maximize green investment, which depends on the offline channel preference threshold.

$$\text{Since } \frac{\partial t_L^{DT*}(r_i, f_i)}{\partial r_L^{DT*}} = \frac{\partial t_L^{D*}(r_i, f_i)}{\partial r_L^{D*}} < \frac{\partial t_L^{ST*}(r_i, f_i)}{\partial r_L^{ST*}} = \frac{\partial t_L^{S*}(r_i, f_i)}{\partial r_L^{S*}} < 0$$

and $t_H^{jT*} = t_H^{j*} > t_L^{j*} = t_L^{jT*}$ ($j = S, D$), the impact of royalty rates on green investment is not altered by government subsidies. Combined with Proposition 6, the dual-channel model exerts a stronger green investment incentive under government subsidies. Thus, Conclusion 4 is drawn.

Conclusion 4. The rational matching of patent licensing contracts and channel modes can effectively motivate the manufacturer to increase green technology investment, and government subsidies can further enhance such incentive effects

7. Summary

7.1. Research Conclusion

First, to address the realistic constraint of asymmetric market scale information, we build a three-echelon supply chain principal agent model that includes a patent technology supplier, a biodegradable materials manufacturer, and a terminal sales company. By comparing the game equilibrium solutions when the terminal sales company chooses single or dual channel sales, we study the optimal licensing contract design and channel selection strategy. Second, compared with the symmetric information case, we reveal the value of market scale information and analyzes how supply chain members can rely on their own actions to disclose true information. Finally, by introducing government subsidies from outside, we discuss how it can reduce the negative impact of information asymmetry on the biodegradable materials supply chain.

The research shows that: (1) Under asymmetric market scale information, both the patent technology supplier and the terminal sales company will strategically design patent licensing contracts and choose sales channels. Specifically, the patent technology supplier will use a single form contract with a fixed fee under high market scale, and the two part tariff contract with "royalty + fixed fee" under low market scale. The terminal sales company will flexibly choose sales channel based on consumers' offline channel preference, green preference, market scale, etc. (2) The reasonable matching between patent licensing contract design and channel selection strategy can encourage the biodegradable

materials manufacturer to significantly increase its investment in green technology, accelerate the diffusion and application of green technology in the biodegradable materials supply chain. (3) Asymmetric market scale information can cause the biodegradable materials supply chain to deviate from the optimal state. Although information sharing negotiations can reduce the negative impact of information asymmetry, supply chain members themselves cannot always reach such negotiations. Internal information sharing requires that members' bargaining power to meet certain thresholds. However, external government subsidies can significantly reduce the negative impact of information asymmetry by encouraging the biodegradable materials manufacturer to invest more in green technology, increasing the profit of all supply chain members, and improving consumer surplus and social welfare. (4) In terms of increasing the profit of the biodegradable materials supply chain, improving consumer surplus and enhancing social welfare, market scale and the consumer green preference coefficient have a synergistic promoting effect, and this effect becomes more significant when government subsidies are introduced.

7.2. Managerial Implications

The managerial implications of this study are as follows: (1) The patent technology supplier should adopt a pure fixed-fee contract under a high market scale to reduce risks and guarantee revenues. Under a low market scale, it should adopt a two-part tariff contract to ease capital pressure and share risks. The terminal sales company shall accurately capture information on market scale and consumer preferences, optimize channel selection, and promote the value transformation of green technology. (2) In view of supply-chain performance deviation caused by information asymmetry, government subsidy can be applied to relieve enterprises' cost burden, lower information barriers and improve supply-chain efficiency. (3) All supply-chain participants should attach importance to the synergy between market scale and consumer green preference, actively share market information, optimize individual decisions, and achieve a win-win situation for both economic and environmental benefits.

7.3. Limitations and Future Research

This study investigates technology licensing from a patent supplier to a single biodegradable materials manufacturer. In practice, however, patent suppliers commonly adopt ordinary licensing contracts for multiple manufacturers. Accordingly, future research can extend the model to a multi-manufacturer supply chain and explore optimal patent licensing contract design in such complex market scenarios. Although multi-agent settings increase contractual design complexity, they also improve model practicality. Furthermore, this study only considers market scale information asymmetry, where the patent supplier is the information-disadvantaged party, and examines corresponding information disclosure strategies. In practice, rapid R&D technological updates may enable patent suppliers to become information-advantaged by concealing information regarding future technological upgrades and competing technologies. Future studies can establish game models incorporating product and substitute competition to further explore licensing contract design, channel selection, and information disclosure strategies.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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Appendix

Proof of the game equilibrium solution under Case S. We solve the three-echelon dynamic game using backward induction. The detailed process is as follows.

1) Stage 3 Solution. Given the decision (r_i^S, f_i^S) of the patent technology supplier and decision (t_i^S, w_i^S) of the manufacturer, the terminal sales company's decision making problem is: $\text{Max}_{p_i} \Pi_{Mi}^S = (p_i - w_i)q_i$. From $\frac{\partial^2 \Pi_{Mi}^S}{\partial p_i^2} = -2 < 0$, we

can derive that Π_{Mi}^S is a strictly concave function of p_i , so the company has a unique optimal solution for its decision. Let $\frac{\partial \Pi_{Mi}^S}{\partial p_i} = a_i + w_i + kt_i - 2p_i = 0$, then the company's optimal

reaction function is $p_i^{S*}(w_i, t_i, r_i, f_i) = \frac{a_i + kt_i + w_i}{2}$.

2) Stage 2 Solution of the Game. Substitute $p_i^{S*}(w_i, t_i, r_i, f_i)$ into Π_{Fi}^S , then the decision making problem of the manufacturer is: $\text{Max}_{w_i, t_i} \Pi_{Fi}^S = (w_i - r_i)q_i - \frac{1}{2}t_i^2 - f_i$. From

$\frac{\partial \Pi_{Fi}^S}{\partial w_i} = \frac{a_i + kt_i + r_i - 2w_i}{2}$ and $\frac{\partial \Pi_{Fi}^S}{\partial t_i} = \frac{k(w_i - r_i) - 2t_i}{2}$, the

Hessian matrix Π_{Fi}^S of $\begin{pmatrix} 1 & k/2 \\ k/2 & 1 \end{pmatrix}$ is negative definite at this time, which means Π_{Fi}^S is a strictly concave function of w_i and t_i . Thus, the manufacturer has a unique optimal solution for

its decision. Let $\frac{\partial \Pi_{Fi}^S}{\partial w_i} = \frac{\partial \Pi_{Fi}^S}{\partial t_i} = 0$, then the optimal reaction

functions of the manufacturer are $t_i^{S*}(r_i, f_i) = \frac{k(a_i - r_i)}{4 - k^2}$ and

$$w_i^{S*}(r_i, f_i) = \frac{2a_i + (2 - k^2)r_i}{4 - k^2}.$$

Before solving for the patent technology supplier's decision in the first stage, we first substitute $t_i^{S*}(r_i, f_i)$ and $w_i^{S*}(r_i, f_i)$ into $p_i^{S*}(w_i, t_i, r_i, f_i)$ and $q_i^{S*}(w_i, t_i, r_i, f_i)$. Given the patent technology supplier's decision (r_i^{DN}, f_i^{DN}) , we can obtain the optimal reaction functions and demand quantities for all parties in the S model as follows:

$$p_i^{S*}(r_i, f_i) = \frac{3a_i + (1 - k^2)r_i}{4 - k^2}, \quad w_i^{S*}(r_i, f_i) = \frac{2a_i + (1 - k^2)r_i}{4 - k^2},$$

$$t_i^{S*}(r_i, f_i) = \frac{k(a_i - r_i)}{4 - k^2}, \quad q_i^{S*}(r_i, f_i) = \frac{r_i - a_i}{4 - k^2}.$$

3) Stage 1 Solution of the Game. At this stage, the optimal decision problem of the patent technology supplier is as follows:

$$\begin{aligned} \text{Max}_{r_H, r_L, f_H, f_L} \Pi_T^S &= \rho(r_H q_H + f_H) + (1 - \rho)(r_L q_L + f_L) \\ \text{s.t.} \quad &\begin{cases} IR(H): \Pi_{FH}^S(w_H^{S*}, t_H^{S*} | r_H, f_H) \geq R \\ IR(L): \Pi_{FL}^S(w_L^{S*}, t_L^{S*} | r_L, f_L) \geq R \\ IC(H): \Pi_{FH}^S(w_H^{S*}, t_H^{S*} | r_H, f_H) \geq \Pi_{FHL}^S(w_{HL}^{S*}, t_{HL}^{S*} | r_L, f_L) \\ IC(L): \Pi_{FL}^S(w_L^{S*}, t_L^{S*} | r_L, f_L) \geq \Pi_{FLH}^S(w_{LH}^{S*}, t_{LH}^{S*} | r_H, f_H) \end{cases} \end{aligned}$$

It is easy to verify that $\Pi_{FHL}^S(w_{HL}^{S*}, t_{HL}^{S*} | r_L, f_L) - \Pi_{FL}^S(w_L^{S*}, t_L^{S*} | r_L, f_L) > 0$ holds. Under the constraints IR and IC, we have $\Pi_{FH}^S(w_H^{S*}, t_H^{S*} | r_H, f_H) \geq \Pi_{FHL}^S(w_{HL}^{S*}, t_{HL}^{S*} | r_L, f_L) > \Pi_{FL}^S(w_L^{S*}, t_L^{S*} | r_L, f_L) \geq R$, which implies that IR(H) always holds. Based on the K-T conditions, we construct the Lagrange function as follows:

$$Y(r_H, r_L, f_H, f_L, \lambda_1, \lambda_2, \lambda_3) = \rho \Pi_{FH}^S + (1 - \rho) \Pi_{FL}^S + \lambda_1 (\Pi_{FH}^S - R) + \lambda_2 (\Pi_{FH}^S - \Pi_{FHL}^S) + \lambda_3 (\Pi_{FL}^S - \Pi_{FLH}^S),$$

, From the K-T conditions $\frac{\partial Y}{\partial r_H} = 0, \frac{\partial Y}{\partial r_L} = 0, \frac{\partial Y}{\partial f_H} = 0, \frac{\partial Y}{\partial f_L} = 0$,

$$\lambda_1 \geq 0 \text{ and } \frac{\partial Y}{\partial \lambda_1} = 0, \quad \lambda_2 \geq 0 \text{ and } \frac{\partial Y}{\partial \lambda_2} = 0, \quad \lambda_3 \geq 0 \text{ and } \frac{\partial Y}{\partial \lambda_3} = 0,$$

we can solve for $r_H^{S*}, r_L^{S*}, f_H^{S*}, f_L^{S*}$. The details

are as follows:

$$\begin{aligned} \frac{\partial Y}{\partial r_H} &= \frac{(\rho - \lambda_3)a_H + a_L \lambda_2 - (2\rho + \lambda_2 - \lambda_3)r_H}{4 - k^2} = 0, \\ \frac{\partial Y}{\partial r_L} &= \frac{a_H \lambda_3 - a_L(\lambda_1 + \lambda_2 + \rho - 1) + (\lambda_1 + \lambda_2 - \lambda_3 - 2(1 - \rho))r_L}{4 - k^2} = 0, \\ \frac{\partial Y}{\partial f_H} &= \rho + \lambda_2 - \lambda_3 = 0, \quad \frac{\partial Y}{\partial f_L} = -\lambda_1 - \lambda_2 + \lambda_3 - \rho + 1 = 0, \\ \frac{\partial Y(r_H, r_L, f_H, f_L, \lambda_1, \lambda_2, \lambda_3)}{\partial \lambda_1} &= \lambda_1 (\Pi_{FH}^S - R) = \left(\frac{(a_L - r_L)^2}{8 - 2k^2} - f_L - R \right) \lambda_1 = 0, \\ \frac{\partial Y(r_H, r_L, f_H, f_L, \lambda_1, \lambda_2, \lambda_3)}{\partial \lambda_2} &= \lambda_2 (2(r_H - r_L)a_L + 2(4 - k^2)(f_H - f_L) - (r_H^2 - r_L^2)) = 0, \\ \frac{\partial Y(r_H, r_L, f_H, f_L, \lambda_1, \lambda_2, \lambda_3)}{\partial \lambda_3} &= \lambda_3 (2(r_H - r_L)a_H + 2(4 - k^2)(f_H - f_L) - (r_H^2 - r_L^2)) = 0, \end{aligned}$$

For the above-mentioned conditions to hold:

$$1) \text{ When } \lambda_3 = 0, \text{ it follows from } \frac{\partial Y}{\partial f_H} = \rho + \lambda_2 - \lambda_3 = 0$$

that $\lambda_2 = -\rho < 0$, which contradicts $\lambda_g \geq 0$. Thus, this case is discarded.

2) When $\lambda_2 = 0$, it follows from $\frac{\partial Y}{\partial f_H} = \rho + \lambda_2 - \lambda_3 = 0$ that

$\lambda_3 = \rho$, and it follows from $\frac{\partial Y}{\partial f_L} = -\lambda_1 - \lambda_2 + \lambda_3 - \rho + 1$ that

$\lambda_1 = 1$. Substituting into the above KT conditions yields:

$$\frac{\partial Y}{\partial r_H} = \frac{\rho r_H}{4 - k^2} = 0, \frac{\partial Y}{\partial r_L} = \frac{(a_H - a_L + r_L)\rho - r_L}{4 - k^2} = 0, \frac{\partial Y}{\partial f_H} = 0,$$

$$\frac{\partial Y}{\partial f_L} = 0, \quad \lambda_1(\Pi_{FL}^S - R) = \frac{(a_L - r_L)^2}{8 - 2k^2} - f_L - R = 0,$$

$$\lambda_2(\Pi_{FH}^S - \Pi_{FHL}^S) = 0,$$

$$\lambda_3(\Pi_{FL}^S - \Pi_{FLH}^S) = \frac{\rho(2(r_H - r_L)a_H + 2(4 - k^2)(f_H - f_L) - (r_H^2 - r_L^2))}{8 - 2k^2} = 0.$$

Solving the simultaneous equations at this time yields,

$$r_H^{S*} = 0, \quad r_L^{S*} = \frac{\rho(a_H - a_L)}{1 - \rho}, \quad f_H^{S*} = \frac{2(a_H - a_L)r_L + a_L^2}{2(4 - k^2)} - R,$$

$$f_L^{S*} = \frac{(a_L - r_L)^2}{2(4 - k^2)} - R.$$

3) When both λ_2 and λ_3 are greater than 0, it follows from

$\frac{\partial Y}{\partial f_H} = \rho + \lambda_2 - \lambda_3 = 0$ that $\lambda_3 = \lambda_2 + \rho$, and it follows from

$\frac{\partial Y}{\partial f_L} = -\lambda_1 - \lambda_2 + \lambda_3 - \rho + 1 = 0$ that $\lambda_1 = 1$. Substituting into the

above KT conditions yields:

$$\frac{\partial Y}{\partial r_H} = \frac{(\rho - \lambda_3)(a_H - a_L) - \rho r_H}{4 - k^2} = 0,$$

$$\frac{\partial Y}{\partial r_L} = \frac{(a_H - a_L)\lambda_3 - (1 - \rho)r_L}{4 - k^2} = 0, \quad \frac{\partial Y}{\partial f_H} = 0, \quad \frac{\partial Y}{\partial f_L} = 0,$$

$$\frac{\partial Y(r_H, r_L, f_H, f_L, \lambda_1, \lambda_2, \lambda_3)}{\partial \lambda_1} \lambda_1 = \lambda_1(\Pi_{FL}^S - R) = \frac{(a_L - r_L)^2}{8 - 2k^2} - f_L - R = 0,$$

$$\lambda_2(\Pi_{FH}^S - \Pi_{FHL}^S) = \frac{(\lambda_3 - \rho)(2(r_H - r_L)a_H + 2(4 - k^2)(f_H - f_L) - (r_H^2 - r_L^2))}{8 - 2k^2} = 0,$$

$$\lambda_3(\Pi_{FL}^S - \Pi_{FLH}^S) = \frac{\lambda_3(2(r_H - r_L)a_H + 2(4 - k^2)(f_H - f_L) - (r_H^2 - r_L^2))}{8 - 2k^2} = 0.$$

Solving the simultaneous equations for r_H^{S*} , r_L^{S*} , f_H^{S*} ,

f_L^{S*} and λ_2 yields no feasible solution, so this case is discarded.

Therefore, only the solution set consisting of $\lambda_1 = 1, \lambda_2 = 0$

and $\lambda_3 = \rho$ satisfies the non-negativity condition. Substituting these values, the optimal royalty rate and lump-sum fixed licensing fee can be derived, and further r_H^{S*} , r_L^{S*} , f_H^{S*} and f_L^{S*} can be obtained.

At equilibrium, the optimal decisions, profit, overall supply chain profit and demand quantities of all parties in the biodegradable product supply chain are as follows: $r_H^{S*} = 0$,

$$r_L^{S*} = \frac{\rho(a_H - a_L)}{1 - \rho}, \quad f_H^{S*} = \frac{2(a_H - a_L)r_L + a_L^2}{2(4 - k^2)} - R,$$

$$f_L^{S*} = \frac{(a_L - r_L)^2}{2(4 - k^2)} - R, \quad t_H^{S*} = \frac{ka_H}{4 - k^2}, \quad t_L^{S*} = \frac{k(a_L - r_L)}{4 - k^2}, \quad w_H^{S*} = \frac{2a_H}{4 - k^2},$$

$$w_L^{S*} = \frac{2a_L + (2 - k^2)r_L}{4 - k^2}, \quad p_H^{S*} = \frac{3a_H}{4 - k^2}, \quad p_L^{S*} = \frac{3a_L + (1 - k^2)r_L}{4 - k^2},$$

$$q_H^{S*} = \frac{a_H}{4 - k^2}, \quad q_L^{S*} = \frac{a_L - r_L}{4 - k^2}, \quad \Pi_{TH}^{S*} = \frac{2(a_H - a_L)r_L + a_L^2}{2(4 - k^2)} - R,$$

$$\Pi_{TL}^{S*} = \frac{a_L^2 - r_L^2}{2(4 - k^2)} - R, \quad \Pi_{FH}^{S*} = \frac{(a_H - a_L)(a_H + a_L - 2r_L)}{2(4 - k^2)} - R,$$

$$\Pi_{FL}^{S*} = R, \quad \Pi_{ML}^{S*} = \frac{a_H^2}{(4 - k^2)^2}, \quad \Pi_{ML}^{S*} = \frac{(a_L - r_L)^2}{(4 - k^2)^2}.$$

Proof of the game equilibrium solution under the case D . Refer to the proof of the game equilibrium solution under Case S in the Appendix.

Proof of Proposition 1. 1) If $\sqrt{\frac{4(1-2b)}{3}} < k < 1$, then

$$\Pi_{TH}^{D*} - \Pi_{TH}^{S*} = \frac{(4(1-b)r_L(a_H - a_L) + a_L^2)(3k^2 + 8b - 4)}{(2 - 2b - k^2)(4 - k^2)} > 0,$$

$$\Pi_{TL}^{D*} - \Pi_{TL}^{S*} = \frac{(a_L - 2(1-b)r_L)^2(3k^2 + 8b - 4)}{8(2 - 2b - k^2)(4 - k^2)} > 0, \quad \text{otherwise,}$$

$$\Pi_{TH}^{D*} < \Pi_{TH}^{S*}, \quad \Pi_{TL}^{D*} < \Pi_{TL}^{S*} \quad 2) \quad \text{If } \theta_1 < \theta < \theta_2, \quad \text{then}$$

$$\Pi_{MH}^{D*} - \Pi_{MH}^{S*} = \frac{(5 + (3 - 16\theta(1 - \theta))b^2 - 4b(2 - k^2) - k^4 + 4k^2)(1 - 2\theta)^2 - (1 - \theta)\theta a_H^2}{8(1 + b)(2 - 2b - k^2)^2} - \frac{a_H^2}{(4 - k^2)^2} < 0$$

$$, \quad \text{otherwise,} \quad \Pi_{MH}^{D*} > \Pi_{MH}^{S*}. \quad \text{If } \theta_3 < \theta < \theta_4, \quad \text{then}$$

$$\Pi_{ML}^{D*} - \Pi_{ML}^{S*} = \frac{(5 + (3 - 16\theta(1 - \theta))b^2 - 4b(2 - k^2) - 4(2 - k^2)^2\theta(1 - \theta) - (4 - k^2)^2k^2a_L^2 - (a_L - 2(1 - b)r_L)^2}{8(1 + b)(2 - 2b - k^2)^2} - \frac{(a_L - 2(1 - b)r_L)^2}{(4 - k^2)^2}$$

$$- \frac{4r_L(1 + b)(1 - b)^2(a_L - (1 - b)r_L)}{8(1 + b)(2 - 2b - k^2)^2} < 0, \quad \text{otherwise,} \quad \Pi_{ML}^{D*} > \Pi_{ML}^{S*}. \quad 3)$$

If $k > \sqrt{\frac{4(1-2b)}{3}}$, then

$$\Pi_{FH}^{D*} - \Pi_{FH}^{S*} = \frac{(a_H - a_L)(a_H + a_L - 4(1 - b)r_L)^2(3k^2 + 8b - 4)}{8(2 - 2b - k^2)(4 - k^2)} > 0,$$

$$\text{otherwise,} \quad \Pi_{FH}^{D*} < \Pi_{FH}^{S*}, \quad \Pi_{FL}^{D*} - \Pi_{FL}^{S*} = R - R = 0. \quad \text{Where,}$$

$$\theta_1 = \Lambda_1 - \Lambda_2, \quad \theta_1 = \Lambda_1 + \Lambda_2, \quad \theta_3 = \Lambda_1 - \Lambda_3, \quad \theta_4 = \Lambda_1 + \Lambda_3, \quad \text{and}$$

$$\theta_1 < \theta_2, \quad \theta_3 < \theta_4. \quad \Lambda_1 = \frac{8(1 - b) - (2(3 - b) - k^2)k^2}{2(2 - 2b - k^2)(4 - k^2)},$$

$$\Lambda_2 = \frac{\sqrt{(7 + b^2 + 8b)k^4 + 8(2 - 4b - 3k^2)(1 - b^2)}}{2(2 - 2b - k^2)(4 - k^2)},$$

$$\Lambda_3 = \frac{\sqrt{(1 + b)(a_L - 2(1 - b)r_L)^2(8(2 - 4b - 3k^2)(1 - b^2) + (7 + b^2 + 8b)k^4)}}{2(2 - 2b - k^2)(4 - k^2)a_L}.$$

Solution to Model SN -Solution to Model DN . Refer to the proof of the game equilibrium solution under Case S .

Proofs of Propositions 2-4. All refer to the proof of Proposition 1.

Proof of Proposition 5. For the patent technology supplier and the biodegradable materials manufacturer to reach an information-sharing negotiation,

$$\tau_1(\Pi_{Ti}^{SN*} + \Pi_{Fi}^{SN*}) - \Pi_{Ti}^{S*} = \frac{r_L^2 - (1 - \tau_1)a_L^2}{8 - 2k^2} + R > 0 \quad \text{and}$$

$$(1 - \tau_1)(\Pi_{Ti}^{SN*} + \Pi_{Fi}^{SN*}) - \Pi_{Fi}^{S*} = \frac{(1 - \tau_1)a_L^2}{8 - 2k^2} - R > 0 \quad \text{should be}$$

satisfied under the single-channel mode, in which case $\tau_1 \in (\bar{\tau}_1, \underline{\tau}_1)$ holds. Under the dual-channel mode,

$$\tau_2(\Pi_{Ti}^{DN*} + \Pi_{Fi}^{DN*}) - \Pi_{Ti}^{D*} = \frac{(1 - \tau_2)a_L^2 + 4(1 - b)^2r_L^2}{8(2 - 2b - k^2)} + R > 0 \quad \text{and}$$

$$(1 - \tau_2)(\Pi_{Ti}^{DN*} + \Pi_{Fi}^{DN*}) - \Pi_{Fi}^{D*} = \frac{(1 - \tau_2)a_L^2}{8(2 - 2b - k^2)} - R > 0 \quad \text{need to be}$$

satisfied, in which case $\tau_2 \in (\bar{\tau}_2, \underline{\tau}_2)$ holds. Among them,

$$\begin{aligned}\bar{\tau}_1 &= \frac{a_L^2 - r_L^2 - 2(4 - k^2)R}{a_L^2}, & \bar{\tau}_1 &= \frac{a_L^2 - 2(4 - k^2)R}{a_L^2}, \\ \bar{\tau}_2 &= \frac{a_L^2 - 4(1 - b)^2 r_L^2 - 8(2 - 2b - k^2)R}{a_L^2} & \text{and} \\ \bar{\tau}_2 &= \frac{a_L^2 - 8(2 - 2b - k^2)R}{a_L^2}.\end{aligned}$$

Solution to Model *ST* and Solution to Model *DT*. Refer to the proof of the game equilibrium solution under Case *S* in the Appendix.

Proofs of Propositions 6-8. All refer to the proof of Proposition 1 in the Appendix.